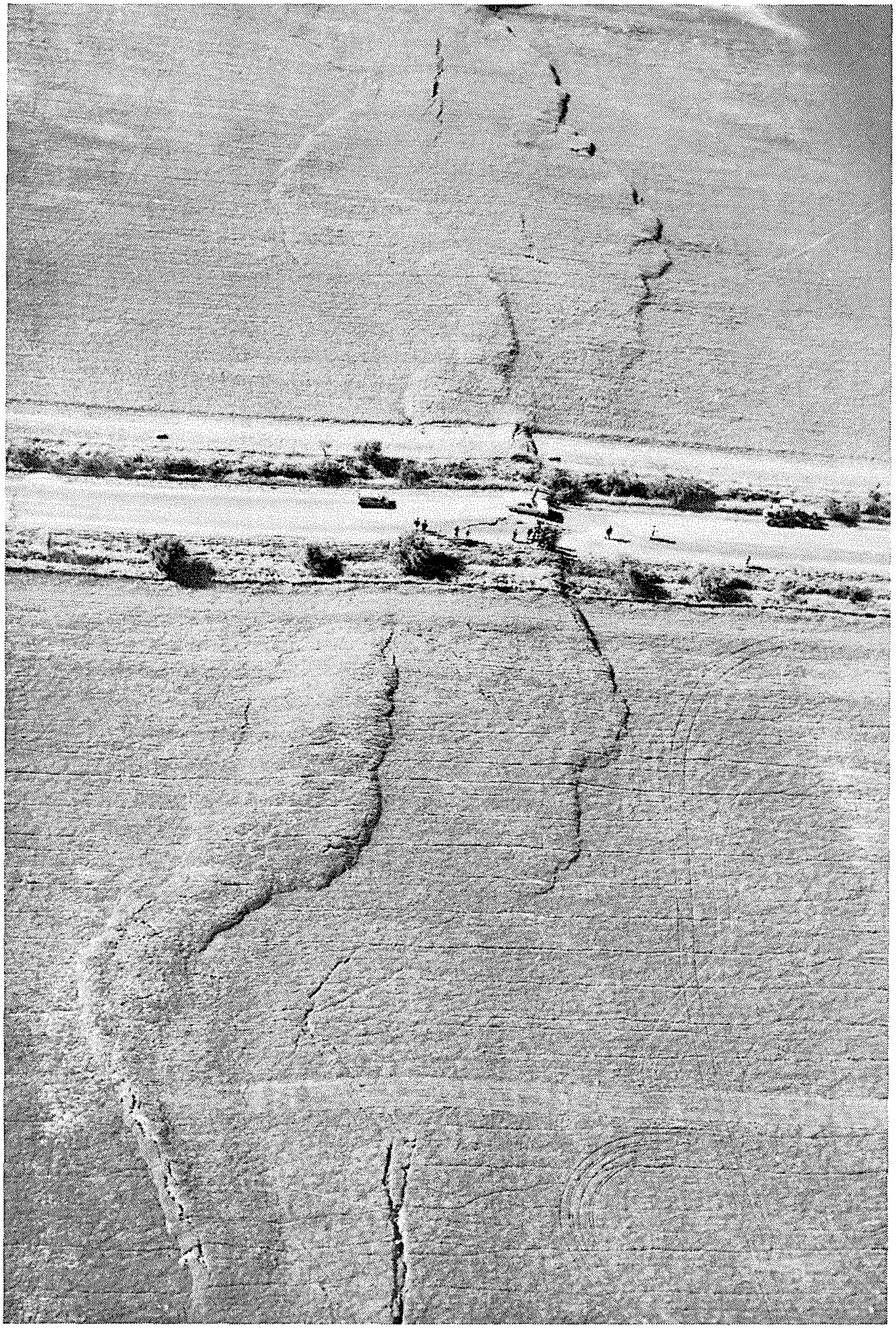
GEOLOGICAL SURVEY OF WESTERN AUSTRALIA

BULLETIN 126

THE MECKERING AND CALINGIRI EARTHQUAKES OCTOBER 1968 AND MARCH 1970

1980



1. The Meckering Fault as it crosses the Great Eastern Highway southwest of the town (Photo: W.A. Newspapers).

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THE MECKERING AND CALINGIRI EARTHQUAKES OCTOBER 1968 AND MARCH 1970

by
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1980

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PREFACE

This bulletin is concerned with an important but transient phenomenon, the Meckering Earthquake of 14th October 1968 and its aftershocks. The earthquake, although moderate by world standards, had a magnitude of 6.9, and was the largest and one of the most damaging in the recorded history of Australia. The small town of Meckering was wrecked, and the tremor was felt throughout much of the state. The event brought a new appreciation of the potential for earthquake damage to the southwest portion of Western Australia which includes the capital, Perth.

Surface faulting is rare, even in major seismic zones, and the fault scarps developed in the Meckering earthquake and the Calingiri aftershock were the first recorded examples in Australia. Both faults were low angle thrust faults, a type not commonly found elsewhere in the world.

The authors have shown that by detailed analysis of field data an insight can be gained into the underlying mechanism of faulting in the South West Seismic Zone. This bulletin is intended as a permanent record of an event whose surface expression has already been largely obscured by erosion and agricultural activity.

The senior author, F. R. Gordon, was in charge of all the field investigations but unfortunately resigned before completing a written account of his investigations. After some years delay it was decided that J. D. Lewis, who had assisted with the regional geological mapping of the fault line should develop the available material into this Bulletin. Mr. Gordon has assisted him in this difficult task for which the Geological Survey is grateful. This is the first bulletin produced by the Geological Survey on earthquakes, and we trust that future events will not cause need for another. As well as for its scientific and historical value the bulletin should be of particular interest to those who experienced the occurrence.

J. H. LORD
Director

1 August 1978

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SUMMARY

Chapter 1. This bulletin reports the results of a study of the Meckering Earthquake of 14th October 1968, and the smaller Calingiri Earthquake of 11th March 1970. The Meckering Earthquake was one of the largest recorded in Australia, and the first to cause surface faulting. The earthquake was felt throughout the southern half of Western Australia, and resulted in considerable property damage.

Meckering is situated near the western margin of the Archaean Yilgarn Block. The regional geology of the district (Plate 1) consists of a series of granite plutons with a general north-northwest foliation, remnants of older gneiss, and younger dolerite dykes. The area mapped lies on the western edge of a downwarped zone of gneisses which outline the main seismic zone of Western Australia. No correlation between geology and faulting was found.

Chapter 2. Meckering is a small agricultural township about 130 km east of Perth, and lies astride all the main communications to the eastern states of Australia and the water supply pipeline to Kalgoorlie.

The earthquake damaged or destroyed most houses in the town, but there were only 17 injuries and no deaths. Only timber houses withstood the shaking, but the degree of damage was also controlled by the foundation material and orientation of the structure with respect to the shaking. Masonry houses built on alluvial sand suffered most damage.

The Eastern Goldfields Water Supply pipeline, the Great Eastern Highway, the transcontinental railway, and telephone lines were all disrupted at the fault scarp. Many minor roads and bridges, and the electricity supply to houses and farms were also damaged. The pipeline was also fractured, in the week following the earthquake, at points where it crossed developing tension fractures. Two reinforced concrete grain storage silos suffered only minor damage.

The fault scarp dammed several tributaries of the Mortlock River, but the main stream was less affected as it ran parallel to the fault throughout part of its length. Flooding was minimized by regrading the stream beds, but more subtle changes in the landscape may take many years to manifest themselves.

Chapter 3. The Meckering Earthquake was felt over an area 700 km in radius and caused damage in many towns, particularly Northam, York and Perth, Significant damage was confined to the area within the MM VI isoseismal.

In Perth the intensity was commonly MM V and damage consisted mainly of cracked walls and plaster. Isolated higher intensities of MM VI were a reflection of poor foundation geology. Damage in areas of unconsolidated sands and clays was greater than in areas underlain by coastal limestone.

The isoseismal map for the Meckering Earthquake shows that shaking was more easily propagated to the east than to the west. The shape of the isoseismals can be correlated with the structure and geology of the region.

Chapter 4. Several minor tremors have been felt in the Meckering district since 1900, but for a number of years before 1968 the area had been seismically quiet. Foreshocks to the main event were felt on 31st August, 29th September, and 3rd October 1968.

Seismic data for the main event are:

Time: 14 October 1968, at 02 58 50.9 hrs U.T.

Location: Lat. 31°36′S Long. 117°0′E, 2.5 km N.E. of Meckering.

Magnitude: M_L 6.9, M_S 6.8, m_b 6.0.

Depth: 7±5 km.

At Meckering, the initial strong motion was a near vertical impulse, followed by two periods of east-west shaking. From observations of displaced monuments a radial pattern of movement is inferred.

The pattern of aftershock epicentres suggests they were associated with an extension of the Meckering Fault and a radial fault. Strain release curves also suggest radial fracturing.

Chapter 5. Three major faults were produced by the earthquake. The largest, the Meckering Fault (Plate 2) was an arcuate dextral thrust fracture 37 km long, with several dextral offsets in the fault trace. The Splinter Fault, a 9 km long dextral thrust fault, was parallel to and 1.5 km northwest of the northern section of the Meckering Fault. The Burges Fault Complex (Plate 3), showed a dominant dextral strike-slip movement, and was a radial fault which caused a 1.6 km dextral offset to the trace of the Meckering Fault.

The maximum displacement of the Meckering Fault was 2 m vertical, 1.5 m dextral slip and 2.4 m heave, measured at the centre of the arc. Displacements decreased both north and south. The fault plane was exposed at several points and its dip varied from 28° to 55°, with an average of 43°. A cadastral survey at ten stations showed a calculated dip of 36°-49°, averaging 42°. The same survey showed a net slip varying regularly from less that 1 m near the ends of the fault trace to 3.08 m at the centre. Slickensides were observed at only three points.

The morphology of the fault scarp was related to the nature and thickness of the soil cover and a variety of simple structures was found (Fig. 41). Generally the fault consisted of a single thrust fracture, but in some areas there were a number of associated fault planes which gave rise to a variety of fracture patterns.

The Splinter Fault was similar in every way to the Meckering Fault, but displacements were only about a quarter of those on the main fault and the fault plane appeared to dip at less than 30°.

The Burges Fault consisted of a number of parallel fractures, often showing different styles of movement on each branch. The dominant movement was a dextral strike slip of up to 1.5 m. The principal fault plane dipped 80° to the south, and showed reverse uplift of 1 m. Slickensides indicated that movement took place in two stages, first the dextral strike-slip, followed by nearly vertical reverse displacement.

The Burges Fault Complex also contains a number of minor branch faults, including the Anterior and Posterior Faults at its eastern end, and the Robinson Fault at the western end. A consideration of the displacement on all the faults in the complex suggests that the Burges Fault is a major independent fault, not parasitic on the Meckering Fault. Together, the Burges, Robinson and Posterior Faults form a radial fault to the arcuate Meckering Fault.

Other dextral offsets in the trace of the Meckering Fault are not associated with radial faulting. The complex fracture pattern at one such offset, near Wilson Street, northwest of Meckering, is fully described (Plate 4).

The Sudholz Fault, a radial fault 4 km long, was adjacent to a small sinistral offset in the Meckering Fault trace and appeared to be a sinistral normal fault of small displacement.

Reverse and thrust faults from New Zealand, California, Japan, Mongolia and Alaska are described from the literature and compared with the Meckering Fault.

Chapter 6. In addition to the major faults, a number of secondary faults were associated with the Meckering Fault, some possibly resulting from elastic creep in the weeks following the earthquake. The Chordal Fault, so named because it formed a chord to part of the arcuate Meckering Fault, was traced for 13 km. The fault was dextral normal, with up to 23 cm strike-slip displacement and 15 cm normal displacement. The fault appeared to develop over a period of six weeks following the earthquake.

In the segment isolated between the Chordal and Meckering Faults there were a number of large tension fractures up to 3 km long. One fracture, which disrupted a pipeline and the concrete floor of a grain silo, probably formed during an aftershock on the day following the principal earthquake.

The Backscarp Zone was a depressed linear zone about 4 km wide, joining the two ends of the Meckering Fault. It marked the eastern limit of faulting, and of the mobile block. Numerous small tension fractures were found within the zone, probably compensating, in part, for the compression observed at the Meckering Fault.

The only new fracture found in fresh rock was the Koolbunine Fault, about 100 m long and with a sinistral displacement of about 0.5 cm. Periodic observation showed that the fracture doubled in length over a period of two years.

Chapter 7. Seismic shaking caused a number of small slumps and clastic extrusions, but no major landslides.

Slumps were common in areas of high water table and occurred as isolated circular structures. Linear slumps were found on steep slopes or as apparent extensions of faulting.
Clastic extrusions were found in the salt flats of the Mortlock River. Water flowed for several hours after the earthquake, depositing low mounds of sand and silt.

Chapter 8. Several lines of evidence suggest that the Meckering Fault was a reactivated feature. At one point compact iron-stained fault breccia was found and in some areas the fault was associated with small quartz reefs and stringers. The fault was also associated with soil containing quartz fragments, and by following such indicators extensions of small faults could be located.

Geomorphological features also suggested a long history for the Meckering Fault. Northeast of Meckering the Mortlock River changes abruptly from wide salt flats to a narrow channel where it is crossed by the Sudholz Fault. The river then follows an arcuate course, parallel to the Meckering Fault. The fault itself does not traverse any fresh rock outcrop, but to the east, on the uplifted block, a line of small granite domes is exposed, while to the west there are wide sandplains.

Chapter 9. Geodetic measurements were made on a line crossing the earthquake affected area and compared with earlier measurements. Over the whole of a 115 km section there was no change, but certain sections showed an increase or decrease in length. Between Karrabein and Cunderdin the apparent increase in distance beteen 1958 and November 1969 was 9.5 cm. Other measurements, however, taken in mid 1968 and September 1969 showed a decrease of 23.2 cm. These conflicting results can be rationalised by assuming a slow dextral movement of 32.7 cm between 1958 and 1968, followed by a sinistral movement of 23.2 cm at the time of the earthquake.

Third order levelling profiles showed that levels were depressed up to 7.6 cm to the west of the overthrust block, and that the maximum elevation of about 1.6 m was reached about 2 km east of the fault. From this point elevations decreased until a further depressed area, the Backscarp Zone, was reached about 13 km east of the Meckering Fault. Levelling anomalies were not found south of the faulted area but there were indications of ground distortion extending northwest from the Meckering area.

Contouring of uplift on the mobile block of the Meckering Fault shows that it was uplifted and tilted to the east.

Chapter 10. The mobile block associated with the Meckering Fault is a segment of a saucer shaped body. Fault movement appeared to be a constant dextral strike-slip of 0.5 m, combined with a thrust movement varying from zero at the ends of the fault to a maximum of about 2 m at the centre of the arc. The model proposed to explain these features involves the straining of a superficial circular cap of rock by sinistral movement on an underlying shear zone. The essential points of this model have been confirmed by focal mechanism studies.

Chapter 11. The Calingiri Earthquake of 11th March 1970 had a magnitude of 6 and its epicentre was located 77 km northwest of Meckering. A small thrust fault scarp was formed, similar to the Meckering Fault. Only minor damage was caused and outside the epicentral area the damage from the Meckering Earthquake was often greater than that from the local event.

The seismic data for the Calingiri Earthquake are:

Origin time: 10 March 1970, at 17 15 11.2 hrs U.T.

Location: Lat. 31°7′S, Long. 116°28′E, about 4 km southeast

Magnitude: M_S/M_L 5.7, m_b 5.7-6.5, m 6.2.

Depth: 1 km.

There was no pattern of foreshocks and aftershocks associated with the Calingiri event. Minor tremors in the region occurred in a broad zone between Meckering and Calingiri and could be related to the declining aftershock sequence of the Meckering Earthquake.

The Calingiri Fault was a slightly arcuate sinistral thrust fault, concave to the east and about 3 km long. The fault plane dipped between 10° and 31° in soil, but the dip calculated from displacements was about 40°. Fault displacements were small, reaching a maximum throw of 38 cm, a heave of 25 cm and a sinistral strike-slip of 14 cm. The form of the thrust scarp was usually a single compressional roll but the northern section was more complex, with two opposed thrust planes 100 m apart uplifting a wedge of material between them.

Field and seismological evidence suggest a mechanism for the Calingiri Earthquake similar to that of the Meckering Earthquake.

Anomalous reports of damage and ground distortion northwest of Meckering, old eroded fractures in the vicinity of Calingiri and the similarity of the Meckering and Calingiri Earthquakes themselves, suggest a connection between the two events. A zone 20 km wide trending 330° encloses most of the anomalous reports and could be the wide shear zone postulated for the model mechanism of Chapter 10, or a zone containing an *en echelon* series of smaller sinistral reverse faults.

Chapter 12. Australia has few large earthquakes, but nevertheless there are several well delineated seismic zones, including the South West Seismic Zone near the western margin of the Yilgarn Block. The South West Siesmic Zone is coincident with a downwarped belt of Archaean gneisses and schists which traverses the southwest corner of the Yilgarn Block. The zone is also marked by gravity anomalies and changes in crustal thickness.

Since 1959, when detailed recording began, many hundreds of small earthquakes have been recorded from the South West Seismic Zone. Most are in the range M_L 2.0-2.9 but a few exceed M_L 4, including the Meckering and Calingiri events. Epicentres are concentrated in several zones, including Meckering and Calingiri, but the most active area is a northeast trending zone between Pingelly and Beverley. No known geological structures can explain the distribution of epicentres.

Stream morphology studies reveal a distinctive arcuate pattern of lineaments within the seismic zone, but without any definite relationship to recent seismicity.

A literature review is presented of the relationship between plate tectonics and the seismicity of the Australian continent.

CHAPTER 1

Introduction

Though terrible . . . to the present inhabitants of the globe, the earthquake has its place in the great system of geological operations, and is part of a series of events, essential . . . to the general order, and to the preservation of the whole.

JOHN PLAYFAIR *Illustrations of the Huttonian Theory of the Earth*
1802.

At 10.59 a.m., on 14th October, 1968, the small town of Meckering, about 130 km east of Perth, was destroyed by an earthquake. Twenty people were injured, but incredibly, no one was killed. The earthquake was felt throughout the southern half of the State and caused damage in the surrounding townships, particularly York and Northam, and in the Perth Metropolitan area.

The magnitude (M_L) of the Meckering Earthquake was 6.9 on the Richter Scale making it one of the largest recorded in the seismic history of Australia. Although the magnitude was moderate the focus of the earthquake was only about 7 km deep and the surface intensity reached MMIX on the Modified Mercalli scale*.

The earthquake and its aftershocks were accompanied by surface faulting extending over an area of 200 km^2 and an arcuate dextral thrust fault 37 km long was formed. Many smaller faults were generated by the earthquake, principally within the quadrant formed by the main thrust scarp, and there is some evidence to suggest that movement on at least one of these faults took place several days after the main fault formation. The Meckering Fault was the first tectonic ground breakage to be recorded in Australia.

The Meckering Earthquake was located in a well documented zone of seismic activity which is about 60 km wide and extends across the southwest corner of Western Australia. Seventeen months after the main event at Meckering, at 1.15 a.m. on 11th March 1970, a magnitude 6.0 earthquake occurred at Calingiri, 80 km northwest of Meckering. This earthquake was again shallow, with a focal depth of about 1 km, and was accompanied by surface faulting similar to that at Meckering.

This location of the faulting at Meckering and Calingiri, in an otherwise stable Precambrian Shield, has shown that damaging earthquakes are a potential hazard in Western Australia, and are not confined to the margins of the major lithospheric plates.

*A glossary of technical terms will be found in Appendix 3 and the Modified Mercalli scale is reproduced in Appendix 4.

PROGRAMME OF INVESTIGATIONS

Immediately after the Meckering earthquake the most urgent problem was the reconstruction and possible relocation of the township. A second problem, important for planning and construction, was an assessment of the future risk of earthquake damage within the seismic zone and surrounding areas. These studies have been published by Gordon (1969; 1972)

Earthquakes of moderate magnitude are unusual events in Australia, and surface faulting had not been previously recorded. Topographic and cultural conditions were ideal for the measurement of fault displacements and the pattern of ground movements, and, between 15th October 1968 and 11th February 1969, the effects of the earthquake were studied in as complete detail as possible. The field investigations were directed by Mr. F. R. Gordon who also investigated the effects of the earthquake on buildings and utilities and mapped the faults and features generated by the earthquake. The main fault traces were located and mapped by Mr. B. Paterson. Mr. J. D. Lewis prepared a regional geology map of the Meckering area, and an office study of the regional geomorphology of a large portion of the southwest of the State was initiated by Dr. J. L. Daniels and completed by F. R. Gordon. The Surveyor General's Department made major contributions to the investigation by providing aerial photography of the main scarps on the day following the earthquake and by making accurate measurements of displaced cadastral boundaries in the Meckering area. Geodetic circuits straddling the fault-affected areas were also remeasured, and traverses along the main road through the area and along roads to the north and south of the fault scarp were relevelled. Seismic information was obtained from Mr. I. B. Everingham of the Mundaring Geophysical Observatory.

Investigations of the Calingiri Earthquake and fault were necessarily more limited than those of the Meckering Earthquake, but F. R. Gordon spent from 15 March to 3 April 1970 in the field on a survey similar to the earlier study.

Preliminary accounts of the faulting at Meckering have been published by Everingham and others (1969), Conacher and Murray (1969), and Gordon (1969, 1969a and 1971). The seismic data have been reported on by Everingham (1968) and Everingham and Gregson (1969). Seismic data for the Calingiri Earthquake have been published by Everingham and Parkes (1971), and a preliminary account of the associated faulting by Gordon (1973).

Many of the phenomena at both Meckering and Calingiri were short lived, and it was only with the assistance of local residents and farmers that records were made. In the following months, rainfall, followed by ploughing and seeding operations, modified many features. Fortunately some of the best fault features were protected by timber or rough terrain and will be available for inspection for several years.

ARRANGEMENT OF THE BULLETIN

A great variety of data was collected from the investigation of the Meckering Earthquake, varying from eyewitness accounts and records of damage to buildings and public utilities, to detailed measurements of the fault displacement and the regional deformation caused by the faulting. The data have been organised, in general, to separate the account of the effects on man-made structures and on individuals from the detailed scientific treatment of the earthquake phenomena.

This introductory chapter continues with an account of the regional geology of the Meckering area as a preliminary appreciation of the setting of the earthquake. Chapters 2 and 3 give eyewitness accounts of the earthquake and a record of the damage caused in Meckering and the Perth metropolitan area. To give an appreciation of the total area over which the earthquake was felt, or caused damage, an isoseismal map of the Meckering Earthquake is presented.

The scientific aspects of the Meckering event are dealt with in Chapters 4 to 10. Starting with the event itself, Chapter 4 considers the pattern of foreshocks and aftershocks which accompanied the earthquake, and its magnitude. The nature of the seismic shaking is deduced from particular instances of damage. Chapters 6 and 7 detail the pattern of faulting and ground movement produced by the earthquake and Chapter 8 considers evidence that the Meckering Fault is a reactivated older fault. Chapter 9 details the regional deformation which was measured by geodetic observations and levelling circuits. A possible mechanism for the Meckering earthquake is described in Chapter 10.

The Calingiri Earthquake is dealt with in a similar manner to the Meckering event and is described in detail in Chapter 11.

The Bulletin ends with Chapter 12, an account of the major faults and the record of recent tectonic activity in the southwest of Western Australia. Appendices include a glossary of technical terms, a complete description of the Modified Mercalli Intensity scale, and reports on several phenomena which were possibly connected with the Meckering Earthquake.

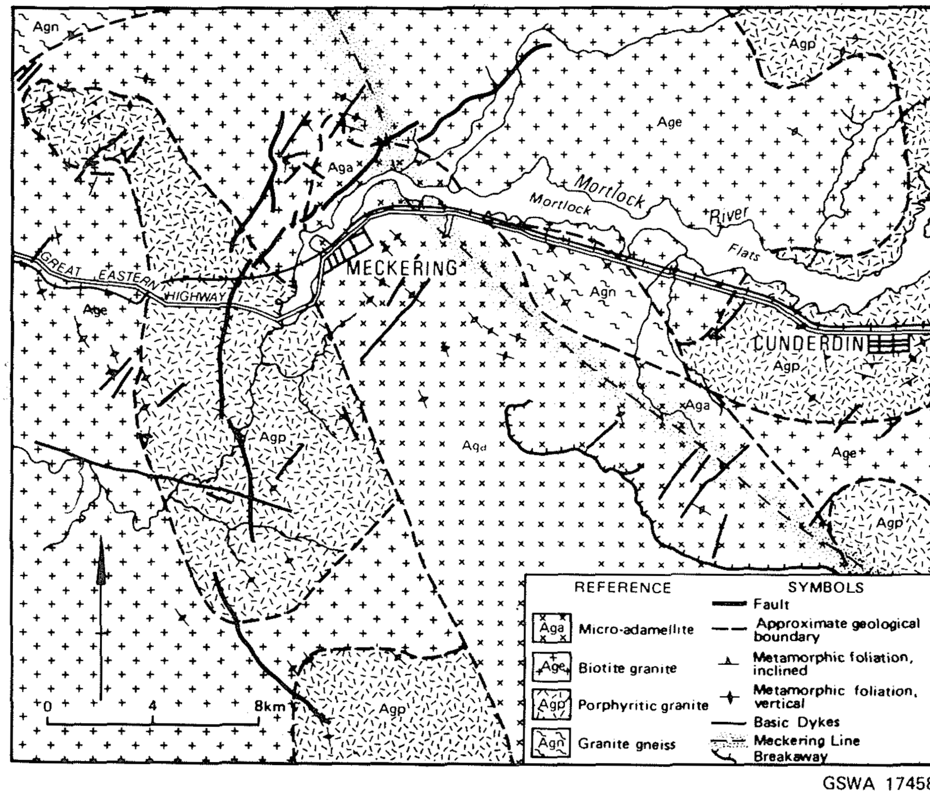
REGIONAL GEOLOGY OF THE MECKERING AREA

Meckering lies near the western edge of the Yilgarn Block, the largest area of Archaean rocks in Australia. The Archaean shield consists largely of granites and granitic gneisses with the dominant structure outlined by economically important north-northwesterly trending greenstone belts. The area mapped as part of the earthquake investigation (Plate 1) lies almost entirely in granite, but is at the eastern margin of a zone of granite gneiss and highly metamorphosed Archaean sediments stretching from Moora in the northwest to Cape Riche on the southeast coast.

The area had not been mapped in detail prior to October 1968, but a regional study of the southwest of the Yilgarn Block has been made by Wilson (1958) and the geomorphology of the region has been discussed by Jutson (1934) and Mulcahy (1967). Certain basic dykes and aplite sills in the Meckering district have been studied by Lewis (1970) and Doepel (1970). Part of the area is covered by the Perth 1:250 000 map recently reported on by Wilde (1974).

PHYSIOGRAPHY

The area lies astride the Meckering Line (Mulcahy, 1967, p. 213) which marks the eastward limit of a rejuvenation of the river system and is the dividing line between the physiographic regions of Swanland and Salinaland (Jutson, 1934). The Meckering Line is probably of tectonic origin and is marked by changes in topography, soil type, and in parts by granite breakaways.



2. Sketch map of the Geology between Meckering and Cunderdin.

East of Meckering, the plateau is about 300 m above sea level and shows little relief; the Mortlock River valley is broad, and its lower parts are occupied by extensive salt lakes. Rock exposures are few and confined to the tops of low hills. West of Meckering, the level of the plateau falls towards Northam and the rejuvenation of the drainage system has led to narrower, more deeply incised valleys, in which more active erosion has uncovered many small rock exposures.

ARCHAEAN

The Archaean rocks of the Meckering district are predominantly granites, but there are several large outcrops of older granite gneiss. The intrusive and tectonic history of the granites is complex, and several types are often found in a single outcrop. On a broad scale the margins of the various intrusions are migmatitic; this makes the sequence of intrusion difficult to determine. The rock type noted on Plate 1 is the most prominent in that exposure, and Figure 2 further simplifies the outcrops to give an overall picture of the distribution of the various granitic rocks.

BANDED IRON-FORMATION

A small, poorly exposed area of banded iron-formation about 1.5 km southeast of Meenaar Hill (G.R. 495083)* probably represents a raft of Archaean metasediments caught up in the granite. The rock consists of finely laminated bands of quartz and magnetite, with a little muscovite. The magnetite has been largely altered to hematite.

MIGMATITIC GNEISS

The main outcrops of gneiss are around Waeel (G.R. 515086), but there are smaller exposures in the northwest of the mapped area. The gneiss is migmatitic, and has a strong north-northwest banding of leucocratic, granitic material and darker, biotite-rich and hornblende-rich layers. The banding is usually on the scale of 2-10 cm and vertical, with persistent mafic bands up to 30 cm wide. Minor structures such as drag folds are common, but exposures are too limited to determine any larger scale structure. The Waeel exposures are further complicated by the intrusion of thick sills of micro-adamellite which carry xenoliths of gneiss.

BIOTITE GRANITE

The principal outcrops of biotite granite are around Meenaar Hill (G.R. 495083), Five Mile Hill (G.R. 494091), and Mount Anne (G.R. 519096). The rock is a fairly coarse-grained, pink, leucogranite containing minor amounts of biotite, and is distinguished from other granites by its coarse texture and lack of phenocrysts. Normally the rock shows no foliation, but biotite-rich schlieren are common, and pods or streaked-out xenoliths of porphyritic granite are sometimes present.

PORPHYRITIC GRANITE

The most distinctive granite in the area is a coarse-grained biotite granite containing large feldspar phenocrysts up to 8 cm long. The principal outcrops occur south of Meckering at Koolbunine Rocks (G.R. 502077), at the eastern edge of the mapped area at Boordabbie Rocks (G.R. 521084), and in the northwest at Bald Hill (G.R. 495091). The alignment of phenocrysts usually gives the rock a prominent, platy, flow foliation which is moderately consistent over large areas. Occasionally small swirls can be seen, and Wilson (1958) has suggested that these might indicate turbulent flow. The rock is often intimately associated with the biotite granite, but appears to be the later intrusion.

MICRO-ADAMELLITE

The youngest major rock unit of the area is a medium-grained, grey or pink micro-adamellite. Mineralogically, the rock is similar to the other granites of the region, but has an average grain size of only 1-2 mm. The rock outcrops in a broad band extending from the Beeberring Hills (G.R. 503092) southeast across the whole map area. In its southern outcrops, the micro-adamellite is coarser grained and resembles the biotite granite, but it can usually be distinguished by the lack of foliation and biotite schlieren, and the paucity of aplite intrusions.

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* Grid References (G.R.) refer to the Australian grid, Zone 1, which is reproduced on Plate I.

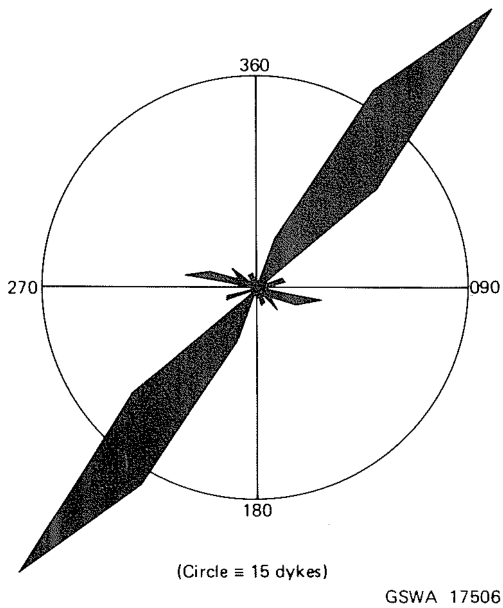
MINOR INTRUSIONS

The whole area is criss-crossed by small, aplite intrusions. Sills and dykes from a few centimetres to about one metre wide are common, and consist almost entirely of quartz and feldspar with very little mafic material. The aplites appear to have been intruded along joint directions in the granite. They are noticeably less common in outcrops of the micro-adamellite, and are possibly related to the emplacement of that rock. Some aplite sills are differentiated, showing a transition from a biotite tonalite at the base to a leucocratic granite at the roof (Doepel, 1970).

BASIC DYKES

The youngest rocks of the Meckering district are basic dykes of possibly Proterozoic or early Palaeozoic age. The most prominent dyke swarm trends northeast and includes over half the total dykes of the region (Fig. 3). A much smaller number of dykes trend approximately west-northwest at an angle of 60° to this swarm. With few exceptions, the dykes are straight and dip vertically, their width varying from about 30 cm to about 30 m.

Most of the dykes are a normal quartz dolerite which is sometimes porphyritic, and contain phenocrysts of labradorite, and rare augite and hypersthene. The rock is quite fresh, but the augite is partly uralitized, and there is usually a little secondary carbonate. Some members of the north-easterly trending dyke swarm are crowded with xenoliths of granitic material, the assimilation of which has led to dykes with the appearance of quartz-feldspar porphyries (Lewis, 1970).



3. Dyke trends in the Meckering district.

The age of the dykes is not known precisely, but Wilson (1958) thinks they are either Upper Proterozoic or Lower Palaeozoic. Granites near Meckering show ages in the range 2 600 to 2 700 m.y., but show a superimposed metamorphic age of 650 m.y. in the Perth area (Wilson and others, 1960). Wilson correlates this latter age with the injection of quartz dolerite dykes in the Darling Range area east of Perth. Compston and Arriens (1968) report biotite ages from the Mundaring granite ranging from 450 m.y. to 750 m.y. and believe that this reflects the emplacement of basic dykes. No age determinations have been made directly on the dykes, but those of the Meckering area are probably similar in age to those in the Darling Range.

QUARTZ REEFS

Two large reefs of barren milky quartz are shown on the map; their age is not known, but they fill fractures parallel to the main dyke swarm and may be of similar age.

SUPERFICIAL DEPOSITS

Superficial deposits of probably Tertiary to Recent age overlie about three-quarters of the Archaean rocks. Jutson (1934) and Mulcahy (1967) divide these deposits into two broad groups, the sandplains to the east of Meckering and a zone of younger laterites to the west, separated by the Meckering Line.

Sandplains are particularly well developed between Cunderdin and Tammin, and in the northeast part of the map area are represented by bright yellow sand containing occasional bands of lateritic gravel. Massive laterite is rare, although some of the lateritic gravel contains only a little sand. In contrast to this, the younger laterites often contain thick, massive laterite layers which form prominent breakaways, especially along the Meckering Line to the southeast of the town. In general, the younger laterites consist mainly of sandy lateritic gravel which forms an extensive capping to the low hills. Although both sandplain and younger laterites are part of a typical laterite profile, the pallid zone of weathered granite is rarely visible except beneath the lateritic capping of breakaways.

Leaching of the sandplain and younger laterite deposit has given rise to a very pale sand, which from air photograph patterns appears to have been windblown into topographic hollows. This is by far the commonest surface deposit, and it blankets the valley sides to depths of up to a metre; water-sorted alluvium covers the valley bottoms.

The broad valley of the Mortlock River and its tributaries carries wide tracts of alluvium, composed of clay, sand, and lateritic gravel which have been derived from weathered granite and superficial deposits. East of Meckering, the valley is very wide and shallow, and is covered by salt lake deposits consisting of a thin layer of salt overlying alluvium.

STRUCTURE

The sequence of intrusion of the granites in the Meckering area is apparently: (i) biotite granite, (ii) porphyritic granite, and (iii) micro-adamellite; evidence for this sequence is limited because, throughout much of the area, the biotite granite and porphyritic granite form a migmatitic complex rather than discrete bodies. Nevertheless, it is probable that the porphyritic granite was intruded as large pods into the biotite granite, and the alignment of feldspar phenocrysts represents an original flow structure. The pattern of granite intrusion outlines a general north-northwest grain to the country, in conformity with the general structural trend of the Yilgarn block. This pattern is, in the granites, reinforced by foliations which are particularly prominent in the west of the map area, marginal to the belt of gneisses and metasediments which trend north-northwest through Northam and York.

The basic dykes were probably intruded along conjugate shear fractures. The rose diagram, (Fig. 3) shows that the prominent dyke directions are 040° and 100°; this suggests that the principal stress was applied parallel to 070°. A number of dykes are intruded along tension fractures parallel to 070° and a few parallel to 335°, which would represent elastic release fractures. Intrusion along shear fractures is supported by the observation of slight shearing parallel to the northeast dyke swarm in parts of the granite, and the presence of xenolith-bearing dykes which have been interpreted as the intrusion of basic magma along faults or shear fractures (Lewis, 1970).

Differences between the superficial deposits east and west of Meckering could be due to climatic differences, but the relative sharpness of the Meckering Line and its parallelism with gravity anomalies and the Southwest Seismic Zone suggests a tectonic origin. This conclusion is supported if a section between Tammin and the Darling Range is considered. Between Tammin and Meckering the plateau is almost horizontal, but between Meckering and Northam there is a considerable downwarp of remnants of the old plateau surface. From Northam to the crest of the Darling Range the plateau is upwarped to a higher level than the salt lake country to the east of Meckering. Drainage is superimposed on these features; the Mortlock-Avon River system flows from the salt lake region across the downwarp and through a gorge in the Darling Range to join the Swan River. These features of the western edge of the Yilgarn Block are caused by tectonic warping. The age of the plateau surface is late Cretaceous (Cope, 1975, p.45), and the warping probably took place in the late Tertiary times and can be correlated with the Kosciusko Uplift (Mulcahy, 1967).

The striking feature of the structure of this part of the Yilgarn Block is the constant direction of the tectonic forces over a long period of time. The Archaean granites were emplaced along a north-northwest axis, the reactivation of this stress field caused the intrusion of a dyke swarm along oblique shear fractures in Upper Proterozoic or Lower Palaeozoic times and in the Tertiary the margin of the shield was warped along the same north-northwest axis.

FAULTING AND REGIONAL GEOLOGY

In the small area mapped, no single geological feature could be identified that would account for the location and trend of the Meckering Fault system. From Figure 2 it will be seen that the southern portion of the main fault takes a gently curving path which is discordant to the foliation of the granite. North of Meckering, the fault is less regular and follows a course made up of several straight stretches, all of which trend northeast in conformity with the common dyke trend. The rocks in this area often show northeast trending shears and it is possible that the dykes and shears have exercised a local control on the fault. The Chordal Fault, southeast of Meckering, also follows closely the trend of the dyke swarm.

The only major structural feature known before the Meckering Earthquake which might have determined the location of the Meckering Fault is the Meckering Line. This marks the eastern margin of a downwarp in the Archaean shield and might possibly be a line of weakness along which faulting could be expected.

CHAPTER 2

EARTHQUAKE EFFECTS AT MECKERING, OCTOBER 1968

THE TOWN

Meckering township, 130 km from Perth on the Great Eastern Highway, is the centre of an important wheat-growing area. The town was originally built on the south bank of the Mortlock River, as a siding and watering point of the Goldfields Railway. It reached its peak about 1906, and in 1913 had a population of about 600. As the surrounding land was cleared, the water-table rose and the Mortlock River became progressively saltier and the townsite liable to flooding; population declined to the gain of the adjacent centres of Northam and Cunderdin. The original site was eventually abandoned and the town moved to the south side of the railway, 750 m northeast of the earlier location.

In October 1968, the population of Meckering numbered about 230; a further 300 people lived on farms in the vicinity. Apart from the two-storied bank and hotel, all buildings in the town were single storied, and built of a variety of materials, ranging from unfired mud brick to reinforced concrete. There were a few modern dwellings, but otherwise the buildings were a reflection of the past, and several were unoccupied. The most substantial modern constructions were two new grain storage silos, each 11 m in diameter and 30 m high, and a horizontal storage shed 90 m long and 30 m wide.

Apart from its local importance, Meckering lies astride all the main arteries connecting Perth to Kalgoorlie and the eastern states of Australia. The Great Eastern Highway, Standard and Narrow Gauge Railways, the Goldfields Water Supply pipe line and the east-west telegraph and telephone systems all pass through the town.

EYE-WITNESS ACCOUNTS

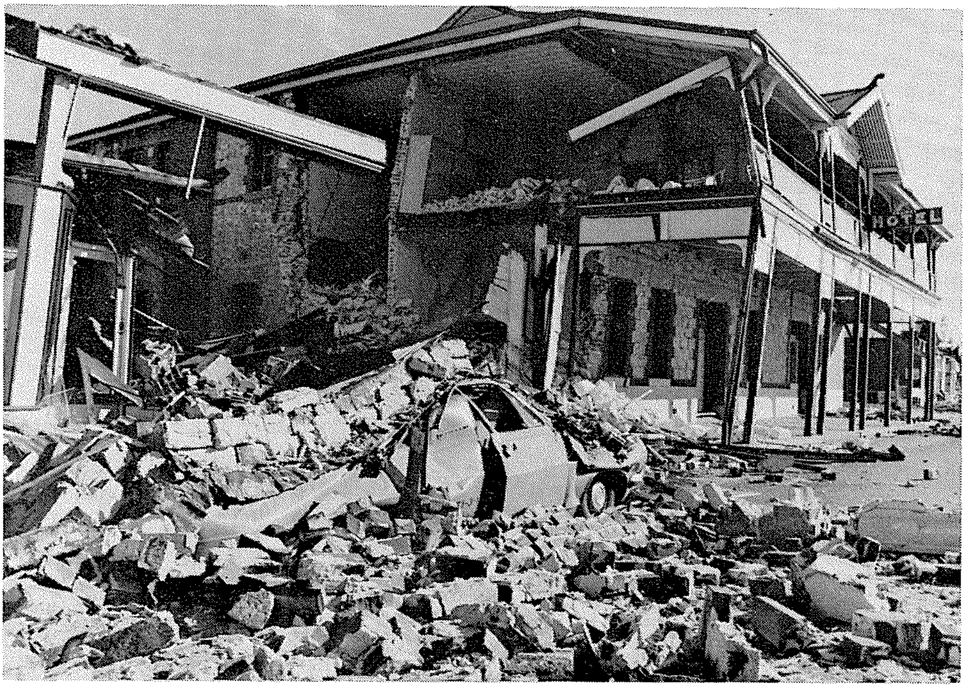
Every person living in, or visiting, Meckering on the 14th October 1968 has a story to tell of how the earthquake affected him, or a providential escape from a collapsing building. The following eye-witness accounts, however, are recorded because transient phenomena were observed which, while undoubtedly connected with the earthquake, cannot be easily accommodated within an account of the final effects of the event.

Eleven days before the main earthquake, at 11.03 am on 3rd October 1968, Constable Skehan, the local policeman, was walking in the main street when, he reported, "the ground seemed to turn to jelly" and he had difficulty keeping his feet. Further shaking at 11.18 am and 11.55 am confirmed the constable's opinion that a severe earth tremor had occurred. Three kilometres north of Meckering in a comparatively new house belonging to Mr. Sudholz, the shocks were strongly felt, the last being the biggest. However, the second shock did the most damage, a light fitting fell down in the kitchen, crockery and groceries fell out of cupboards and some bricks were cracked. These events were reported in Perth newspapers but raised little interest.

On the 14th October, small tremors were felt by the licensee of the Railway Hotel, Mr Gordon Berryman, at 1.00 am and 7.15 am. The shaking raised considerable dust on the second storey of the hotel. Later in the day, just before 11.00 am, the publican went upstairs and was surprised to see the verandah door suddenly swing open. While moving forward to shut it he saw the unusual sight of a flock of swallows walking around the verandah in a group. As he shut the door a violent shaking commenced, accompanied by a noise like an explosion. The easterly corner and walls of the building fell inwards, and the south, or back wall fell away as two further distinct periods of shaking occurred. Later in the day the hotel barometer was found in the rubble with the needle jammed at 28.5 inches, and the pointer at 29.7 inches where it had been set at 9.00 am in the morning.

Miss Glenys Nichol was alone in the general store when it started to collapse around her. She escaped through the front door and ran across the street to the parking area. As she ran, numerous ground cracks in the parking area were opening as much as 5 cm and shutting again, and she felt a slight burning sensation on the skin and there was a slightly nauseous smell reminiscent of carbide. She experienced a similar smell following one of the major aftershocks.

The local butcher, Mr. Vic Edwards, lived on the north side of the railway, about 750 m northeast of the town centre. At the time of the earthquake he was in his back yard



4. The Railway Hotel, Meckering (Photo: W.A. Newspapers).

with his family. All suddenly experienced the sensation of being thrown into the air. Mr. Edwards got to his feet but was knocked to the ground twice more and there seemed to be coincidental explosions. He saw cracks in the ground opening as much as 3.5 cm with spurts of white vapour or dust rising about 2.5 m high as the cracks shut. Most of the cracks in the ground around the ruined house settled down and were not visible a week later, but two large openings about 75 cm deep and 7.5 cm wide remained in the alluvial soil.

Three distinct pulses of shaking were also felt by Mr. Owen Burges who was yarding sheep on his property 13 km south of Meckering. As he was about to enter the shearing shed, he was thrown against the east wall of the sheep race, and the sliding door of the shed opened violently eastward. He shut the door, but the same process was repeated. Thinking that a 'cockeyed bob'* had gone through his shed, he slammed the door, but was again thrown against the east wall of the sheep race as the door flew open for a third time.

At the time of the earthquake, Mr. T. H. Morrell and his son were driving in the farm truck on the outskirts of Meckering, close to the cemetery. They heard a loud noise which seemed to be moving north, and the truck suddenly thumped up and down with a sensation akin to a flat-tyre. Looking to the side of the road they saw laterite pebbles jumping and bouncing as much as 50 cm from the ground.

Mr. L. Solomon was sitting in his truck in Meckering at 10.59 am when the heavy vehicle seemed to be be thrown into the air then dumped down. Simultaneously there was a large explosion, and immediately in front of him the front wall of the general store crashed down on an unoccupied utility van. Joined by his son he ran across the road to the parking area where, amid loud noise, two distinct groundwaves were seen to move easterly across the main street. The rolls were travelling at about 12 km/h, and the ground appeared to rise sharply and fall away slowly with about a two-second interval between the crests. Both men were brought to their knees by the ground movement. In the parking area the railway water tank was swaying alarmingly and two tie-rods parted audibly.

The Solomons immediately left town, and as they drove up the main street observed the chimneys on the two-storied bank building fall northward, and on recoil, the south wall fall outward. Eight hundred metres further along the Goomalling Road mud bricks were still falling from a house as they passed by. About 2 km further along the road, when the truck was travelling at about 100 km/h, they reached the scarp of the Meckering Fault. On crossing the 1.8 m high fault scarp, the vehicle was airborne until it landed with such force that the front bumper hit the ground. Driving on, Mr. Solomon came to a second, smaller fault scarp 0.3 m high, adjacent to his ruined home.

The observer closest to the Meckering Fault at the time of formation was Mr. L. A. Sheehan of Cunderdin, who was driving eastwards towards Meckering, about 6.5 km away. The trees along the roadside, already agitated by wind and rain, started to whip violently and at the same time the car rocked as if a tyre had blown out. The driver at first thought he was involved in a 'cockeyed bob' but then immediately in front of him a

*Cockeyed bob: a Western Australian name for a small, but violent cyclonic disturbance, particularly one which causes localised wind damage. The name is derived from the language of the Aborigines in the Roebourne district: "Kook-ai", a warning shout, equivalent to "look out!", and "baba", meaning "water", in reference to heavy rains which sometimes accompany the storm (Vollprecht, 1972).

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2.5 m high bump rose in the road where two seconds before none had existed. Another observer, travelling in the opposite direction along the Great Eastern Highway, felt the shaking and saw the scarp rise, and crashed into a tree at the roadside, breaking an arm.

The fault scarp was also seen within minutes of its formation by Mr. Eric Smith of Meckering, who was driving with his son-in-law along the York-Meckering road. Shortly after the shock of the earthquake, they passed a damaged bridge and noticed slumping of the creek banks, and 11 km from Meckering they came to the 1.8 m high fault scarp which disrupted the road. Mr. Smith noticed a strong smell, reminiscent of a hard-rock mine after blasting, and saw vapours emerging from the cracks.

Observations which might be construed as animal precognition of the earthquake are few, but two examples were reported. Mr. R. Baxter was herding sheep on his property 14 km east of the town where he noted that immediately prior to the earthquake the sheep had drawn into two circular groups with their heads inward. Mr. T. A. Liddell, of Greenhills, 32 km south-southwest of Meckering, was feeding his horse at the time of the earthquake. A roaring noise, like a strong wind preceded the shock; the horse jumped in the air and then stood stock still.

Such were the experiences and observations of a few of the residents of the Meckering district. Every house in the town was damaged, and most were totally destroyed, yet incredibly there were no deaths or serious injuries. Seventeen people from the Meckering area and three from York were admitted to hospital with injuries ranging from broken limbs to concussion, cuts, bruises, and shock. The time of day and date of occurrence were undoubtedly the main reasons for the low casualty rate. October 14th was a public holiday which meant that shops were shut, and school buildings unoccupied. In addition, many farmers were working in iron framed sheds, preparing machinery for the coming harvest.

HOW EARTHQUAKES CAUSE DAMAGE

Damage during an earthquake is usually caused by fault displacement, seismic shaking, ground failure or tectonic warping (Wallace 1968). Other variables which determine the degree of stress brought to bear on a structure are: the magnitude and focal depth of the earthquake, the extent and magnitude of faulting, the intensity and duration of shaking, and the distance of the structure from the epicentre. Finally, the damage caused to an individual structure will be determined by its design, materials of construction, and the foundation conditions.

Fault displacement causes damage when a structure is located astride the actual plane of movement and is torn apart by differential movement. Unless such movement has been allowed for, then no matter how well designed, the structure will fail. However, if fault displacement is the only cause of damage, then structures a few metres from the fault plane may well remain undamaged. In Meckering, damage due to fault displacement is illustrated by the Goldfields Water Supply pipeline and the two railway lines.

Damage to structures by shaking occurs when earthquake vibrations are transmitted from the ground to the structure. In the Meckering area, this was the commonest cause of damage. Other factors being equal, the seismic shaking resulting from an earthquake will decrease with distance, but the most important determinant is the type of foundation soil on which the structure rests. In general, solid rock such as granite carries only short-period earthquake waves which cause a rippling motion at the surface. At the opposite extreme, deep uncemented saturated alluvium can support only long-period waves and this results in a lurching motion at the surface. Structures built on such materials are likely to be subjected to more violent shaking than those on hard rock.

Seismic shaking may also cause landslides, slumps or settlement of foundation soils, and such ground failure may cause damage to structures. A study by Seed (1969) showed that landsliding during earthquakes was invariably started by the liquefaction of saturated poorly consolidated sandy soils. Around Meckering such effects were observable in creek banks and in the abutments of bridges.

DAMAGE TO BUILDINGS, MECKERING TOWNSITE

Prior to 14th October 1968, Meckering town contained 51 occupied dwellings, 12 private business premises and 15 buildings devoted to government, public or sporting uses. The ANZ Bank and the Railway Hotel were the only two-storied buildings, the remainder being single storied. There were no new public or commercial buildings. Many of the private houses were built from mud bricks manufactured on the site, and had been completed or embellished in a variety of materials. A few substantial brick houses reflected a recent tendency for local farmers to retire to the town to be near social and sporting amenities.

The following types of structure had been used:

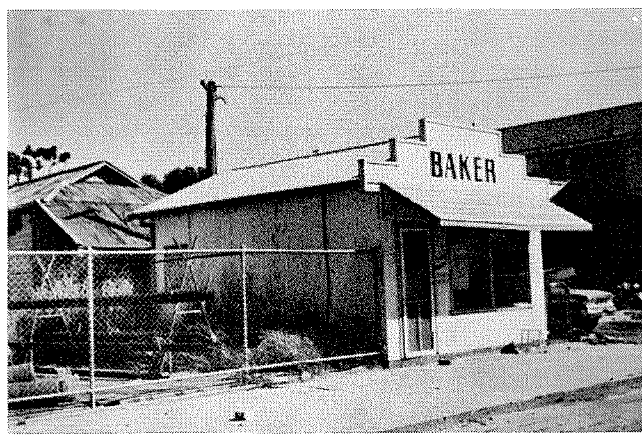
(1) timber frame, with wooden, asbestos, or brick-veneer cladding;
(2) steel frame with corrugated iron, asbestos, or aluminium cladding;
(3) reinforced concrete;
(4) double brick, with some reinforcing;
(5) double brick;
(6) concrete block;
(7) granite block or masonry;
(8) sundried brick (mud batt); and
(9) various combinations

Buildings which survived the earthquake and were still usable came from construction types 1 to 4, and consisted of 16 houses and 3 business premises. An analysis of the performance of various types of construction is given in Table 1, which is a slightly modified version of a table presented by Smith (1969) from an architectural appraisal of damaged buildings in Meckering.

Many of the houses had multiple defects, and, while one weakness alone would have been enough to have brought about collapse under the stresses imposed by the earthquake, the combination prevented later analysis.

In an analysis of the damage to houses the following variables were considered: (1) age, (2) materials of construction, (3) design and workmanship, (4) orientation, (5) foundation material, and (6) location relative to epicentre.

A



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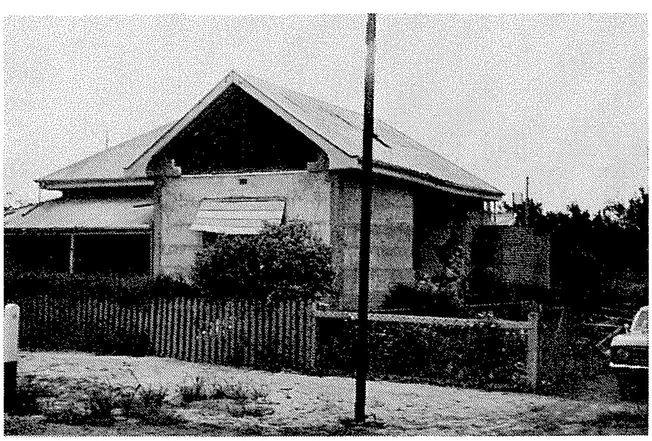

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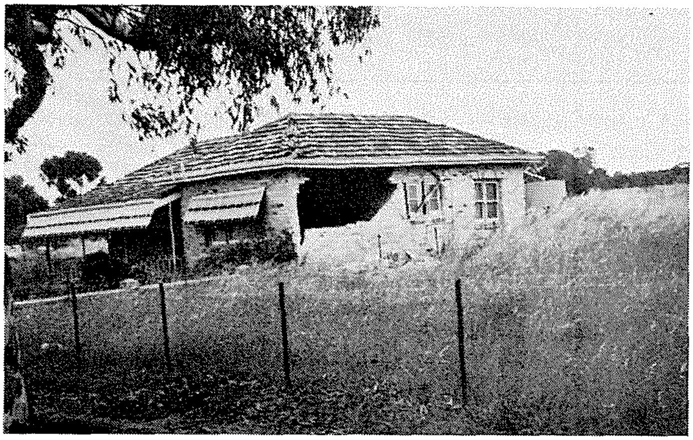
5. Damage to buildings in Meckering:
(a) Wooden house in Johnson St, distorted but intact.
(b) The baker's shop, of asbestos, on the east side of the Railway Hotel.
(c) House in Dreyer St. The concrete walls are intact but the concrete-block gable, and the granite masonry at the rear, have collapsed.

A



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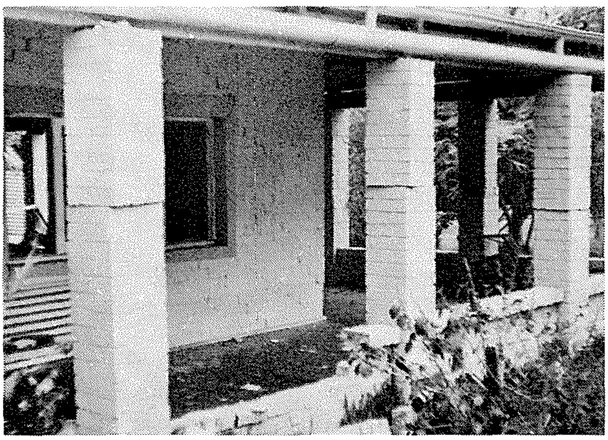

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6. Damage to brick houses in Meckering:
   (a) Older type of double-brick house in Dreyer St.
   (b) Modern double-brick house, Dreyer St.
   (c) Modern brick house. Note the diagonal fractures in the brickwork and the anticlockwise rotation of the upper parts of the pillars (Photo: B.M.R.).

TABLE 1. DAMAGE TO BUILDINGS, MECKERING TOWNSITE

Wall material	Buildings surveyed		Demolished		Minor damage		Negligible damage	
	Number	Per cent of total	Number	Per cent of those surveyed	Number	Per cent of those surveyed	Number	Per cent of those surveyed
Timber	27	30.7	2	7.4	16	59.2	9	33.4
Steel frame	2	2.3	—	—	—	—	2	100
In situ concrete	1	1.1	—	—	1	100	—	—
Brick veneer	1	1.1	—	—	1	100	—	—
Brick or brick & stone	32	36.4	31	97	1	3	—	—
Concrete block	4	4.5	4	100	—	—	—	—
Mud & concrete block or bricks	16	18.2	16	100	—	—	—	—
Timber & brick, stone or concrete blocks	5	5.7	4	80	1	20	—	—
Totals	88		57		20		11	
Per cent of Total		100.0		64.8		22.7		12.5

Combinations of various types of block with brick or concrete proved unsound because of the differing periods of vibration of the materials. However, several houses of unit masonry had wooden or asbestos lean-tos built on, and these survived while the main building collapsed (Fig. 7a).

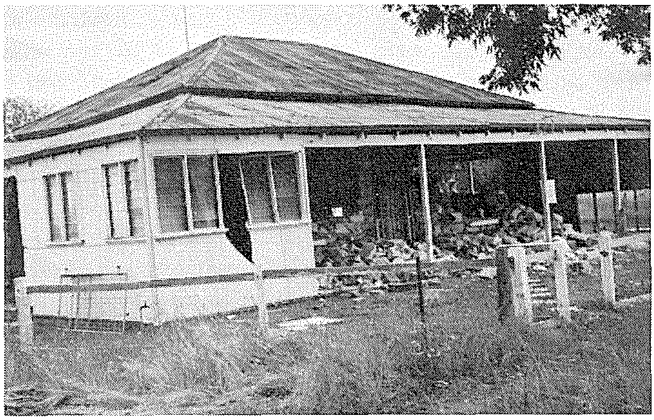
The brick veneer building that survived had only been built for 12 months, which meant that the mortar was at optimum strength. The building was damaged; part of the east wall was broken off, and the west wall and car-port were badly cracked. Although the house was still habitable, part of the structure had to be rebuilt.

The only double brick house that survived the shaking was about 3 years old, and had some reinforcing above the door and window openings. Damage consisted of the loss of the 4 rows of bricks above the windows and doors on both the rear (east) and the front (west) of the house. The top of the chimney was snapped off and some roof tiles were displaced. The remaining part of the chimney was cracked.

The degree of fragmentation of unit masonry walls was related to the amount of cement used in the mortar. Old lime mortar offered no adequate bond, but fresh cement mortar, while not enough to save the building from destruction, at least prevented collapse.

Brick and block chimneys were an obvious earthquake hazard because of the manner in which they broke off at roof level (Fig. 7b). Several wooden or asbestos houses otherwise intact were damaged by falling chimneys.

A notable feature was the integrity of galvanised iron roofs, as in many cases the walls had collapsed, leaving the roof intact on top of a pile of rubble or on the internal partition walls (Fig. 7a, c). The iron roof appeared to possess a stressed skin action of considerable strength (Lay, 1968). Tiles, particularly ridge tiles, were dislodged in most instances, and there was definite evidence that the inertial weight of a tiled roof contributed substantially to structural damage by forcing the walls of houses apart.



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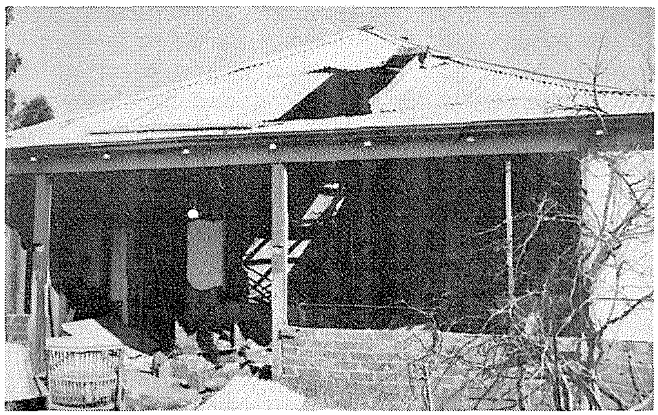

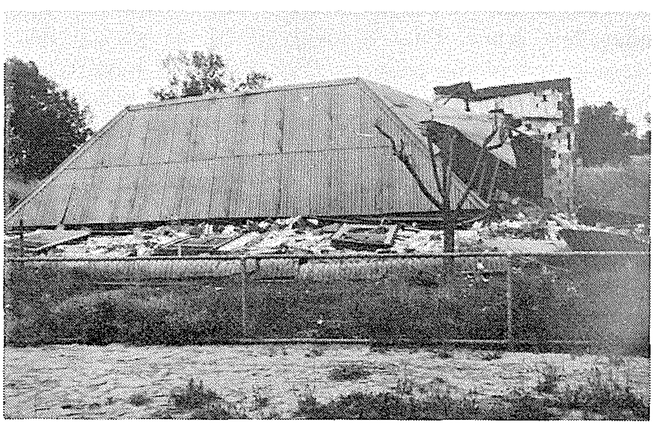

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7. Damage to mud-brick houses in Meckering:
   (a) Mud-brick external walls have collapsed, leaving an asbestos lean-to standing and the roof supported on the verandah posts and internal walls.
   (b) Mud-brick house 7km south of Meckering. Note that a brick chimney broke off and fell through the roof.
   (c) Mud-brick and concrete-block house in Knight St. The front wall collapsed outward but the iron roof remained largely intact.

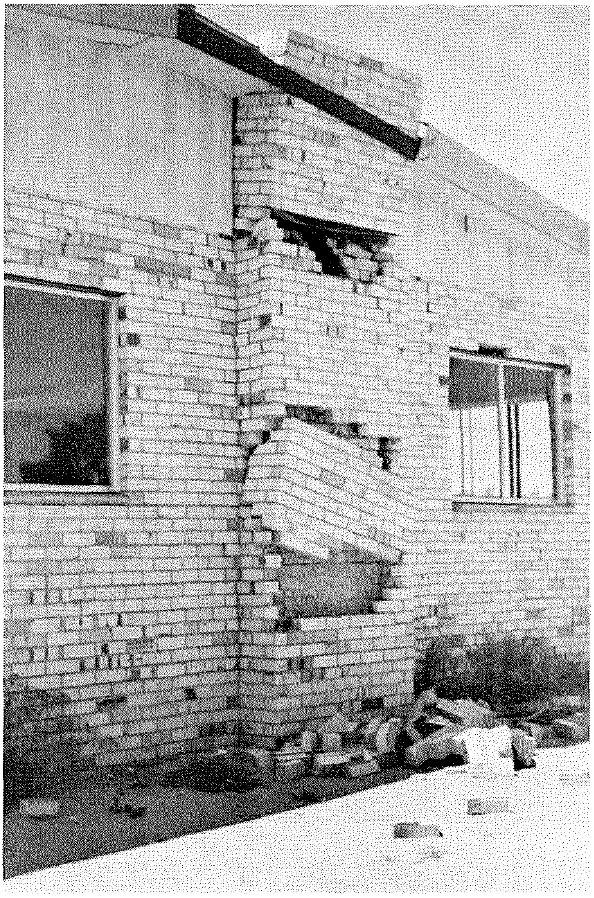
One of the most instructive instances of damage concerned a newly erected double brick house in Dempster Street. The outer walls were largely intact, but all the internal walls were cracked and broken. The outside strip-footings were up to 0.5 m deep, and were resting on a stiff black clay, which is a good foundation material. The damage was not the result of poor workmanship, poor materials, age, or foundation settlement, but was the result of seismic shaking which caused differential movement between the outside strip-footings and the individual footings supporting the interior walls.

Foundation assessment showed that, in general, more severe damage was recorded for structures on loose alluvial foundation soils than for those on residual or weathered granite foundations. The main shopping centre and the houses in Throssell, Gregory and Dreyer Streets, which sustained maximum damage, were all on areas of alluvial sand. These locations on the northern edge of the townsite were closer to the epicentre than most of the other townsite dwellings, so the effect is not clear cut.

The cumulative effect of earthquake damage was shown by structures that were not repaired following the main earthquake. The former power station in Byfield Street was a reinforced concrete building which showed no obvious signs of major damage after the main earthquake shock. On Saturday 15th February 1969 at 7.45 pm a severe local earth tremor appeared to come up vertically beneath the building. A small reinforced concrete wall 1 m long by 0.75 m wide by 0.3 m thick broke along a horizontal surface and pivoted on a reinforcing rod. At the same time a concrete partition wall cracked and spalled two pieces of concrete 23 x 10 x 13 cm, exposing the reinforcing rods. No coincident earthquake was recorded at Mundaring Observatory, which indicates that the local magnitude was less than 2.5 on the Richter Scale.

The Meckering Golf Club, a double brick structure completed only a month before, was effectively damaged by the main earthquake, although the walls and roof remained standing. The chimney was wrecked, and the walls were severely cracked and moved away from the floor block. On Monday 21st April, 1969, a local aftershock shifted the wall about 8 cm and completed the destruction of the chimney (Fig. 8). Eight hundred metres to the southwest, the same aftershock shifted all the moveable items in the butcher's shop. Heavy machinery, such as the band saw, was moved up to 23 cm, but there was no consistent direction of movement in the six items measured, and this suggests that the shock movement was vertical. Additional local aftershocks continued to accentuate damage for a period of at least 2 months after the main earthquake.

Smith (1969) summed up his observations of damage in the Meckering townsite by stating that masonry, mud and concrete blocks were unsuitable building media for structures in the area, particularly as little attention had been given to adequate bonding or reinforcement of walls. They are also unsuitable for building in any area liable to seismic shaking. One of the most potent factors in causing damage was the duration of shaking. From the eye-witness account of Mr. Solomon, the hotel and general-store were largely wrecked by the initial motion, but it was at least 9 seconds later, following the second and third earthquake pulses, that the bank building fell apart. At least 45 seconds later mud bricks were still falling from a house on the Goomalling Road. Orientation of a structure with respect to ground movement was another factor in the nature of the



8. **Chimney of the Meckering Golf Club house, damaged by the main earthquake and progressively wrecked by aftershocks.**

damage sustained. Although often obscured by other factors which led to complete destruction, the selective destruction of the northeast and southwest walls of the hotel and bank buildings is in accordance with the displacement of initial ground movements.

DAMAGE TO PUBLIC UTILITIES AND COMMUNICATIONS

GOLDFIELDS WATER SUPPLY PIPELINE

Water for the Eastern Goldfields and many small wheatbelt towns is carried by pipeline from Mundaring, near Perth, to Kalgoorlie through twin 76-cm concrete-lined steel conduits. In the vicinity of Meckering, the earthquake broke the pipeline in several places. It was estimated by Belford (1969) that total damage would cost $35 000 to repair, but this could easily be doubled if the internal concrete lining was broken over any considerable distance.

9. **Impaction of the Goldfields Water Supply 76cm pipeline at the Meckering Fault, 4km southwest of the town. The compression at this point was 1.32m.**

THE PIPE FAILURE AT THE MECKERING FAULT

To the west of Meckering, the water mains follow the narrow gauge railway. The Meckering Fault, in the form of a series of *en echelon* scarps 3 m apart and offset to the right, cut the pipelines about 4 km west of the townsite. Both pipelines were telescoped for 1.32 m (Fig. 9). The crustal shortening at this point was 2.11 m, as measured on the standard gauge railway line, and the additional 0.79 m of shortening was taken up by arching of the pipe and compression, which caused damage to the pipe supports on either side of the impacted zone.

No lateral movement was evident in the line of the pipes, or in the adjacent railway lines, in spite of a local 1.5 m dextral movement. This was because the pipelines and railway were paralled to the local resultant direction of 268°.

Considerable damage was done to the reinforced concrete pipe collars in the vicinity of the fault. The initial westward movement of the eastern block sliding on the fault plane meant that there was maximum compression at the scarp, decreasing to the east, while further east, in the backscarp zone there would be a local tendency for the pipe to be placed in tension. In the immediate vicinity of the main fault, the compression pushed a 1.2 km section of the pipe through the concrete collars towards the west on the western block. To the east of the fault the relative movement of a 400 m section of pipe was to the east.

The net effect of the local crustal shortening at the fault was to put tension on the pipeline to the east. In the ground this tension was relieved by the formation of tension cracks, particularly in the backscarp zone 13 km east of the fault. The pipeline, however, could only respond by fracturing.

PIPE FAILURE AT A TENSION FAULT

On Tuesday, 15th October, at about 5 am, the northern of the two water mains fractured at a weld 2.6 km east of the earthquake scarp. The break followed a strong aftershock, after the major break in the pipe at the fault scarp had been repaired. A band 23 cm wide was welded in to make good the damage. On 31st October, following a cold night, the southern pipe parted at a point 160 m to the west of the earlier break, and was restored by the addition of an 18 cm band.

The break in the northern pipe was caused by the opening of a tension crack which could be traced for over 5 km. The concrete floor of the Co-operative Bulk Handling (C.B.H.) grain storage building was cracked by the same event and construction joints in the walls were opened. A farm water-supply service line, 1.5 km to the north, was also severed. The correlation of this tension crack with a magnitude 3.8 aftershock indicates the very low threshold of the earthquake magnitude that can cause damage if a structure is already weakened.

There were two further breaks caused by tension in the pipelines between November 1968 and June 1969, and small sections were welded in. It was considered that cold weather would cause the pipes to contract, thus increasing tension, but this was obviated by cutting the pipe at the main fault and tension fault areas to relieve stress and then rewelding.

PIPE FAILURE IN A SLUMPED AREA

At the time of the main earthquake a break in the northern pipeline took place 2.5 km east of Meckering. The pipeline at this location is at the foot of a hillslope with a considerable amount of granite outcrop and at the foot, salt flats. A series of five small arcuate scarplets with a total downthrow of 15 cm showed that the cause of the break had been slumping in the poorly consolidated soil. A month later, after some local aftershocks, a further three small scarplets had developed with a total depression of 11 cm. The net effect of the slumping was to lower the concrete pipe supports on both pipelines by about 10 cm.

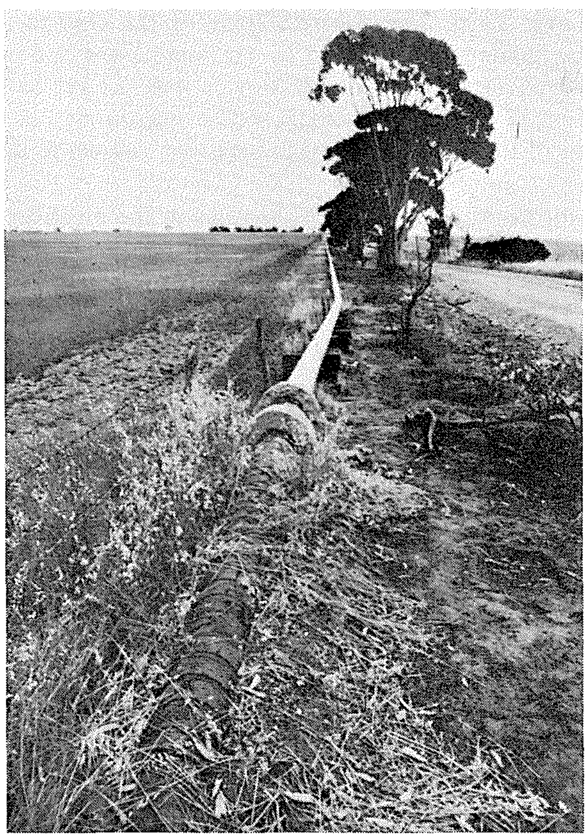
MOVEMENT OF THE MAIN CONDUIT AT MECKERING

A single conduit, 1 m in diameter, situated in Vanzetti Street, carries the goldfields water supply through Meckering. Examination of the pipeline in the vicinity of some damaged collars near the show ground revealed that on the southeast side of the pipe there was a gap of 15 cm between the tall grass and the pipe, whereas, on the northwest side, the grass had been caught under the pipe. At several of the concrete block supports, stalks of grass were found caught between the pipe and the supports.

In this area the pipeline is closest to the epicentre, and would have been subjected to the initial vertical movement followed by two periods of east-west translation that were clearly evident elsewhere. The pipe was largely restrained by collars 67.5 m apart, but between the supports appears to have moved in an eliptical orbit to pull down and catch the grass. The concrete collars were damaged over a distance of about 200 m.

DISRUPTION OF THE MECKERING-GOOMALLING PIPELINE

The Meckering Fault disrupted the Meckering to Goomalling pipeline at the corner of Stewart Road, Moore Road and Goomalling Road, 1.6 km northwest of the town. The pipeline was broken by the eastern block's lifting 1.22 m, moving westward 1.22 m, and moving southward 0.76 m. The geometry of the move is clearly shown by the abandoned support blocks on the western side of the scarp (Fig. 10). Further north along the Goomalling Road, the pipeline was disturbed, but not broken by the small scarp of the Northern Splinter Fault.



10. The Meckering-Goomalling pipeline at the Meckering Fault, 1.6 km northwest of the town. The original line of the pipe can be seen from the position of the abandoned pipe support.

FARM SUPPLY PIPELINE

A 7.5 cm service pipeline alongside the Meckering to York Road was broken, 10 km from Meckering, where it was intersected by the Robinson Fault, a minor branch of the Meckering Fault. A dextral movement of about 25 cm was responsible for the break.

WEST AUSTRALIAN GOVERNMENT RAILWAYS

DISRUPTION OF TRACK AT THE MECKERING FAULT

West of Meckering, the standard gauge and narrow gauge rail lines run together and are parallel to the Goldfields Water Supply pipeline. The Meckering Fault disrupted the tracks 4.2 km west of Meckering, at the location of maximum uplift and crustal shortening. The tracks were parallel to the local resultant, and no lateral movement was visible, but there was a 1.52 m uplift to the east and a 2.11 m shortening. This resulted in spectacular patterns of surplus track in the form of a double reverse *S* on the standard gauge line, and a reverse *S* on the narrow gauge (Fig. 11). The crest of the scarp on the standard gauge line was about 3 m high as a result of compression of plastic residual clay. The tracks were restored by cutting out the twisted section and regrading of the rail bed across the scarp.

11. Distortion of the standard and narrow gauge railtracks at the Meckering Fault. The figure is standing on the 3 m-high fault scarp.

Levelling showed that the standard gauge line had been uplifted for a distance of 10 km east of the fault. The newly laid standard gauge track was more affected by misalignment and settlement, than the old track; such irregularities continued for about 20 km east of Meckering (Keane, 1969). The estimated damage to track, telephone and signalling services was about $25 000.

The railway line to the east of the fault was under considerable tension after the initial break. It is preferable to have rails under tension rather than compression because tensional breaks rarely cause derailments, but even the advent of colder weather did not produce any tension breaks in the rails. Nevertheless, the shortening of the rails by over 2 m indicates remarkable ductility, particularly when it is remembered that the stresses produced considerable tension cracking in the ground.

DAMAGE TO RAILWAY BRIDGES

The standard gauge railway bridge over the west branch of the Mortlock River was damaged when the concrete deck separated from the piers. The deck was contained laterally by the abutments at either end, and the maximum movement took place at its mid-point, where a protruding piece of concrete 75 cm long, was spalled off the pier. The relative displacement of pier and deck was 1.2 cm. The railway line, ballast and deck appear to have remained in place because of the tensional strength of the rails, while the piers were displaced to the south.

The bridge over the east branch of the river exhibited exactly the same damage, with minor spalls of concrete at the northern ends of the piers, and the deck separated clearly from its supports.

A bridge over a minor stream 1.2 km east of the fault was damaged by the same type of southerly ground movement. The motion was severe enough to split the northern wing wall of the east abutment horizontally at the level of the deck, and a block of concrete 60 × 30 × 23 cm was broken off. The displacement shown by the central piers was about 0.6 cm southwards. The damage to the abutments on both sides of the track shows that the ground was shaken in an east-west direction before final settlement.

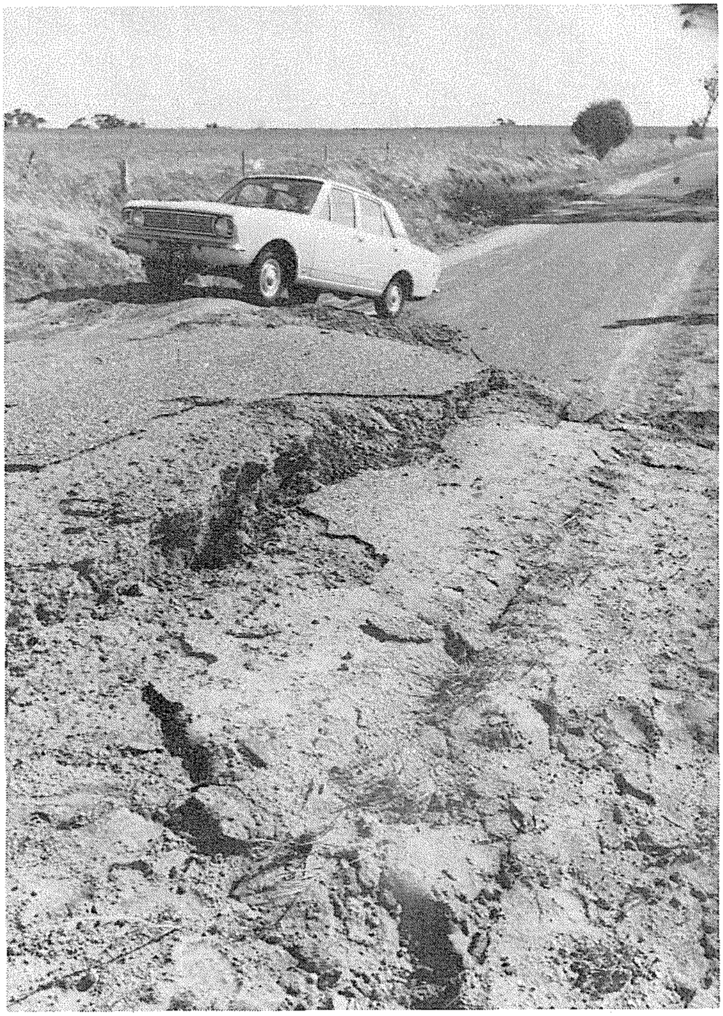
MECKERING STATION

The platform of Meckering Railway Station dropped about 25 cm during the earthquake. The wooden station building moved away from the platform, allowing the filled platform area to settle, leaving a gap of about 30 cm between the building and the fill and a further 8 cm between the fill and its concrete retaining wall. This type of damage was due to ground slumping and spreading during shaking.

DAMAGE TO HIGHWAYS

The formation of a fault scarp in a 37 km arc around Meckering had the immediate consequence of isolating the town from the north, west and south. The highways to Dowerin, Goomalling and York (Fig. 12) were severed by a scarp up to 2.4 m high in places. The Great Eastern Highway was cut at a point 7.25 km west of Meckering by a scarp 2.1 metres high (Fig. 1). Fortunately there were no serious accidents caused by people driving over the scarp. Although it was made passable within four hours, the Great Eastern Highway was kept closed for a further day to allow inspection of the Mortlock River bridge.

Minor damage was done to the highway by tension cracks that formed at the time of the earthquake, or appeared subsequent to aftershocks (Fig. 13a). Most of these openings were between Meckering and the fault, but there were many to the east of the town, particularly in the backscarp area adjacent to Waeel railway station. There were also several areas where the roadway obviously deteriorated following the movement of the fault block, and this damage was apparent as far east as Cunderdin.



12. The Meckering Fault scarp on Koolbunine Road, 11 km south-southwest of Meckering. (Photo: W.A. Newspapers).

A

B

13. Road damage:
    (a) Tension faulting across the Great Eastern Highway, 2 km west of Meckering.
    (b) Lateral spreading of road fill, and consolidation below culverts causing damage to buttresses, 1.6 km southwest of Meckering.

A bridge on the York road, 2.5 km south of Meckering, was seriously damaged. The bridge was already under repair at the time and workmen who inspected it on 15th October found that rows of new piles had been displaced as much as 15 cm at the base, while the heads remained fixed to the main bearers. In addition, the approach fill on the southern end of the bridge had slumped and displaced the wooden retaining wall, and the guard rail had been broken.

Almost all concrete box-culverts in the Meckering district showed slumping and lateral movement of the abutments (Fig. 13b). Where a residual movement was measurable it appeared that the ground moved to the south while the road remained in place.

ELECTRICITY SUPPLY AND COMMUNICATIONS

STATE ELECTRICITY COMMISSION INSTALLATIONS

Two high-tension lines followed the Great Eastern Highway southwest of Meckering, and traversed the fault at an angle of about 60°. The poles straddling the fault were brought 1.8 m closer and those on the eastern block were displaced, relatively, 1.2 m to the south. The ground clearance of the 66 KV line was lowered from 6.7 m to 2.7 m at the fault. An extra pole was added to regain clearance temporarily, but all conductors were eventually shortened by 1.8 m.

Although the high-tension supply to Meckering was maintained, the transformer fuses blew when the low-tension mains clashed (Le Souef 1969). Numerous house service leads were broken as poles swayed out of phase with the buildings.

POSTAL AND TELEPHONE INSTALLATIONS

The damage to plant and operations of the Postmaster General's Department were summarized by Parker (1969) as threefold:

(1) interruption to some interstate telephone circuits,

(2) severe structural damage to the Meckering Post Office Building, and

(3) damage to the automatic telephone exchange and interruption of all subscribers services in the area.

The interstate telephone and telegraph channels were carried on an aerial route alongside the standard gauge railway line, and the block movement on the thrust plane caused the wires to sag and touch the ground. About two metres of wire was cut out in retensioning.

The destruction of the Post Office, containing the local exchange, isolated Meckering from the national trunk network, and cut off the 120 local telephone subscribers. By 3 pm on 14th October the first emergency service was in operation between the Police Station and Cunderdin Exchange and normal telephone services were connected within 48 hours.

DAMAGE TO A GRAIN SILO AT MECKERING

The Mortlock River Valley, southwest of Meckering, is dominated by a grain storage silo adjacent to the standard gauge railway yards. The vertical storage consists of two circular cells 30.5 m high and 11 m in diameter, interconnected with an elevator and surmounted by a tower 5 m square and 12 m high. The cells are built on slightly decomposed granite, and the walls are 20 cm thick. The horizontal storage shed measures 100 m long, 30 m wide, and has walls 5 m high and between 20 and 40 cm thick. The units are inter-connected by a tunnel below road level and by a conveyor and gallery at the apex of the horizontal storage shed (Nash, 1969).

The silo is 1.2 km east of the main fault scarp, and about 2.5 km west of Meckering. The interest of this installation lies in the fact that it was a new, well founded, tall reinforced concrete structure, not designed for seismic forces, yet subjected to seismic shaking about 10 km from the earthquake epicentre.

At the time of the earthquake, the vertical silos were full, and the horizontal shed was about half full, with a pile of grain at either end of the shed. The grain in both piles moved to the west during the earthquake but this fact is not diagnostic as there is a slope in the floor of 2.2 m in 100 m towards the west. In the event, grain from the western pile spilled over the western end of the shed.

The walls of the vertical cells showed extensive fine hair-line cracking, but no obvious structural damage. There was separation of the elevator tower from the tops of cells, but no lateral displacement was seen. Hair line cracks also developed at the corners of all openings of the elevator tower between the cells. Cracks up to 0.3 cm wide showed in the pits and tunnels under the cells, but Nash (1969) summarized the effects as only minor.

The truss linking the shed and the silo cells was buckled by lateral motion between the two buildings, probably as a result of north-south shaking.

After the wheat had been removed from the horizontal storage shed, two connected cracks each having an opening of about 2.5 cm were found running across the western end of the shed on a trend of 008° in the 12.5 cm thick concrete floor. There was also clear evidence of settlement in the 6.7 × 6.7 m square floor slabs between construction joints in the vicinity of the tension opening. The walls of the long shed are divided into sections by expansions joints; these were opened up to 3.2 cm on the northern wall, and up to 1.2 cm in the east and west walls. Movements of up to 10 cm had occurred in some of the gaps. The water stop in the construction joint was twisted out of shape but remained integral (Lay, 1968). Outside the shed, a tension opening trending 020° was found cutting across the northwestern corner of the shed, and this could be traced continuously for 5 km until it crossed Great Eastern Highway (Fig. 58). This major tension fault was activated on Tuesday 15th October at 5 am as the result of a local aftershock, the same movement as broke the northern Goldfields Water Supply pipe. The tension fault cannot be traced continuously past the silo to the north, but there is a tension opening coming off the main scarp and trending 167°, that is probably a continuation of the same feature.

In summing up the earthquake effects, Lay noted that the silo complex was strong evidence of the capability of well designed structures to withstand earthquake loadings of the type experienced at Meckering. It suffered only minor damage, of a type allowed for by the designer. However, the damage also showed that aftershocks of low to moderate magnitude can be accompanied by tension faulting of considerable potential for destruction if any structure is located astride them. In general, damage from fault motion is not confined to the immediate vicinity of the main fault, the secondary faults and faults generated by the earthquake over several hundred square kilometres may have destructive potential.

EARTHQUAKE EFFECTS ON RIVER DRAINAGE

The Meckering district is drained by the Mortlock River and its tributaries, which flow westerly from Cunderdin through salt flats nearly two kilometres wide. Four kilometres northeast of the town, the river channel narrows, but continues its westerly flow for a further kilometre. There is then an abrupt change to a northerly course for 800 m, from which point the river flows in a large southerly arc around Meckering. Ten kilometres southeast of the town, the Mortlock changes from its southerly course to a southwest course and after a further 4 km abruptly changes to a northwest trend for 3 km. From this point the meandering westerly course of the Mortlock is resumed. The general course of the river, particularly the arc, concave to the east, around Meckering and the sudden changes of direction appears to be governed by faulting similar to that accompanying the Meckering Earthquake.

The general parallelism of the fault scarp and the river course meant that the channel was not intercepted by the fault until the river commenced a southwesterly course, about 10 km southwest of Meckering (Fig. 14). The river bed was disrupted by an uplift of about 1.5 m, but because of the parallelism of scarp and channel the grade of the river was not substantially reduced in the section between the Great Eastern Highway and the fault. In

14. The Meckering Fault scarp as it crosses the Mortlock River, 10 km southwest of Meckering.

15. A small stream, west of Meckering, dammed by the Meckering Fault. The stream flows east and on the uplifted block the stream bed has dried out (air photo W.A. 1112, 5150).

the vicinity of Meckering, the uplift of the eastern block was not as great as at the scarp, and the grade of the river was flattened from approximately 0.91 m/km to 0.76 m/km (Green, 1969). The tilting of the upraised block had the effect of raising potential flood levels in Meckering by 12 cm.

The formation of the fault scarp also meant that a considerable barrier had been erected to the tributaries of the Mortlock that flowed from the west. In particular, four streams near Meckering were dammed, and a considerable area of farmland would have been flooded before the drainage readjusted itself (Fig. 15).

Flooding and salt intrusion had earlier caused the townsite to be moved in the 1930's and the new site was badly affected by flooding in 1963 and 1967. It was therefore decided that the main river channel should be cleared and improved for a distance of about 16 km. At the same time the minor watercourses were redefined and the fault scarp cut through to maintain the previous stream pattern. This work was done by the Public Works Department and the results summarized by Green (1969) as: "... flood levels have been restored to at least their previous level, and the flooding hazard to roads and railways servicing the town is at least no worse than previously".

Perhaps, however, this is not the last word on the situation. Apart from the obvious manifestations of surface disruptions such as fault openings and ridges, there have been many subtle changes in the landscape as a result of the movement of the eastern mobile block. Levelling work done by the Lands and Surveys Department in October 1969 (Chapter 10) showed that there were settlement and consolidation features over a wide area. In particular, where the backscarp zone crosses the Mortlock River salt flats 10 km east of Meckering, the pattern of small normal faults akin to slumping is likely to cause some ponding in the river. Throughout the Meckering area, the aspect of many small streams will have changed by minor amounts, and the physical effects of the earthquake are not likely to be fully manifested until revealed by a period of flooding.

CHAPTER 3

Earthquake effects outside the Meckering area

EXTENT AND DURATION OF SHAKING

Earth tremors from the Meckering Earthquake were felt in all the major centres of the southern half of Western Australia, including Geraldton, Kalgoorlie, Esperance, Albany and Perth. Although this area has a radius of about 700 km, significant damage was confined to an area of about 80 km radius of Meckering and isolated pockets of damage in the Perth Coastal Plain, particularly in the Perth metropolitan area.

The duration of earthquake shaking is generally poorly estimated because "... the brief emotional moments of an earthquake are not conducive to sustained or accurate observation..." (Dunn and others, 1939). Earthquake shaking does not commence abruptly and cease absolutely at determinable moments. The strongly felt main shock is preceded by minute tremors and is followed by longer and slower movements, both of which may be felt in differing degrees by different people. The position and activity of the observer has a considerable effect on the length of sensible shaking, and an observer in a tall building will usually record a longer duration than a person at ground level.

The table below gives the duration of shaking throughout Western Australia according to the best estimates of timing available.

TABLE 2 DURATION OF SHAKING

Place	*Duration*	*Direction and distance from Meçkering*	*Foundation soil or Location*
MECKERING	40 seconds	—	Alluvial and residual sand, weathered rock
YORK	4-5 minutes	225°, 40 km	Alluvial sand
BRUCE ROCK	20 seconds	103°, 110 km	Residual sand
PERTH	24 seconds	258°, 114 km	Residual and alluvial sand, limestone
	3 minutes	253°, 114 km	10 storey building
MILING	1 minute	335°, 140 km	Weathered granite gneiss
BUNBURY	10 seconds	215°, 230 km	Sand over basalt
BRIDGETOWN	5 seconds	200°, 274 km	Alluvium, weathered rock
MARGARET RIVER	5-6 seconds	215°, 322 km	Weathered gneiss
ALBANY	5 seconds to 1 minute	168°, 382 km	Residual sand over granite

As earthquake waves radiate out, the duration of perceptible shaking at first increases rapidly with distance and then decreases. Geological factors may have a considerable influence on the variations of duration from place to place. Shocks may be felt more intensely in some geological environments than in others. For example, above a thick sequence of alluvial material, shaking will be felt more strongly and for longer than on crystalline bedrock. Under certain conditions the ground motion may be amplified by resonance.

EARTHQUAKE DAMAGE OUTSIDE THE EPICENTRAL AREA

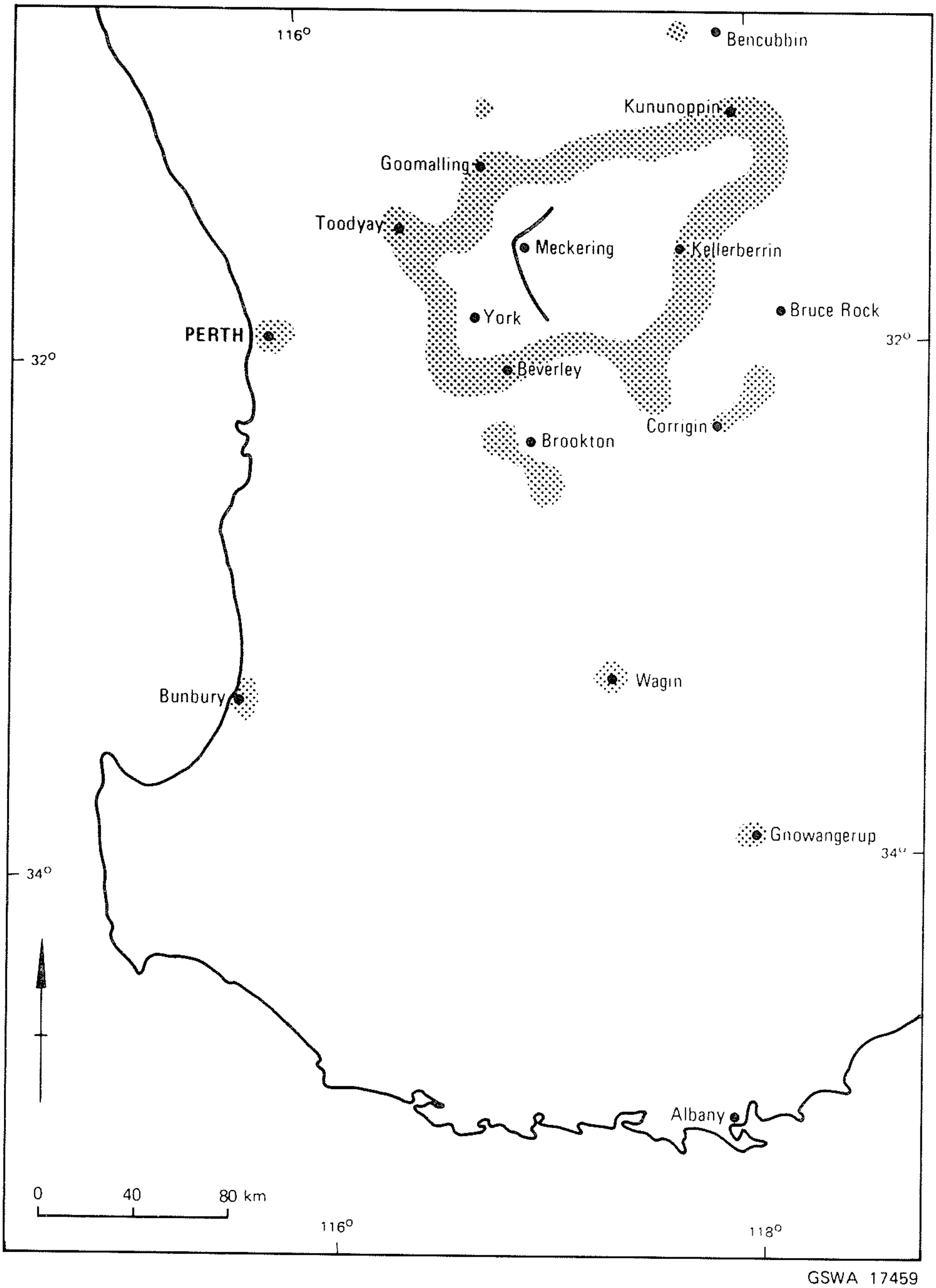
In Chapter 2 the damage in Meckering township caused by the earthquake was described. It is obviously more difficult to catalogue the damage that was inflicted over the whole of the earthquake affected area, particularly when it is realized that in districts far from the epicentre, the damage may be no more than hair line cracks in plaster. In the absence of detailed knowledge of the condition of a building prior to the earthquake, it is often difficult to assess whether minor damage was even caused by the earthquake. A crude indication of the extent of damage can, however, be obtained by a consideration of claims for more than $300 damage made to the Lord Mayor of Perth's Earthquake Relief Fund. Claims from townsite areas are given in Table 3, and the area over which damage was proven by the Relief Advisory Committee is given in Figure 16.

An examination of this data shows that significant damage was largely confined to the area where the intensity of the earthquake was MM VI or greater, but that there are well developed lobes extending towards Toodyay, Goomalling, Kununoppin and Corrigin. Figure 16 also shows that the envelope enclosing damage claims is eccentric, with its centre located to the east of the epicentre, indicating that seismic affects were felt more strongly to the east than to the west of the source.

The intense damage caused by the earthquake in York is more a reflection of the age and state of repair of buildings in that town than of closeness to the epicentre. In addition, the alluvial deposits of the Avon Valley provide relatively poor foundation conditions; this

TABLE 3. LORD MAYOR'S RELIEF FUND: CLAIMS FOR DAMAGE IN EXCESS OF $300 (TOWNSITE AREAS ONLY)

Town	*Number of claims*	*Distance and direction from epicentre*
York	245	40 km SW
Northam	177	32 km W
Meckering	62	3 km SE
Cunderdin	37	24 km E
Beverley	22	56 km SSE
Toodyay	10	50 km WNW
Wyalkatchem	5	63 km NE
Quairading	5	58 km SE
Tammin	5	48 km E
Perth metropolitan area	17	114 km WSW



16. **Areas of proved damage claims (courtesy of the Relief Advisory Committee, Lord Mayor of Perth's Earthquake Relief Fund).**

explains the extension of the area of damage northwards through Northam to Toodyay and southwards towards Beverley. Isolated areas of damage at Brookton, Wagin and Gnowangerup are structurally controlled, and all occur in the belt of gneisses which marks the southwest seismic zone, and lie to the west of the Meckering Line.

The minor bulges in the damage envelope towards Goomalling and Dowerin probably also represent a structural control. The Goomalling trend, about 330° from the epicentre is probably related to the regional structure which caused the earthquake. Around Dowerin, the regional distortion caused by the earthquake was evident from minor local ground cracks.

Perhaps the most interesting examples of structural control of damage are the extensions of the damage area towards Kununoppin in the northeast and towards Corrigin in the southeast. In the epicentral region the arcuate shape of the Meckering Fault is accompanied by a zone of almost complete destruction extending 5 km west of the fault and 20 km to the east. The damaged areas extending towards Kununoppin and Corrigin form 'wings' to this central crescent of intense damage and may represent shaking propagated along subsurface extensions of the Meckering Fault from the points where it loses surface expression.

ANOMALOUS DAMAGE NEAR JURIEN

There were several reports of apparently anomalous damage, but one is of particular interest as it occurred 240 km northwest of the epicentre. A newly constructed timber framed asbestos house was situated 32 km northeast of Jurien (Grid Reference: Hill River 317277), and although the earthquake was scarcely felt by people on surrounding farms the house was considerably damaged. One corner was tilted 5 cm higher than the others and the concrete floor cracked, with two sets of fractures at right angles. A parked vehicle rocked vigorously, and objects on a work bench jumped up at least 5 cm. The earthquake was heard with a noise like a diesel train coming from a nearby gully.

Mr. D. Lowry of the Geological Survey, who recorded these facts, noted that about 200 m from the house there is a ridge of ferruginized sandstone which marks the position of the Lesueur Fault. This is a major fault in the Perth Basin sediments which strikes north-northwest, and has a throw of perhaps a thousand metres. After the earthquake, however, there was no evidence that the Lesueur Fault had moved recently, it appears to have acted merely as a channel for the shock waves.

ACTIVATION OF A SPRING NEAR NORTHAMPTON

Apart from the seismic shaking which was felt widely throughout the state, the most distant permanent or semi-permanent effect of the earthquake was noted on a farming property 20 km north-northeast of Northampton and 420 km north-northwest of Meckering. Immediately after the earthquake a spring developed in a dry creek bed and was still flowing in January 1969. The water was brackish (salinity 1340 mg/1), and as it bubbled to the surface brought up a quantity of coarse sand and clay. The property owner attempted to enlarge the spring, but came to solid rock at a depth of 45 cm. The spring appeared to be similar to the clastic extrusions or 'sand volcanos' found in the vicinity of Meckering (Chapter 7). The Northampton district is not in the South West Seismic Zone but is on-line with its northern extension.

EARTHQUAKE EFFECTS IN THE PERTH METROPOLITAN AREA

To the east of Meckering seismic shaking was easily propagated, but its westward transmission was possibly impeded by strongly reflecting boundaries of old arcuate faults.These geological barriers probably caused the partial confinement of strong seismic shaking to the east, rather than allowing free propagation westward towards Perth.

The Meckering Earthquake was felt for about 24 seconds in the Perth metropolitan area, although some tall buildings apparently vibrated for as long as 3 minutes. Felt intensity was usually about MM V although there was an isolated area of MM VI reports from the city block. The height of the buildings in which the observers were located, however, is not recorded. Between Bellevue and Midland, and at Guildford, there were also reports of MM VI intensity, which accords with reports of significant damage from this area. This local intensification of seismic shaking occurred when the shock waves entered the unconsolidated sediments of the coastal plain from the granitic terrain of the Darling Range. Differing foundation conditions also gave rise to local variations in intensity. The clay foundations of the Guildford area, and sand and alluvium in the city area gave rise to high intensities whereas in the 'Coastal Limestone' belt the intensity of shaking was noticeably lower than in surrounding districts. Most structural damage occurred because of shaking, but there were several areas where damage resulted from landslides and the consolidation of saturated soils.

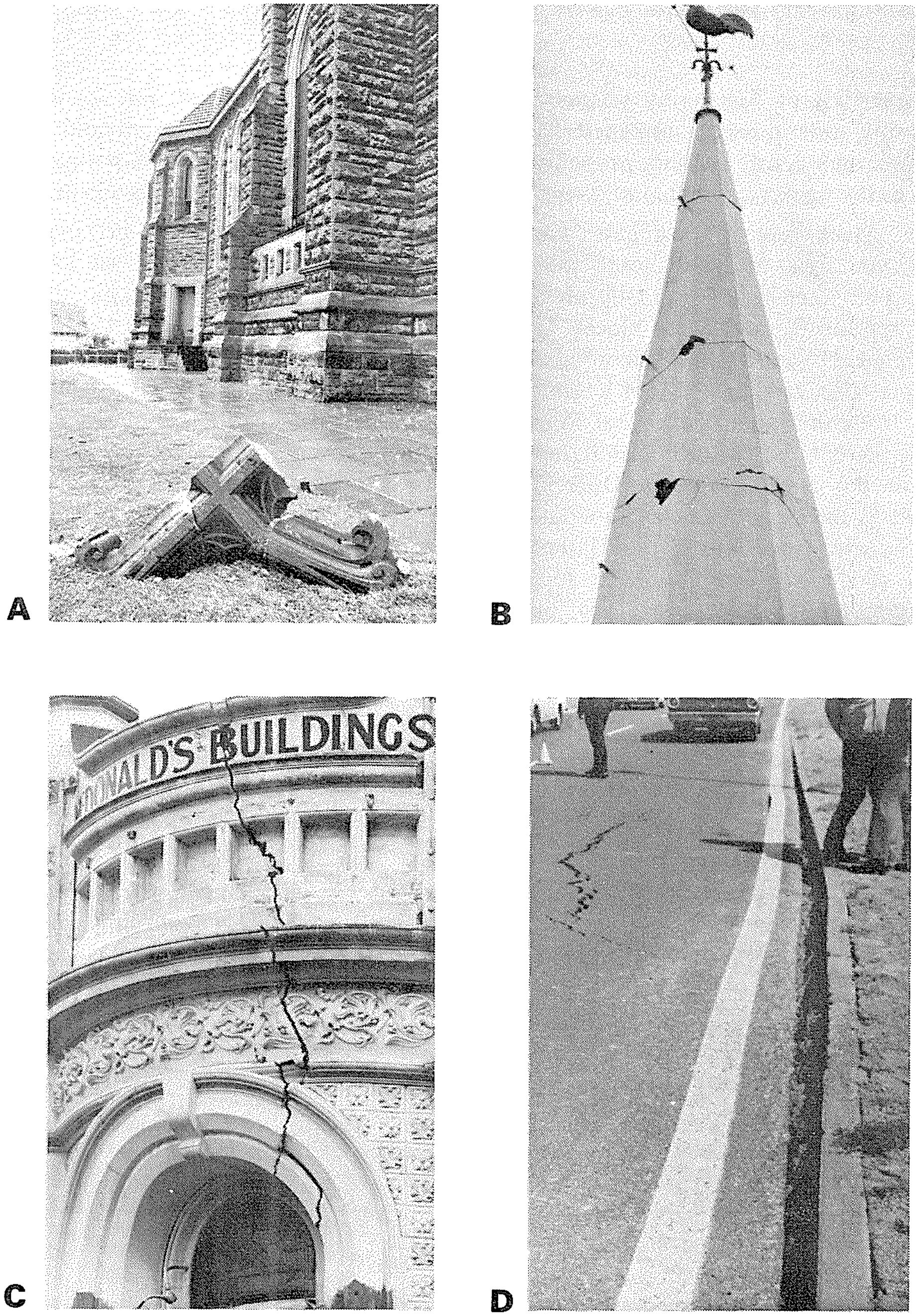
DAMAGE TO BUILDINGS

The most widespread type of damage was the cracking of walls and plaster ceilings. In general, two-storey houses were more badly affected than single-storey dwellings, but the total extent of damage will never be known, as many people were unsure of the prior condition of their property.

As a guide to the extent of damage the Fire and Accident Underwriters Association of Western Australia have provided the statistics shown in Table 4 regarding earthquake claims submitted to member companies. (Note that the metropolitan area is defined as being within a radius of 48 km from the General Post Office, Perth).

TABLE 4 EARTHQUAKE DAMAGE—INSURANCE CLAIMS AS AT 28 FEBRUARY 1969

	Fire policies		*Houseowners and Householders policies*	
	Number of claims	*Amount incurred ($)*	*Number of claims*	*Amount incurred ($)*
		Metropolitan		
Dwellings	33	7 850	6 450	697 748
Other	357	202 250	—	—
		Country		
Dwellings	54	22 602	743	330 223
Other	69	80 082	—	—
Total number of claims 7 706				
Total amount incurred $1 346 763				



17. **Earthquake damage in the Perth Metropolitan Area:**
(a) **Stone cross fallen from St Mary's Cathedral.**
(b) **Cracked spire of Wesley Church.**
(c) **McDonald's Buildings, corner of Barrack and Murray Streets.**
(d) **Slumping of landfill on the Kwinana Freeway.** (Photos: W.A. Newspapers).

STRUCTURAL DAMAGE

The best roster of structural damage to Perth buildings has been obtained by the earthquake committee of the Perth Chapter of the Australian Consulting Engineers Association (ACEA, 1970), but this is restricted in scope. Of the 24 damaged buildings, all were either old, or were uncompleted shells under construction. In many cases the buildings had shown previous signs of deterioration because of subsidence or old age. In certain areas, notably in the Cannington district some new buildings suffered structural damage because of the spreading of alluvial clay foundations.

Ornamentation on the older major churches was particularly vulnerable to the seismic shaking, and heavy stone crosses and bricks fell more than 30 m at both St. Mary's Cathedral (Fig. 17a) and St. George's Cathedral. The spire of Wesley Church was badly cracked and damaged (Fig. 17b). St. George's Cathedral, an old load-bearing brick building, suffered serious structural damage.

ROADS AND BRIDGES

Land for the Kwinana Freeway and the Narrows Interchange was reclaimed by dumping large quantities of sand to displace mud. Several slips were developed during this operation and the reactivation of these old slip surfaces by the earthquake caused subsidence and movement affecting the freeway. Movement of up to 30 cm horizontally and vertically occurred (Marsh, 1969), causing depression and cracking of part of the freeway, damaging boat sheds and tilting jetties (Fig. 17d). There was subsidence behind the northern abutment of the Narrows Bridge and the approach road moved down about 2 cm and laterally about 10 cm. The Bridge abutment is contained in the fill and there could have been serious damage to the bridge had the movement been larger. Further reactivation of this particular slip surface by an earthquake would endanger the bridge.

DAMAGED TRANSFORMERS

The seismic shaking tripped many of the State Electricity Commission's power transformers. Approximately 70 megawatts of load was dropped, out of the 198 megawatts on the system at the time. Out of 81 transformers in the metropolitan area 24 registered relay operations, and 15 of the 33 major stations were affected (LeSouef, 1969). The trips were caused by the operation of relays activated by oil movement in the transformers or the slopping of mercury in mercury switches, or by a combination of both. At the Welshpool Substation no transformers tripped, but the support insulator of a capacitor stack was broken, the only recorded structural damage to installations.

The trippings gave a good guide to foundation conditions in the Perth area. All six stations on the calcarenite of the 'Coastal Limestone' survived the shaking, but two situated in the unconsolidated Safety Bay Sand to the west of the limestone had 7 out of 17 transformers tripped. Similarly, all transformers tripped in the Claremont, Daglish, City Beach, and Innaloo areas were situated in small depressions on quartz sand leached from the Coastal Limestone. The five transformers in the city area were not tripped because they were sited on relatively high locations with lime sand foundations.

All except two of the transformers sited on the Bassendean leached sand or the alluvial Guildford Formation were tripped. In the Hamersley area, north of Perth, two stations were situated about 4 km apart on leached Bassendean sands. In one station the long axis of the transformers was east-west and both were tripped, at the other the long axis lay north-south and the two transformers were unaffected by the shaking.

DAMAGE AT YANCHEP CAVES

At Yanchep, 51 km north of Perth and 127 km west of Meckering, a shallow cave system in the Tamala Limestone formation forms a popular tourist attraction. In five major caves, water percolating through the porous sandy limestone has produced a variety of solution and secondary deposition features of considerable aesthetic appeal. Seismic shaking caused rock falls and displacements, damaging stalactite formations. Changes in water level have caused a new set of deposition features to develop and the old ones to be truncated. Two of the caves, including the Silver Slipper Cave, were sufficiently damaged to be declared unsafe, and were closed.

ROCK CUTTINGS, AVON VALLEY DEVIATION

Considerable care was taken in shaping the major rock cuttings of the standard gauge railway line in the Avon Valley Deviation (Gordon, 1968). However, there were areas of potential instability and these were examined to determine if any changes had occurred because of the earthquake.

Windmill Hill cutting, 8 km east of Toodyay, was not apparently affected. Horseshoe Hill cutting, 8 km west of Toodyay, had sustained a minor rock fall of about 5 cubic metres, and other areas had been sufficiently loosened by the shaking to make rock falls probable. The major structural defect of a possible block glide on sheet joints at the south end of the cutting was not worsened.

No. 1 Rock Cut, in the Swan Gorge about 0.8 km east of the Darling Scarp, and 97 km from Meckering, showed four minor rock falls and several loosened blocks. No. 2 Rock Cut, a further 0.8 km to the east, showed only one rockfall, but the effects of shaking were clearly seen. A block 1.2 x 1 x 0.6 m on the north side of the cutting had separated 5 cm from the rock mass and was left in a position vulnerable to further shaking.

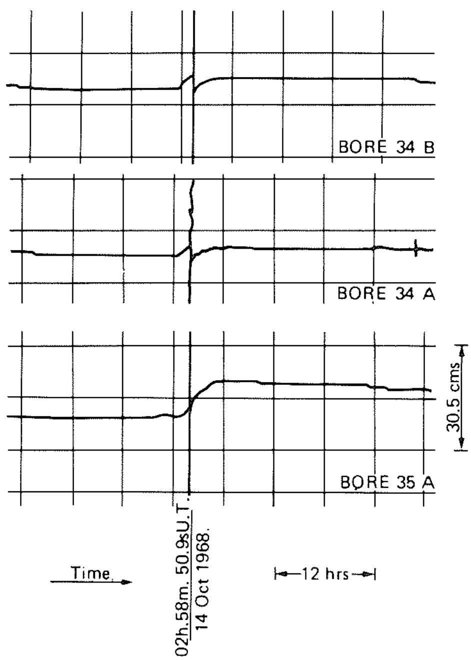
EFFECT ON WATER LEVELS IN WELLS AND BORES

Apart from the collapse of a few old or poorly constructed wells numerous reports were received of changes in level or temperature of the water. Town water supply throughout the area comes from the Mundaring dam via the Goldfields Water Supply pipeline so that all the reports came from shallow wells and bores sunk for farm supplies. None of these had been properly monitored before the earthquake so that although the reports may have been correct, particularly in the epicentral region, there was no way of measuring the changes.

Several springs were also reported to be flowing much stronger after the earthquake, but the only one that could be monitored in any way was Yangedine Spring, 17 km south-southeast of York. This spring was used to fill a swimming pool on a continuous basis and the flow monitored visually. Immediately after the earthquake the spring was reported to be flowing more strongly and at a higher temperature. The temperature of the spring was measured in early November 1968 at 21.5°C which is normal for the area, and it is possible that the apparent increase in temperature of the swimming pool was brought about by increased turbulence and replacement of cold bottom layers caused by the greater flow from the spring.

Within the Perth Metropolitan Area, the shallow groundwater of the Gnangara area, 19 km north of Perth and 110 km west of Meckering, is being utilized for the city's water supply and recorders were attached to a number of the bores. The unconfined aquifer is in Quaternary sands with interbedded clays, which overlie the sediments of the Perth Basin.

Three bore records are reproduced in Figure 18, boreholes 34A and 34B are close together on a east-west line 35A is about 440 m to the north. All show the main Meckering shaking as strong vertical displacements on either side or rest level, but only the record of 34A shows the strong aftershock of magnitude 5.7 which occurred on the following day. In addition, each record shows a rise in the water level from 3 to 10 cm which began about 1.5 hrs before the earthquake and reached its maximum about 4 hrs after the event. This rise is superimposed on the gradual seasonal decline in levels and was originally thought to have been caused by the earthquake (Gordon 1970). Further work by Gregson and others (1972), however, has shown that the rise was probably caused by local rainfall on the 14th October 1968.



18. Water level records from Boreholes 34A, 34B and 35A, Gnangara.

TIDE GAUGE RECORDS

The automatic tide gauge records for Fremantle, Geraldton, Albany and Esperance were examined for possible earthquake effects. None of the records recorded the earthquake itself but several showed anomalous oscillations. From Albany, 386 km south of Meckering, the record showed oscillations commencing at 12.20 pm WST and these gradually diminished over the next 18 hours. The record from Esperance, 526 km southeast of Meckering, showed an unusually large amplitude series of oscillations commencing at about 5.20 pm WST and lasting for about 18 hours. Neither of these can be connected with certainty to the seismic events of the day, and oscillations in the Geraldton record between 9.00 am and 3.00 pm WST probably resulted from wind generated swell.

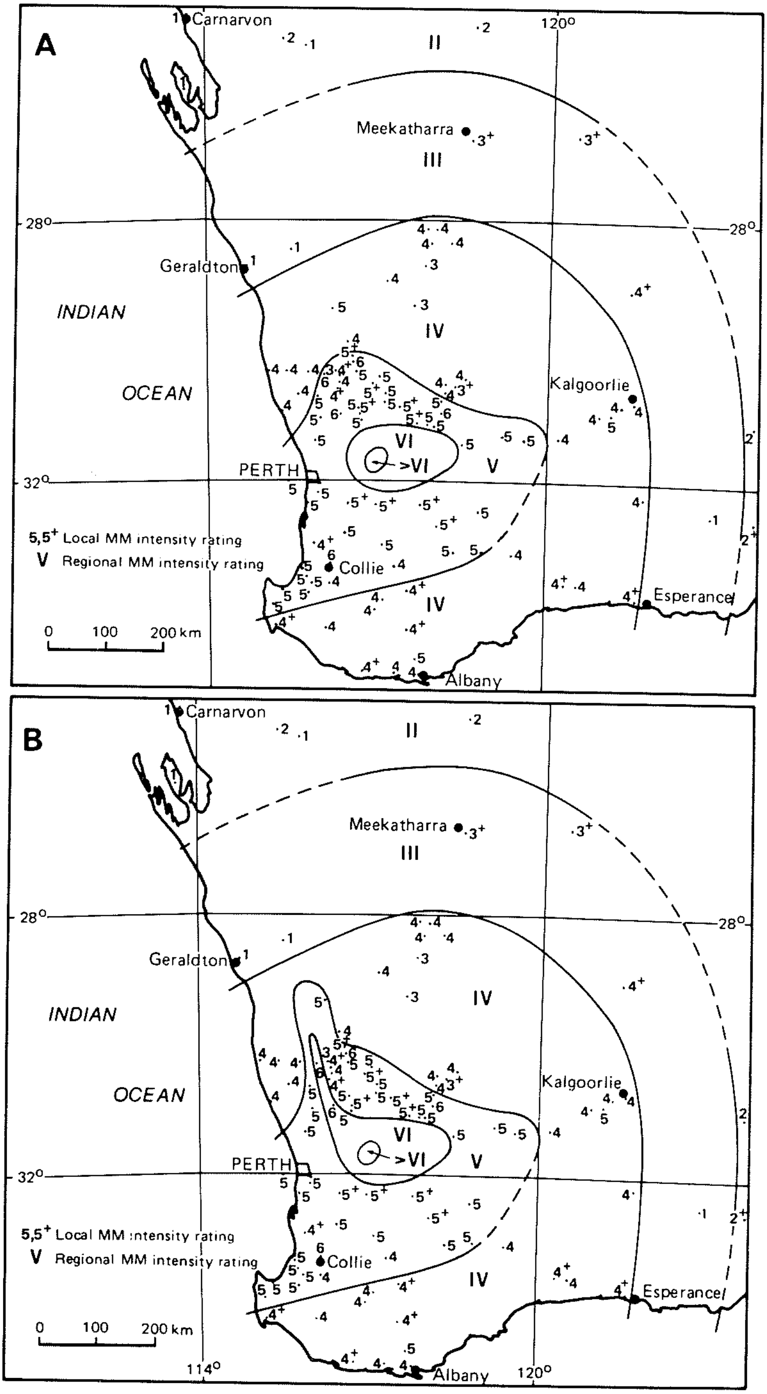
ISOSEISMAL MAP OF THE MECKERING EARTHQUAKE

The regional pattern of seismic shaking arising from the Meckering event is shown by the isoseismal map drawn by Everingham and Gregson (1969) from the results of about 400 questionnaires distributed immediately after the earthquake. Figure 19a is the original map and Figure 19b is a reinterpretation of the data by F. R. Gordon. The central area, within the MM VI isoseismal, is enlarged in Figure 20.

At intensities greater than MM VII, damage was severe, and the isoseismal is elliptical having its major axis oriented approximately north-south, enclosing the line of the fault. Intensities of MM VIII and IX were recorded close to the fault, and the isoseismals are probably arcuate and follow the fault closely. The influence of regional structure on the propagation of the earthquake waves is shown best by the MM VI and MM V isoseismals. The MM VI isoseismal is elliptical with its axis east-west and its western focus at Meckering. It is apparent that seismic shaking was propagated more easily towards the east than towards the west. Transmission towards the west was probably impeded by structural discontinuities and the reflecting boundaries of older arcuate faults. This isoseismal correlates well with the area of major damage caused by the earthquake (Fig. 16).

Isoseismal MM V is irregular in shape and has a bulge towards the east, similar to isoseismal VI, but in addition there is a bulge north-northwest of the epicentre which marks the trend of the Southwest Seismic Zone. Within the MMV zone there are several anomalous recordings of MM VI, and in an attempt to accommodate those, the data have been reinterpreted in Figure 19b. If this interpretation is accepted then both the MM VI and MM V isoseismals show a very pronounced extension along the line of the Southwest-Seismic Zone. Evidence supporting this reinterpretation includes the existence of ground distortion near Dowerin, and the occurrence in March 1970 of the Calingiri Earthquake, both in the northward extension of the MM VI isoseismal.

As intensity decreases the local Modified Mercalli rating becomes more difficult to determine and not everybody will recognize the minor shaking as an earth tremor. In Western Australia this difficulty is compounded by a lack of population in outback areas and a corresponding paucity of reports. In consequence the MM IV and MM III isoseismals of Figure 19 are only generalizations.



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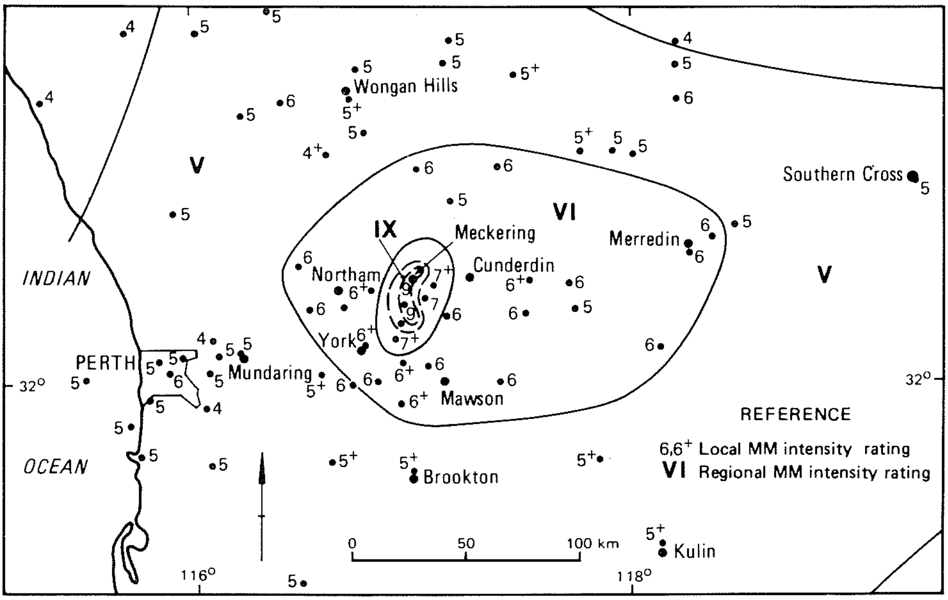
19. Isoseismal maps of the Meckering Earthquake:
(a) after Everingham and Gregson, 1969.
(b) as modified by F. R. Gordon.



20. Isoseismal map of the epicentral region of the Meckering Earthquake (after Everingham and Gregson, 1969).

DISTANCES OF DESTRUCTIVE INTENSITY

The limit of damage for an earthquake is the MM VI isoseismal. For the Meckering Earthquake this isoseismal is an ellipse with major and minor axes of 195 km and 115 km respectively. The area enclosed by the isoseismal is underlain entirely by crystalline Archaean rocks covered with a thin subsoil of weathered granite. In addition there was an isolated area of MM VI intensity 130 km from the epicentre in the Perth metropolitan area which is underlain by unconsolidated sands and clays. This illustrates, for an earthquake of magnitude 6.9, the variation in the area of destruction that can be expected for the two types of subsoil conditions of southwestern with the magnitude of the earthquake and Everingham and Gregson (1969) have calculated the isoseismal radii for a range of magnitudes and for each of the two subsoil types.

TABLE 5. RELATIONSHIP BETWEEN MAGNITUDE AND RADIUS FOR WESTERN AUSTRALIAN EARTHQUAKES

Magnitude	*Radius of isoseismal MM VI (km)*	
	Crystalline rock	*Unconsolidated sub-soil*
4.5	—	20
5.0	20	40
5.5	30	60
6.0	50	100
6.5	80	160
7.0	120	240
7.5	180	360
8.0	260	520
8.5	400	800

After Everingham and Gregson (1969)

CHAPTER 4

Seismic effects of the Meckering Earthquake

SEISMIC HISTORY OF THE MECKERING AREA

Meckering has experienced minor seismic events since the town was built in the early 1900's. Local residents speak of persistent subterranean 'booms', more sound than shake, which were explained as the collapse of underground caverns. Another local opinion was that earth rumblings were more numerous during wet years in the period from late September till December.

The first shakings in the Meckering district which were considered to be earthquakes were reported in September and October, 1916. The Acting Government Astronomer wrote:

6th October: From the manager of the Union Bank and from the Postmaster at Meckering, I have just received letters giving particulars of a series of sounds and shocks which have been felt in the district during the last four weeks, and referring especially to a very distinct shock which occurred on the night of the 4th October, which is thus described: 'From midnight until 1 am fully a dozen shocks were felt, two of which rattled the windows and appeared to shake the building (the bank). These were followed by a very distinct shock at 10 am (usually the shocks took place at night). The noises which accompanied them resembled a constant explosion or the bumping of heavy object on a wooden floor. From enquiries made in the district no explosives were being used, and therefore the causes of the noises and shocks could not be explained in that way. The general opinion in the town was that the explosion was underground'. As the Perth seismograph did not record any of the shocks they were almost certainly quite local . . . In countries subject to earthquakes slight tremors are of frequent occurrence and rumbling noises are often heard . . .

On 1st December 1916, between 11 am and noon, several earth tremors were reported. Buildings were shaken and crockery rattled. On 1st November 1932, at a centre 13 km northeast of Northam, underground rumblings and tremors were reported during the evening. Window frames rattled and verandah posts shook, but the tremors were not recorded at the Perth Observatory. The following day similar tremors were experienced at Northam. During one of these episodes damage was done in Meckering, when a bookcase was shaken off the wall in the Anglican church.

Apart from the occasional 'subterranean explosion', the Meckering district became seismically quiescent until 1968. Thirteen kilometres to the west, however, a zone between Quellington and Southern Brook was sporadically active between 1958 and 1963.

FORESHOCKS TO THE EARTHQUAKE OF 14th OCTOBER 1968

On 31st August 1968, people standing in the Meckering Golf Club House felt a solid bump and saw a small whitish cloud mushroom up from the rear of the town rubbish dump, one kilometre away. A farmer, 4 km to the south, also felt the movement and thought it came from the quarry, 4 km to the west. Investigation of the area showed no sign of blasting, but doubt remains as to the authenticity of this 'foreshock'. The event was not recorded at Mundaring Observatory so that if it was an earthquake then the local magnitude was less than 2.5.

About a month later, on 29th September, between 3 pm and 7 pm, three strong shocks were felt a few kilometres to the northwest of Meckering, but were not appreciable in the town. A local magnitude (M_L) of 2.3 was assigned by Mundaring Observatory to the largest of the three and the epicentre was placed northwest of the town.

The main event was preceded by three shocks on 3rd October, between 11.03 am and 11.55 am. The first two, at 11.03 am and 11.18 am were felt most strongly north of the town and caused minor damage to a farm house. The local magnitude of these earthquakes was 3.8 and 3.7 respectively.

The third tremor at 11.55 am was the largest, with M_L 4.2, and this was felt most strongly in the township of Meckering.

On the day of the main earthquake, 14th October 1968, some people in Meckering felt distinct tremors at 1 am and 7.15 am. North of the town, close to where the Sudholz Fault was later found, small tremors were felt later in the morning at 2.35 am, 7.15 am and 8.10 am. Despite the frequency of these tremors their intensity was no greater than those that had been experienced in past years. Little damage had been caused and there appeared to be no reason why the local populace should expect a major earthquake.

THE PRINCIPAL EVENT: THE MECKERING EARTHQUAKE

The exact time of occurrence of the Meckering Earthquake, as determined by the Mundaring Geophysical Observatory, was 14th October, 1968, at 02 h 58 m 50.9 s U.T. (Universal Time) (Everingham, 1968). The local time is eight hours in advance of this, that is, 10 hrs 58 m 50.9 s WST. The location of the epicentre, depth of focus, and magnitude of the earthquake were also determined by the Observatory and much of the information in the following sections is taken from the publications of Everingham and Gregson.

LOCATION OF EPICENTRE

The classical method of finding the epicentre is from the graded intensities of damage observed in the field. This method can only delimit a general area rather than a point location but has the advantage that it can be obtained from local observers. Everingham, Gregson and Doyle (1969, Fig. 2) mark the felt epicentre in the southeast corner of Meckering townsite, at the centre of the MM IX isoseismal.

A preliminary instrumental determination of the epicentre was made by the United States Coast and Geodetic Survey, and given as Latitude 31.5°S and Longitude 117.0°E, with probable radius of error of 10 km. This position is 14 km north of Meckering and to the west of the east dipping fault. A refinement of the epicentral position, using four stations in Western Australia, was given by Everingham (1968) as Lat. 31° 37′S, Long. 116°58′E, some 3.7 km west of Meckering and 1.3 km west of the fault. The final location adopted by Mundaring from their instrumental readings, is Lat. 31°36′S, Long. 117°00′E, which is 2.5 km northeast of Meckering and about 500 m west of the fault. This position is consistent with the mechanism of faulting suggested in Chapter 11 of this bulletin.

DEPTH OF FOCUS

From a consideration of the faulting produced by the Meckering Earthquake and the smallness of the area of intense damage it is obvious that the earthquake occurred at shallow depth. The USCGS gave a preliminary focal depth of 0 ± 8 km while the Mundaring Observatory calculated it as 7 ± 5 km from the network of four West Australian stations. (Everingham, 1968). Applying an empirical formula to the radii of successive isoseismals Everingham and Gregson (1970) obtained a mean depth of 13 ± 5 km for the focal depth. These figures are in agreement for practical purposes, with 7 km as the most likely focal depth.

MAGNITUDE

The instrumental magnitude of the Meckering Earthquake could not be determined locally as the seismographs of the Mundaring Observatory were overdriven. The United States Coast and Geoletic Survey, using thirteen stations, reported $M_S = 6.8$ and $m_b = 6.0$. These figures suggest a local magnitude, commonly called the Richter magnitude, of $M_L = 6.9$ (Everingham, 1968).

THE ENERGY OF THE EARTHQUAKE

The magnitude scales in normal use are calculations made from seismogram traces and give only the relative size of an earthquake on a logarithmic scale. Ideally an absolute magnitude scale would be based on the energy released by the shock, but present knowledge does not permit a reliable determination of the energy involved. Several workers have, however, developed empirical formulae to relate magnitude, intensity and surface faulting to energy, and although the formulae often relate to earthquakes in specific areas, they are applied to the Meckering data to give some impression of the energy involved.

MAGNITUDE AND ENERGY

The relationship between manitude and energy is discussed fully by Richter (1958, p.364-366). The formula most commonly used is:

$$\text{Log}_{10} E = 11.8 + 1.5\ M_S$$

E is the energy in Substituting $M_S = 6.8$ in the formula gives a value of 1×10^{22} ergs, or 1×10^{9} MJ, for the energy of the Meckering earthquake.

INTENSITY AND ENERGY

Just as magnitude is related to energy so the intensity of shaking is related to the depth of focus and the energy of the shock. Shebalin (Richter 1958) has developed the following formula relating the variables for earthquakes of shallow focus:

$$0.9\ \text{Log}_{10} E - I = 3.8\ \text{Log}_{10} h - 3.3$$

where I is the maximum felt intensity on the Modified Mercalli scale and h is the depth of focus. Using $h = 7$ km and $I = 9$, the formula gives an energy of 7.97×10^{9} MJ.

COMPRESSIONAL AND SHEAR ENERGY

In Chapter 11, a possible mechanism for the Meckering earthquake is considered, and an attempt made to calculate directly the energy required to produce the surface faulting which accompanied the earthquake. Briefly, it is thought that the earthquake occurred when a relatively thin cap of granitic rock, strained by a deep-seated, sinistral shear zone, detached itself from its basement and resumed its original shape. The calculations are fully detailed in Chapter 11 where it is shown that by making several assumptions the energy released was about 1.1×10^9 MJ.

ENERGY COMPUTED FROM SURFACE FAULTING

Tocher (1958), noting that all major earthquakes in northern California and Nevada have produced surface faulting, has deduced several relationships between the length of the main fault, movement on the fault, and the energy released by the earthquake. Faulting at the surface will not become evident until a threshold magnitude is exceeded, and in California Tocher has suggested a threshold magnitude of 6. An approximate correlation of magnitude, intensity and surface faulting has been made by Fraser (1963) and Richter (1958) and is reproduced as Table 6. The *LD* factor is the product of the length of surface fault in kilometres, and *D*, its maximum net displacement in centimetres.

TABLE 6. CORRELATION BETWEEN MAGNITUDE, INTENSITY AND SURFACE FAULTING

Magnitude	2	3	4	5	6	7	8
Maximum intensity (MM)	I-II	III	V	VI-VII	VII-VIII	IX-X	XI
Radius of perception (km)	0	15	80	150	220	400	600
LD for surface faulting		NA		...	$<10^4$	$>10^4<10^5$	$>10^5$

The Meckering earthquake, magnitude 6.8, had a maximum intensity of IX, and was felt over an area of radius 700 km. The *LD* factor was more than 10^4, which accords reasonably with the American data. The Calingiri event, however, was of magnitude 6.0, with a maximum intensity of MM VI and was felt over an area of radius 250 km. The *LD* factor was only 10^2 for this event, and suggests that in Western Australia the threshold magnitude for surface faulting is lower than in California, perhaps as low as 5.5.

The calculation of energy from the fault dimensions depends on empirical relationships between the instrumental magnitude and the length of the fault or the product of its length and displacement. The first formula derived by Tocher is:

$$\text{Log } E = 5.33 + 1.83 \text{ Log } L$$

where L is the length of the fault in kilometres. For the Meckering fault of 37 km, this gives 1.58×10^8 MJ. When fault displacement is included the formula is:

$$E = 3.4 \times 10^4 \times LD$$

where D is in centimetres. The maximum net slip of the Meckering fault was 349 cm which gives an energy calculation of 4.4×10^8 MJ.

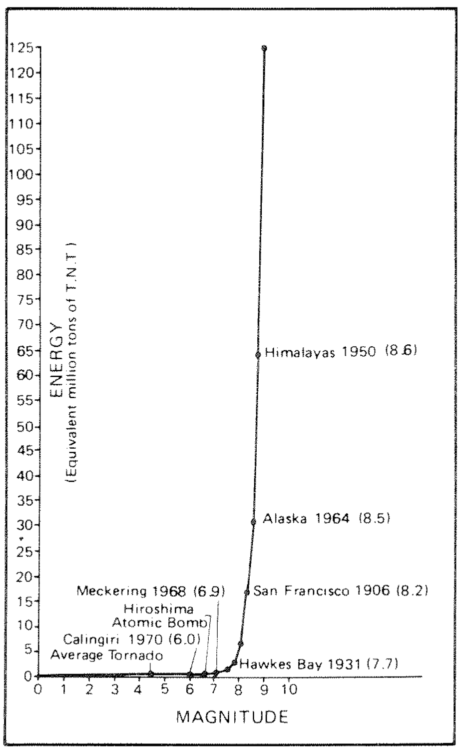
Both of the formulae by Tocher depend on a relationship between magnitude and energy which is different from that given earlier. Substituting the more common formula in Tocher's calculations gives energies of 3.76×10^9MJ and 7.96×10^9 MJ respectively.

EQUIVALENT EXPLOSIVE ENERGY

A final method of assessing the energy release of an earthquake is to express it in terms of the total chemical energy available in TNT. Hill (1969) has produced a table and graph, reproduced here as Table 7 and Figure 21, which shows that the Meckering earthquake, of magnitude 6.9 was equivalent to about 200 000 of TNT, or about ten of the 20 kiloton atomic bombs of the Hiroshima type. In addition the graph places the Meckering event in its proper perspective with respect to other well known earthquakes and shows that despite the impressive figures it was only a moderate sized earthquake by world standards.

SUMMARY

The determination of magnitude from seismogram traces involves several assumptions, as does the calculation of the energy involved in earthquakes. The geological structure between the earthquake and the recording station affects the transmission of shock waves, as is shown by isoseismal maps. Similarly, not all large earthquakes produce surface faulting, and the total extent of faulting may be masked by surface conditions. Most studies involve earthquakes in a relatively small segment of the earth's crust and



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21. Earthquake magnitude and equivalent explosive energy (after Hill, 1969).

TABLE 7. EARTHQUAKE MAGNITUDE AND EQUIVALENT EXPLOSIVE ENERGY

Magnitude	*Approximate equivalent energy in TNT*
1.1	0.2 Kg
1.5	0.9
2.0	5.9
2.5	28.6
3.0	180
3.5	903
4.0	6t.
4.5	32
5.0	202
5.5	1 016
6.0	6 370
6.5	32×10^3
7.0	202×10^3
7.5	$1\,016 \times 10^3$
8.0	$6\,370 \times 10^3$
8.5	32×10^6
9.0	202×10^6

(adapted from: Mineral Information Services, Vol. 22, No. 5 Calif. Div. Mines)

thus contain an unknown element dependent on local conditions. Despite these uncertainties, the application of the various equations to the data of the Meckering event produces a reasonably consistent result of between 1×10^9 MJ and 8×10^9 MJ for the energy released during the earthquake.

SURFACE FAULTING AND MAGNITUDE

If a shallow earthquake produces surface faulting, then, in general, the greater the magnitude the larger the fault displacement and the longer the surface fault trace. Because of the many variables affecting the extent of surface faulting no exact relationship can be expected but Bonilla (1970) has developed two equations based on measurements from over thirty faults produced by known earthquakes in North America.

For the relationship between local magnitude (M_L) and the maximum fault displacement (in metres) Bonilla found the line of best fit to be:

$$\text{Log } D = 0.57\ M_L - 1.91$$

Substituting the Meckering Earthquake magnitude of 6.8 in this formula gives a calculated displacement of 0.93 m whereas the measured maximum displacement was 3.08 m (Table 9). The difference is large, but the measured displacement is well within the limits found by Bonilla.

The length of surface faulting and maximum displacement are related, according to Bonilla, by the approximate formula:

$$\text{Log } D = 0.86 \text{ Log } L - 1.15$$

For the Meckering Fault, 37 km long, this gives a calculated displacement of 1.58 m, about half of the measured displacement. Although neither formula fits exactly the known data from the Meckering Fault, the data do fall within the same range as found in North

America. This suggests that the formulae could be applied in Western Australia to give realistic estimates of surface faulting to be expected from earthquakes of known magnitude.

THE NATURE AND DIRECTION OF SHAKING

In addition to data obtained from the examination of inanimate objects, human observation has yielded information on the direction and sequence of ground shaking during the earthquake. This material is presented unhesitatingly in spite of the warning of Brauner (1915) in his account of *The untrustworthiness of personal impressions of directions of vibration in earthquakes*. The various pieces of evidence of the Meckering event are largely confirmatory, and the movements appeared to be relatively simple.

HUMAN OBSERVATIONS

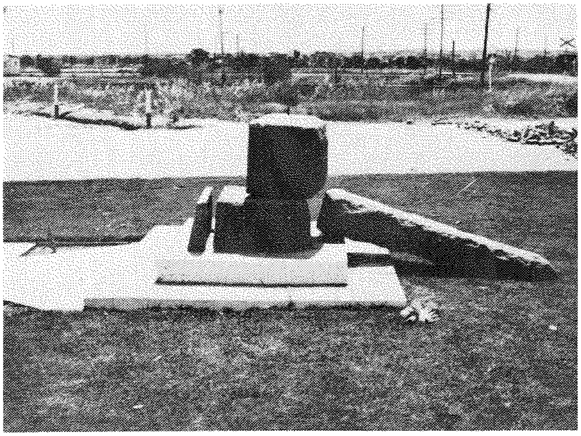
All observers in the vicinity of Meckering townsite agree that the initial strong motion was in the form of a near vertical impulse or blow. This was followed by two distinct episodes of east-west shaking, and all three major pulses were accompanied by bursts of noise. Following the east-west shaking, there was a broad spectrum of shaking of diminishing intensity. Thirteen kilometres south-southwest of Meckering the three distinct pulses were recorded, but at this locality they all appeared to be directed to the east.

DISPLACEMENT DIRECTIONS

The actual direction of shaking may be determined from its effects on various structures and objects. Headstones and monuments in the town cemetery, along with the War Memorial, were overturned, and these, with many minor observations provided not only directional information but confirmation of the sequence of events reported by the people of Meckering.

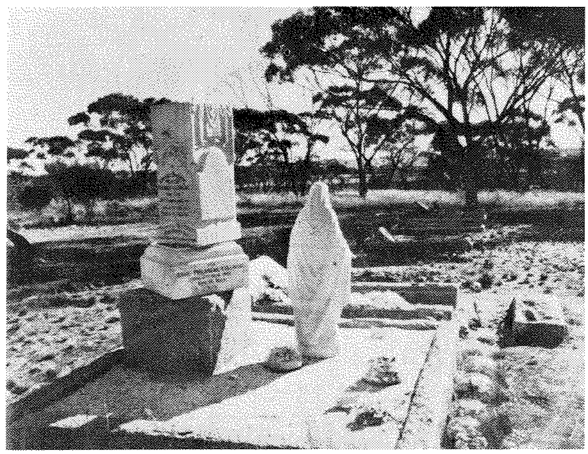
The War Memorial consisted of a tapered granite column, 1.98 m long with a 0.53 × 0.53 m base, sitting on two pedestal blocks and facing 235°. A 1.9 cm iron pin, 7.6 cm long, in the top pedestal block fitted into a 1.9 cm diameter hole in the centre of the column. The final disposition of the memorial is shown in Figures 22a and 23. The granite column was overturned towards 033°, and displaced a horizontal distance of 53.3 cm. The column also showed a small clockwise rotation of about 12°, and the base was displaced about 2.5 cm to the south. The top pedestal stone, with the pin, was displaced 17.8 cm towards 033° and also showed clockwise rotation of about 5°.

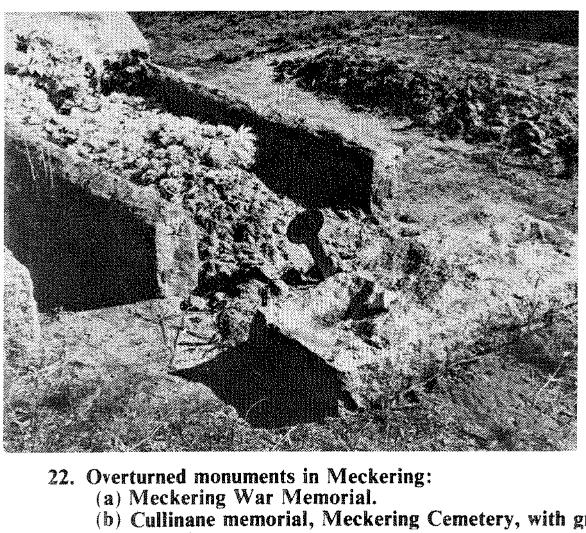
An examination of the pin which secured the column to its pedestal showed that it was unbent and that rust scales were intact. This indicates that the column was thrown more or less vertically from its position by the initial shock. Two small chips were missing from the northeast edge of the base of the column, but the mortar in the centre of this edge remained attached to the pedestal. Along the southwestern edge of the base of the column the rim of mortar remained intact. This indicates that the column was not rocked back and forth while riding up the pin, although chips indicate a slight initial tilting to the northeast which was insufficient to bend the pin. In its final resting place the column was slightly overhung by the displaced pedestal block, showing that the horizontal movement of the block took place after the overthrow of the column.



A

B





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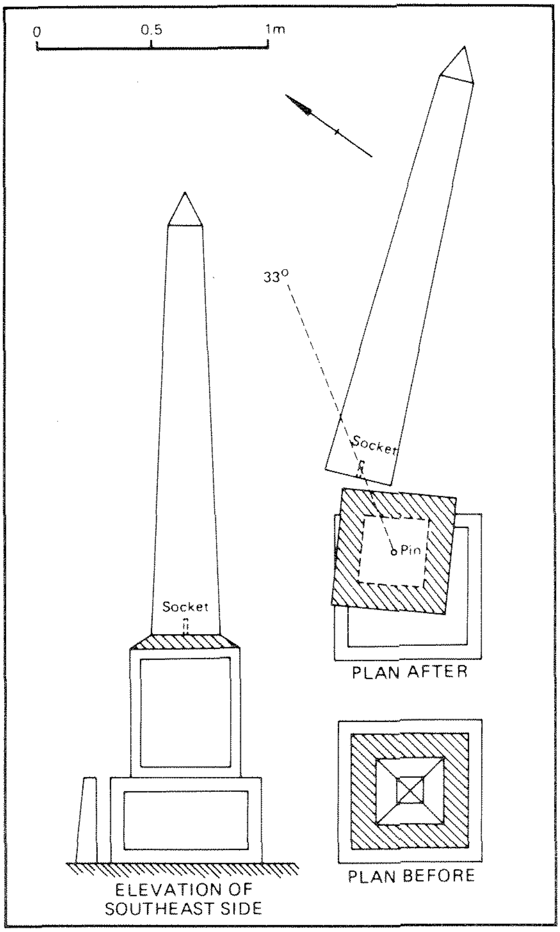
22. Overturned monuments in Meckering:
(a) Meckering War Memorial.
(b) Cullinane memorial, Meckering Cemetery, with grave No. 28 in the background.
(c) Grave No. 28, Meckering Cemetery.



23. The Meckering War Memorial, before and after the earthquake.

The Cullinane Memorial in the Meckering cemetery consisted of a 76 cm high marble statue with a 38 cm diameter circular base, resting on two marble pedestal blocks and a granite plinth (Fig. 22b). The statue was held to the top block by cement mortar and a 5 cm long pin which fitted into a hole in the base of the statue. The statue was thrown off the pedestal to land head first in the direction of 352°, leaving the pin unbent and with no sign of scaling. A small sliver of marble from the base of the statue was left adhering to the pedestal. The lower block of marble was rotated clockwise 36° and moved to the southeast. The granite plinth was not disturbed. Numerous chips of marble missing round the base of both pedestal blocks indicate chattering as they rotated. Similar rotation was noted in a number of brick built columns, and Figure 6c shows an example with anticlockwise rotation.

Grave 28 in the Meckering cemetery, next to the Cullinane Memorial (Fig.22c), had been opened and re-used about 2 months prior to the earthquake. Four separate pieces of heavy granite kerbing had been dug into the ground, but were resting on top at the time of the event. The front kerb, a granite block 15.2 cm wide, 116.8 cm long, and 43.2 cm high, weighing about 200 kg, had been thrown over an undisturbed grave marker 25 cm high. The upper inside edge of the block was displaced 96.5 cm from its original position, in the direction of 042°. The kerbing, originally resting on its 15 cm wide base and bearing 132°, finished lying on its side with a minimum horizontal displacement of 30 cm.

Several massive, horizontal, granitic slabs in the cemetery were displaced towards the west and tombstones were overturned. From these, some idea of the horizontal acceleration of the earthquake shock waves could be obtained. There were no recording instruments in Western Australia capable of giving the acceleration directly but the formula to obtain the acceleration required to overturn an object is:

$$f = g \frac{x}{y}$$

where f is the acceleration, y the height of the centre of gravity, x the horizontal distance between the centre of gravity and the hinge line, and g the acceleration due to gravity. Calculating the acceleration for several tombstones gave an average of 210 cm/s^2, but it must be remembered that objects often move laterally on their base before falling so that the hinge line is not the outer edge, and the value of x is often smaller than that measured.

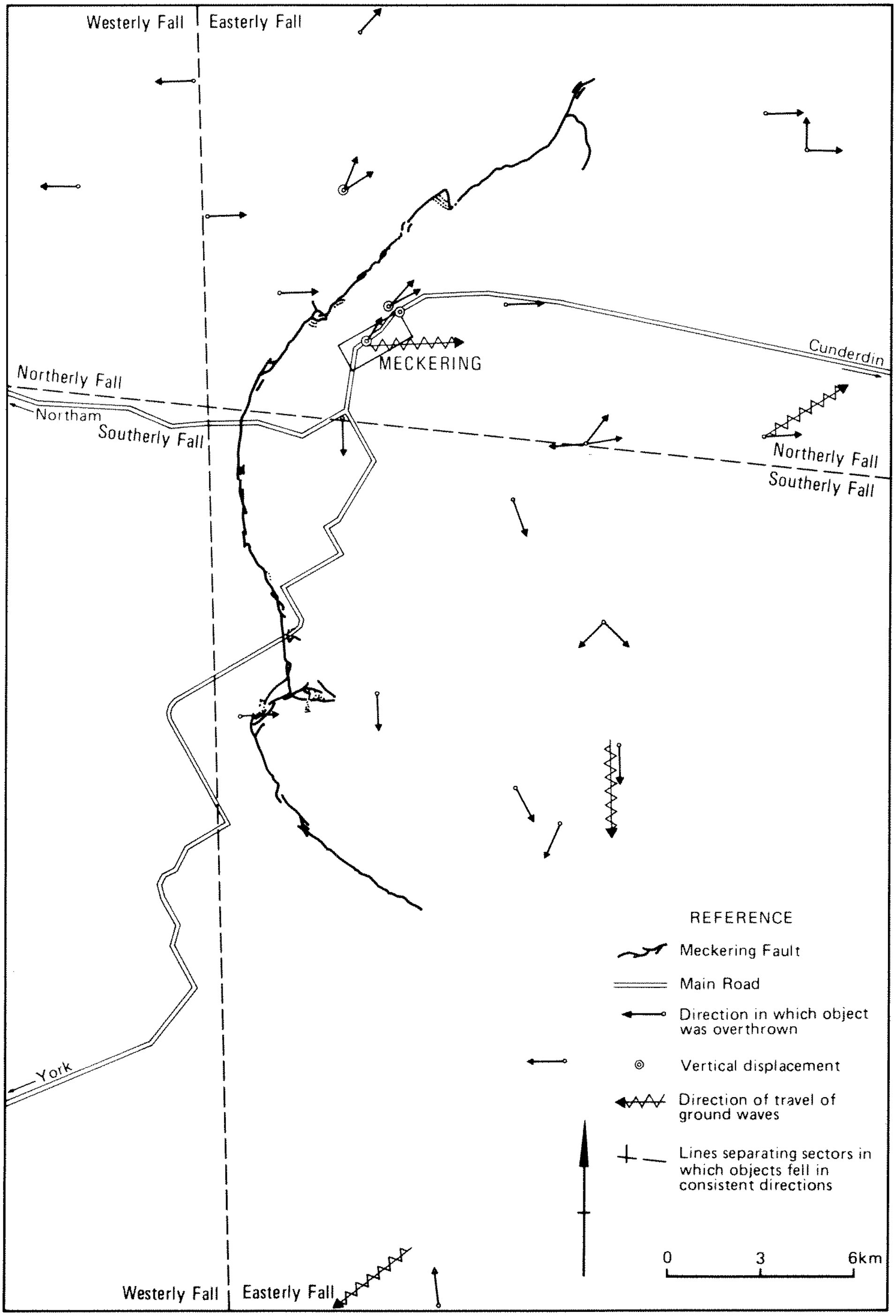
Several directional observations were also made on items of displaced farm equipment in the vicinity of Meckering. At a farm 13 km south-southeast of the town, a truck laden with bags of superphosphate was shaken so that many bags were thrown off to the east and a large fuel tank was vibrated 30 cm to the east. At the same farm, the west wall of the garage was thrown towards the west, breaking the corner bricks, while the north and south walls remained standing. Five kilometres north of Meckering, a laden truck was vibrated sufficiently to cause the wheels to sink into the ground, leaving four pits 23 cm deep.

As noted earlier, the east and west facing walls of buildings in the township were usually the first to collapse, and the same phenomenon was noted with fences. Several farm houses to the east of Meckering were surrounded by fences of consistent composition. It was found that the east and west fences were commonly overthrown, while the north and south fences remained standing.

All directional observations gathered during the survey have been recorded on Figure 24. There are a few anomalous events, but a rather surprising uniformity of pattern is apparent. The Meckering area may be divided into quadrants, with an east-west boundary separating southerly directed displacements from northerly directed displacements and a north-south boundary defining the limits of eastward and westward displacements. The boundaries intersect about 2 km south of the position of the epicentre.

GROUND WAVES

Several reliable observers reported the appearance of undulating waves, or slowly moving rolls on the surface of the ground. Although the objective existence of actual ground waves produced directly by earthquakes has been discredited by seismologists (Eiby, 1957) the consistent reports remain to be explained. It has been suggested that



24. Displacement direction of objects, and the direction of observed ground waves in the Meckering district.

because the observer's senses, as well as his environment, are being affected, the waves are largely illusory. However small surface undulations were actually seen, and in some cases felt, by many people, and, although the dimension reported may be in error and their origin doubtful, their occurrence in this and other earthquakes must be accepted as authentic. Richter (1958) quotes eyewitness accounts of ground waves from a number of Indian and North American earthquakes. It is noteworthy that despite the different circumstances the reports are very similar to those that follow.

The observations and experiences of Mr. Solomon and his son in Meckering townsite have already been recorded but in the surrounding area there are several other occurrences. Mr. R. Baxter, 14 km east of Meckering observed three distinct earth waves with a north-south front moving east-northeasterly. The first appeared to be between 8 cm and 15 cm high, followed two seconds later by a second wave about 8 cm high and a third wave of similar amplitude. A utility truck, some 20 m east of the observer, lifted and tilted about its long axis as the waves passed, so that the floor of the tray could be seen. About 800 m away an elevated 23 kl water tank, which was full at the time of the earthquake, was found to have slopped 4 kl over the easterly side.

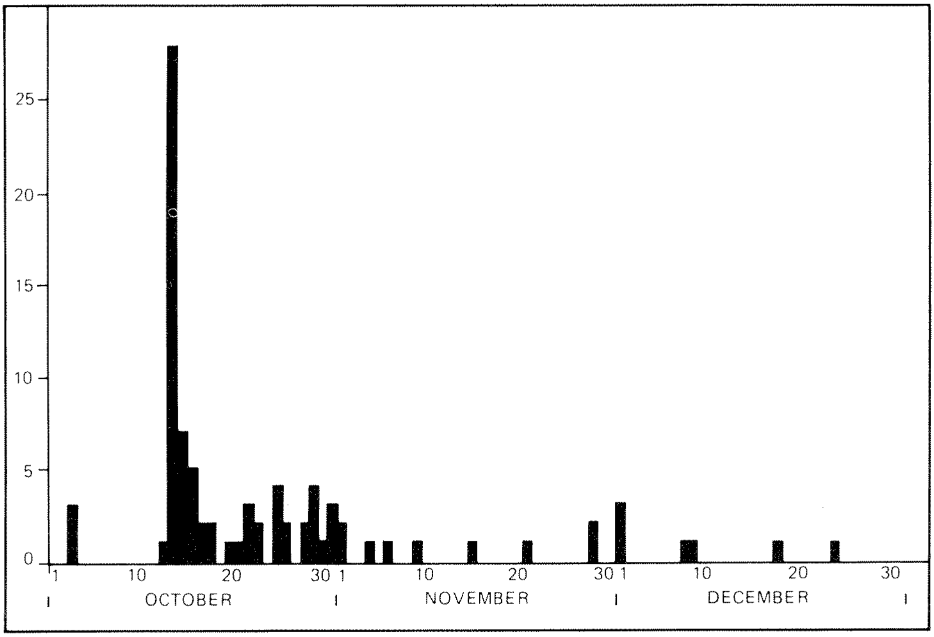
Three distinct ground waves were also seen by Mr. K. Broad on his farm 19 km south of Meckering, near the Mortlock River. The waves travelled from north to south, the first about 45 cm high and the others 23 to 30 cm high. There was a two-second interval between the first two, and, following the third, a general shaking was felt.

At Greenhills, 32 km south-southwest of Meckering, Mr. T. A. Liddell saw eight or nine ground waves or surface swells on the main York road. Each appeared to be about 45 cm high and 1 m apart, moving regularly down the road to the southwest at a speed of 8 to 16 km/h.

These slow moving undulations are distinct from the high acceleration earthquake shock waves, although they are probably generated by the true earthquake waves. Ground waves were observed only in the thick alluvial sands of river valleys, and were probably local manifestations produced by the earthquake waves, not continuous wave fronts travelling from a central source. However, the direction of travel of the ground waves are plotted on Figure 24 and are not inconsistent with a central source southwest of Meckering.

SEICHES

Although there were numerous small farm dams in the area which would have been set in oscillation by the seismic shaking there were no reports, no doubt because the dams were well away from habitations and remained unobserved. The only report of seiche type oscillations came from a swimming pool located 20 km south of Meckering where waves up to 30 cm high ran up and down the pool both during and for some minutes after the shaking. As the pool was normally filled to within 10 cm of the top a considerable amount of water splashed over the sides.



GSWA 17466

25. Daily earthquakes totals (M_L>2.9) in the Meckering district, October-December 1968.

AFTERSHOCK ACTIVITY

Following the main event at Meckering, there was considerable aftershock activity in the district, culminating in a magnitude 5.7 earthquake at 11.30 am WST on the following day, 15th October. For the remainder of the month, small earthquakes of magnitude 3.0 or greater were felt daily, but this activity declined rapidly over the next four months. Since April 1969 large tremors have been infrequent in the Meckering district, but as late as October 1976 a magnitude 4.7 shock occurred which was felt in Perth. A total of 142 earthquakes of magnitude greater than 2.9 have been recorded in the Meckering district up to October 1976. These are listed in Table 8 and their epicentres plotted on Figure 26. The daily total of earthquakes for the most active period between October and December 1968 is shown on Figure 25.

In addition to the larger aftershocks, there have been several hundred smaller tremors of M_L 2-3 which have been recorded at the Mundaring Observatory, and innumerable tremors, presumably of local magnitude less than 2.5, which have been felt in the Meckering district but not recorded at Mundaring. For about a year such tremors were of almost daily occurrence, but this activity has since declined, although it has not completely ceased.

Aftershocks may have a variety of causes. Ground settlement, after the movement of the fault block, was probably responsible for the many small, unrecorded, local tremors, whereas the release of residual strain could have caused many of the larger shocks. In addition, the movement of a large block of rock up a shallow dipping fault plane could impose new strains which would result in minor tremors. As can be expected, the epicentres of the majority of aftershocks are located on the mobile block and are within the arc of the Meckering Fault (Fig. 26). Relatively few aftershocks are centred outside the fault block, but there are two groups, one near Quellington and the other near Mawson, which are limited in space and time and will be discussed further.

The majority of aftershocks only intensified damage that had been caused by the main earthquake (Fig. 8), but in a few instances damage and new faulting could be directly attributed to an aftershock. Damage to the grain silos and the Goldfields Water Supply pipeline from an aftershock on 15th October have already been detailed, and the major tension fracture formed at the same time will be described in Chapter 6, but even some minor tremors caused local damage. A typical occurrence in February 1969 appeared to be centred at the rear of the railway station and the temporary "Quake Arms Hotel". Patrons in the hotel experienced the aftershock in the form of two rapid vertical pulses; a refrigerator full of glasses was displaced and two dozen glasses broken. At the same time a small ridge about 4 m long and 7.5 cm high appeared in the parking area and across the earthen floor of the bar. On 28th April, 1969, a small tremor, unrecorded by the Mundaring Observatory, was felt only within Meckering townsite and five heavy items of equipment in the butcher's temporary shop were displaced. Movement in each case was about 2.5 cm, either to the east or west.

AFTERSHOCKS IN THE QUELLINGTON AREA

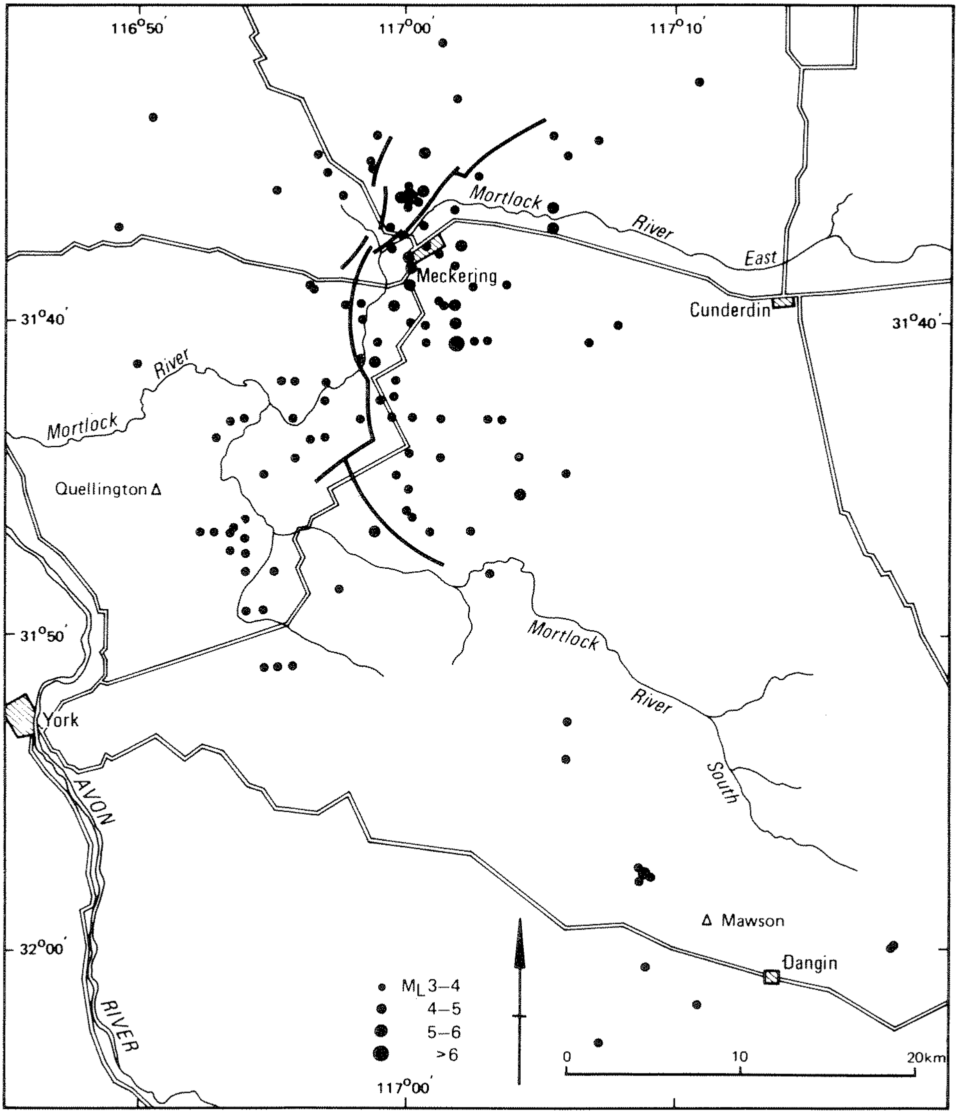
Since 14th October, 1968, a total of fifteen tremors of $M_L > 2.9$ have occurred near Quellington, about 20 km southwest of Meckering and 9 km west of the Meckering Fault. The epicentres are on line with an extension of the Robinson Fault, part of a radial fault which offsets the main fault (Chapter 5). Throughout most of its length, the Robinson Fault is a strike-slip fault with a small dextral movement, but it is terminated 5 km from Quellington by a northwest trending fault which is in part a thrust, and in part a tensional fault. Most of the strain resulting from the faulting was probably dissipated by a host of minor fractures into which the Robinson Fault merges, but is possible that the fault continues, without surface expression, towards Quellington. Alternatively, it must be noted that a zone between Quellington, and Southern Brook to the northwest, recorded a number of small tremors between 1958 and 1963, and the major seismic activity resulting from the Meckering event may have acted as a trigger for further activity along a pre-existing line of weakness.

Other patterns of aftershock epicentres which may be connected with radial faulting are located northeast of Quellington and along the Goomalling road, northwest from Meckering. Northeast of Quellington a line of five epicentres is parallel to, and about one kilometre north of the Robinson Fault. There is a possibility that this represents a similar line of weakness or a concealed radial fault. Northwest of Meckering, a line of three epicentres is similarly located, perpendicular to the main fault trace.

AFTERSHOCKS IN THE MAWSON AREA

Aftershocks in the Mawson area, 45 km southeast of Meckering, did not begin until 20th January, 1969 but on 1st and 2nd February a series of ten tremors of $M_L > 3.0$ shook the area; the largest, at 11.30 am WST was of magnitude 4.0. Intense local seismic activity continued for over a month culminating with a final major tremor of magnitude 3.5, on 9th May, 1969.

The southernmost part of the Meckering Fault trace trends southeasterly at its termination close to the West Mortlock River. Extended to the southeast, this trend passes through the Mawson district, and it is probable that the seismic activity in the area represents the release of residual strain accumulated by the movement along the Meckering Fault, and not released by surface breakage.



26. Location of aftershock epicentres in the Meckering district, October 1968 to October 1976.

TABLE 8. EARTHQUAKES OF MAGNITUDE (M_L) GREATER THAN 2.9 IN THE MECKERING AREA, OCTOBER 1968 TO DECEMBER 1978

Date	*Origin time (U.T)*	*Latitude (°S)*	*Longitude (°E)*	*Magnitude M_L*	*Remarks*
1968					
Oct 03	03 02 57.6	31.62	117.00	3.8	Foreshock
03	03 17 56.2	31.60	116.96	3.7	Foreshock
03	03 55 33.4	31.59	116.98	4.2	Foreshock
13	22 51 31.7	31.60	116.98	3.3	Foreshock
14	00 04 45.8	31.58	116.94	3.4	Foreshock
14	02 58 50.3	31.60	117.00	6.9	Main shock
14	03 15 21.4	(31.6)	(117.0)	4.0	
14	03 29 45.0	(31.6)	(117.0)	3.3	
14	03 38 43.2	31.63	117.02	3.4	
14	03 53 31.9	31.66	117.02	3.4	
14	03 57 47.7	31.66	116.99	4.0	
14	04 09 07.5	31.60	117.01	4.6	
14	04 54 10.8	31.61	117.11	3.8	
14	06 00 54.4	31.65	116.94	3.2	
14	06 17 08.4	31.67	117.00	3.5	
14	06 47 50.4	31.69	116.98	4.2	
14	07 59 52.2	31.63	116.99	3.0	
14	08 04 33.9	31.72	116.89	3.4	
14	08 05 50.4	31.72	117.06	3.6	
14	08 08 11.6	31.73	116.88	3.2	
14	08 18 19.4	31.74	117.07	3.3	
14	08 38 13.6	31.66	117.03	3.1	
14	08 46 57.1	31.67	117.13	3.3	
14	09 29 42.5	31.66	116.96	3.8	
14	10 15 58.9	31.85	116.91	3.1	
14	12 25 35.8	31.67	116.97	3.4	
14	12 55 25.2	31.68	117.05	3.1	
14	16 13 34.0	31.68	117.04	3.2	
14	18 28 56.7	31.75	116.91	3.2	
14	19 04 04.7	31.72	116.99	3.4	
14	21 12 59.1	31.68	117.11	3.0	
14	23 51 20.4	31.65	117.04	3.0	
15	00 04 51.1	31.80	116.90	3.0	Quellington
15	02 49 38.1	31.66	116.97	3.6	
15	03 30 07.0	31.68	117.03	5.7	
15	06 08 20.6	31.74	116.93	3.2	
15	06 31 11.3	31.69	116.97	3.5	
15	12 46 19.3	31.81	116.96	3.8	
15	18 16 10.4	31.59	116.95	3.4	
16	00 55 10.2	31.66	117.02	4.2	
16	02 55 52.0	31.77	117.00	3.3	
16	08 24 26.6	31.63	117.01	3.7	
16	08 34 59.1	31.78	116.95	3.0	
16	12 11 53.1	31.57	116.98	3.3	
17	09 52 58.1	31.64	117.03	3.4	
17	12 24 15.5	31.74	117.02	3.5	
18	10 31 47.9	31.76	117.07	4.1	
18	19 46 40.0	31.70	116.95	3.0	
20	09 06 49.0	32.04	117.31	3.8	Quairading
20	15 04 26.6	31.57	117.09	3.8	
21	15 32 59.2	31.61	117.09	4.6	
22	01 04 04.9	31.58	117.01	4.1	
22	10 15 04.4	32.06	117.30	3.0	Quairading
22	13 24 15.0	31.70	116.95	3.4	
22	16 26 20.8	31.55	117.03	3.2	
23	08 52 16.8	31.68	117.01	3.3	
23	20 13 57.1	31.57	117.12	3.2	
25	00 44 48.3	31.63	117.01	3.3	
25	11 45 14.7	31.78	116.90	3.4	Quellington
25	13 18 32.4	31.77	116.90	3.7	Quellington

Table 8—continued

Date	Origin time (U.T)	Latitude (°S)	Longitude (°E)	Magnitude M_L	Remarks
Oct 25	23 31 29.8	31.78	117.04	3.9	
26	04 22 30.2	31.67	117.03	4.9	
26	11 31 20.2	31.71	116.98	3.2	
28	10 33 11.0	31.77	116.90	3.5	
28	10 40 47.5	31.78	116.89	3.3	Quellington
29	03 28 11.5	31.71	116.95	3.8	
29	06 23 53.2	31.78	116.89	3.3	Quellington
29	06 39 47.3	31.78	116.88	3.3	Quellington
29	14 00 04.5	31.79	116.89	3.8	Quellington
30	02 50 23.8	31.60	117.00	3.7	
31	00 58 48.9	31.78	116.98	4.1	
31	01 04 08.2	31.78	116.98	3.8	
31	05 24 10.2	31.67	117.01	3.4	
Nov 01	10 02 26.7	31.76	117.00	3.0	
01	10 11 21.4	31.56	116.84	3.2	
04	03 43 27.5	31.74	117.00	3.8	
06	20 04 07.9	31.54	117.18	3.5	
06	21 38 07.5	32.15	117.19	3.0	
09	11 07 33.0	31.72	116.97	3.5	
15	03 20 53.3	31.60	117.00	3.0	
Nov 21	23 19 30.9	31.79	116.90	3.0	
28	14 17 31.5	31.64	117.00	4.0	
28	21 12 11.9	31.73	116.95	3.7	
Dec 01	05 42 04.7	31.85	116.92	3.2	
01	07 25 17.6	31.80	116.92	3.0	Quellington
01	22 17 06.3	31.78	116.90	3.6	Quellington
08	12 28 45.5	31.82	116.91	3.5	Quellington
09	17 00 18.2	31.73	116.94	3.4	
18	08 19 03.3	31.62	116.99	3.3	
24	08 12 13.3	31.58	117.10	3.1	
1969					
Jan 11	06 59 47.8	31.62	117.01	3.5	
16	14 24 42.8	31.92	116.90	3.2	Quellington
20	02 27 00.7	31.9	117.10	2.9	12 km NW Mawson
20	23 50 51.1	32.13	117.23	3.7	
29	14 32 54.8	32.03	117.18	3.0	Mawson
29	16 00 45.8	31.85	116.81	3.0	
30	06 15 43.0	31.96	117.15	3.7	Mawson
30	06 16 31.5	(32.2)	(117.3)	3.0	
31	09 47 44.5	32.17	117.28	3.3	
Feb 01	02 39 35.6	31.96	117.15	3.5	Mawson
01	03 29 57.7	31.96	117.15	4.0	Mawson
01	04 52 02.5	31.96	117.15	3.7	Mawson
01	04 54 53.6	31.96	117.15	3.8	Mawson
01	07 22 11.7	31.96	117.15	3.6	Mawson
01	07 35 22.3	31.96	117.15	3.0	Mawson
01	08 51 29.3	31.96	117.15	3.3	Mawson
01	20 25 57.1	32.01	117.15	3.2	Mawson
01	23 12 18.8	31.88	117.10	3.0	14 km NW Mawson
02	03 03 30.8	32.05	117.12	3.4	10 km SW Mawson
15	12 14 31.1	31.75	117.10	3.2	
Mar 15	09 24 33.4	31.61	117.03	3.3	
18	05 41 28.9	31.77	116.88	3.6	Quellington
21	19 50 50.0	32.15	117.25	3.0	
May 09	11 20 28.5	32.00	117.30	3.5	11 km ESE Mawson
July 01	00 19 11.3	31.60	117.00	3.1	
Sep 07	01 16 23.0	31.69	116.83	3.1	
Oct 05	12 15 50.3	31.72	116.90	3.0	
08	20 26 56.6	31.80	116.90	3.4	Quellington
11	16 40 46.6	31.65	116.94	3.0	

Table 8—continued

Date	*Origin time (U.T)*	*Latitude (°S)*	*Longitude (°E)*	*Magnitude* M_L	*Remarks*
1970					
Jan 07	03 39 35.8	31.62	116.82	3.2	
(Mar 10	17 15 11.2	31.11	116.47	5.7	Calingiri Earthquake)
Aug 27	22 02 02.7	31.59	117.04	3.4	
Oct 02	06 08 56.7	31.78	117.01	3.1	
04	16 03 32.6	31.80	117.05	3.2	
24	02 35 56.2	31.78	116.89	3.5	Quellington
24	02 36 06	31.8	116.9	(3.5)	Quellington
Nov 01	05 37 24.0	31.75	116.99	3.2	
26	20 41 05.8	31.72	117.00	3.3	
1971					
Jul 16	12 32 26.9	31.61	117.09	4.0	
Dec 22	18 46 19	31.72	117.02	3.1	
1972					
Feb 07	19 10 11.7	31.70	116.99	3.2	
Mar 28	00 35 11	31.85	116.93	3.1	
Jul 01	19 41 46.6	31.70	116.93	3.3	
Aug 12	05 53 18.0	31.52	117.02	3.7	
Oct 23	15 46 20.2	31.60	116.92	3.2	
1973					
Feb 26	14 35 17.1	31.70	116.95	3.0	
Apr 30	00 58 42.5	31.77	117.00	3.3	
Aug 19	19 50 25.3	31.65	117.06	3.8	
1974					
May 02	23 00 57.0	31.68	116.98	3.1	
Jul 09	10 46 47.4	31.65	117.00	4.3	
Nov 19	09 30 22.6	31.63	117.03	4.0	
1975					
May 02	12 10 41.2	31.73	116.93	3.0	
Jul 17	23 07 18.5	31.65	117.00	3.1	
Sep 11	12 23 51.8	31.64	117.03	3.2	
Nov 20	09 08 27.0	31.72	117.05	3.0	
1976					
Oct 29	06 04 48.2	31.64	117.00	4.7	
1977					
Mar 21	15 09 30.9	31.70	117.68	3.0	
Jun 12	09 34 06.0	31.70	117.00	3.9	
1978					
Nov 3	14 19 09.5	31.73	116.87	3.0	
24	22 09 44.4	31.73	117.04	3.1	

Compiled from the Annual Reports of the Mundaring Geophysical Observatory 1968-1974 and preliminary data for 1975 and 1976 made available by Mr. P. J. Gregson, Officer in Charge. (Everingham and Gregson, 1971a, 1971b; Gregson, 1971, 1972; Gregson and Smith, 1973, 1974, 1975).

SEASONAL OCCURRENCE OF AFTERSHOCKS

A common belief of the residents of Meckering, prior to the earthquake of 1968, was that 'earth rumblings' and tremors were unusually pronounced from late September through to December, particularly during wet years. An explanation of this phenomenon could be that increased fluid pressure triggered the tremors in the same way that the pumping of waste liquids into porous strata at the Rocky Mountain Arsenal artificially triggered minor earthquakes at Denver, USA (Evans, 1966; 1967).

Moderate earthquakes are commonly associated with the filling of large dams (Endersbey, 1969), the largest known being a shock of M_L 6.4 from the Koyna Dam in India (Gupta and others, 1969). For major overthrusting Hubbert and Rubey (1959) have established that fluid pressure is an important factor and it is not unlikely that similar factors might influence more modest faulting as at Meckering.

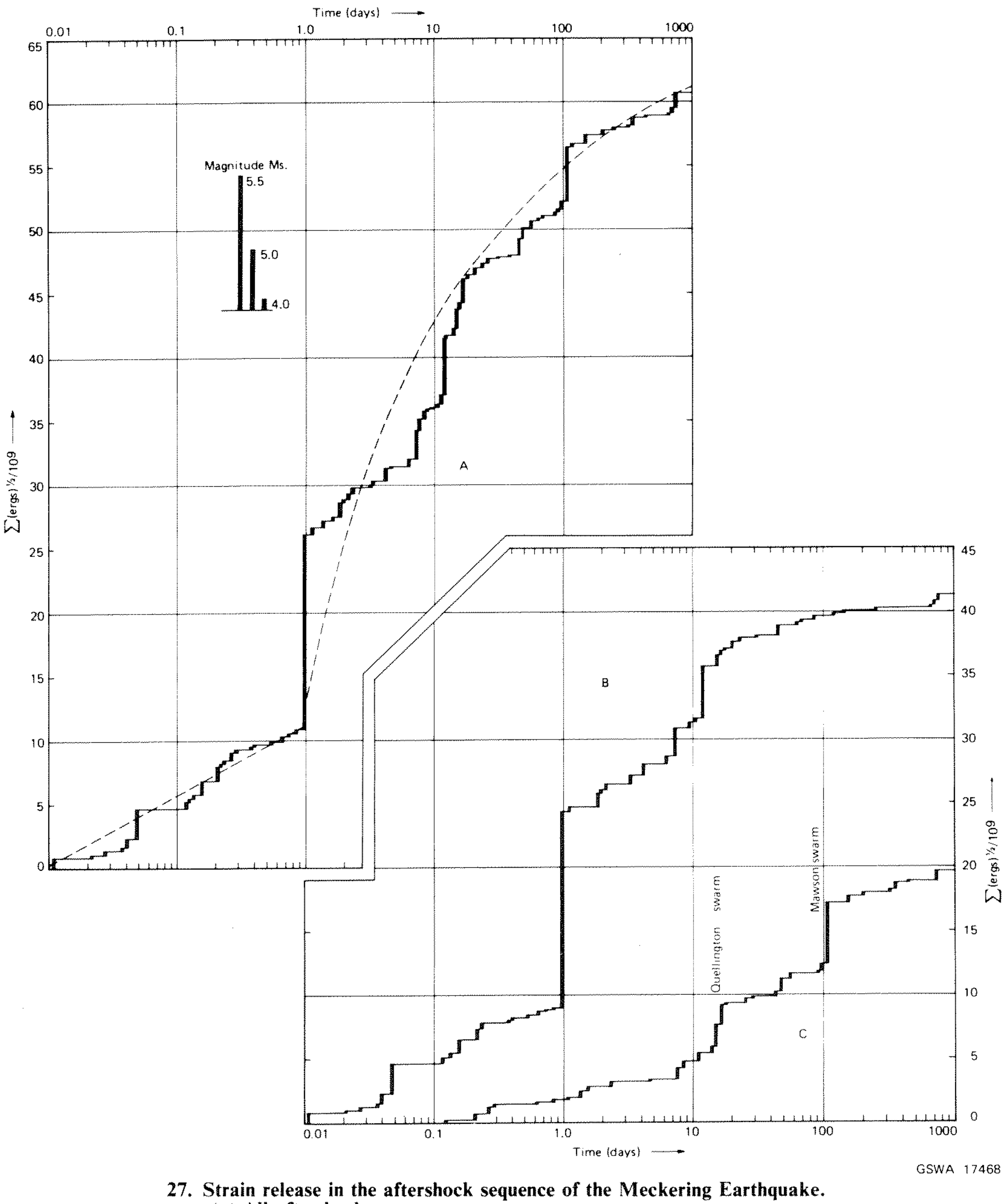
The occurrence of the Meckering earthquake, and the bulk of its aftershocks, in the October-December period would lend weight to the local belief, but an examination of the seismic record since 1970 does not provide conclusive support. For the period 1970 to 1976, the monthly totals of minor earthquakes ($M_L > 2.9$) recorded by the Mundaring Observatory range from eight in February to twenty one in November, but shows no consistent pattern; and in any particular year the maximum activity is rarely in the September to December period. An examination of Table 8 for the same period, however, does show that the total of ten earthquakes of M_L 3 or more in October and November is not matched by any other two month period, and is approached only by the seven in the July-August period. In addition, if it is assumed that there is a constant background of small tremors up to M_L 3.3, then larger earthquakes only occur in the July-August and October-November periods. It is tempting to see this result as confirmation of the local opinion, and correlate the periods with the onset of the main winter rains in July and August and maximum fluid pressure in October and November. However, the present study covers only a period of seven years and twenty six earthquakes of magnitude 3.0 to 4.7.

STRAIN RELEASE IN THE AFTERSHOCK SERIES

From Table 8, it will be realized that the energy released by the train of aftershocks is at least equal to that of the main earthquake. According to the elastic rebound theory **of earthquake formation (Reid, 1911), the energy released by the main shock represents the** release of elastic strain stored in the rock whereas the aftershocks are due to elastic creep. Thus, a further method of investigating the aftershock sequence is to consider the cumulative release of strain.

Making several simplifying assumptions, Benioff (1951) showed that the strain released by an aftershock was the square root of the seismic energy, and that if the cumulative strain was plotted against the time elapsed since the principal event, then a characteristic curve resulted. Briefly, the curve consists of in initial straight portion of the general formula, $strain = a + b \log t$, followed by a more complex curve with a steep initial slope. Such a curve is plotted as Figure 27a for all the aftershocks of the Meckering earthquake from 14th October 1968 to 16th July 1971. The linear section of the graph ends, and the curved portion begins, with the magnitude 5.7 aftershock of 15th October, 1.02 days after the principal shock. The curved section is stepped and consists of several linear sections of diminishing slope joined by steep sections which represent either large individual aftershocks or periods of minor but continuous activity.

This pattern of strain release was thought by Benioff to represent an initial release of compressional stresses followed by release of shear stresses, but this has not been confirmed by experimental work (Båth, 1973). The theoretical interpretation of the graph is not known, but the elapsed time before the change in slope does appear to increase with the greater magnitude of the initial earthquake (Benioff, 1955).



27. Strain release in the aftershock sequence of the Meckering Earthquake.
(a) All aftershocks
(b) and (c) Aftershocks east and west of the Meckering Fault.

As the epicentres of the aftershocks are known (Table 8) it is possible to plot strain release curves for the blocks on either side of the Meckering Fault. Figure 27b does not show the separation of 'compressional' and 'shear' curves, as found by Benioff (1955) for the White Wolf Fault, but the curves are interesting in that they allow the possible correlation of features on either side of the fault. It was earlier stated that the group of aftershock epicentres in the Quellington area might be connected with an extension of the Robinson Fault and it will be seen that the aftershocks in this area caused a distinct step in the strain release curve between 11 and 16 days after the main shock. At the same time, a magnitude 4.9 shock caused a step in the curve for those aftershocks to the east of the Meckering Fault. The location of this shock is near the geometric centre of the arc of the fault and on line with a possible extension of the Robinson-Burges Fault to the east. Again, the major 5.7 aftershock of 15th October, which initiated the break in slope of the graph, was located nearby. This suggests the possibility of the migration of aftershocks, with diminishing magnitude, along a radial fault which is only partly exposed, and emphasises the importance of the Robinson-Burges Fault to the mechanism of the Meckering earthquake. Conversely, the intense aftershock activity near Mawson in February 1969, 110 days after the main earthquake, causes a step in the graph for strain release to the west of the fault but not to the east. Mawson may be on the line of extension of the Meckering Fault but there is no obvious radial feature east of the fault line which could be activated.

CHAPTER 5

Primary effects on terrain—earthquake generating faults

The main Meckering Fault (Plate 2), can be traced as an arcuate feature for 37 km. Two other major faults outside the arc can be traced for a few kilometres, but within the arc there are numerous smaller faults and fractures. The faults, and the earthquake of 14th October, 1968, were formed directly by the breakage of rock under accumulated elastic strain, and its sudden release. The faults have been classified into earthquake generating and earthquake generated faults, following Lensen (1976). The major fractures, the Meckering, Burges, Splinter, and Robinson Faults, along which most of the movement occurred, were generated directly by the release of accumulated strain energy during the earthquake. Residual strain in the block enclosed by the arcuate main scarp, and stresses produced by movement along the faults, gave rise to the second class of minor faulting and aftershock activity. Of particular note in this group are the Chordal and Koolbunine Faults, and the backscarp zone of faulting which marks the eastern limit of the mobile block. A third group of fractures were the secondary slumps, landslides, and elastic extrusions, which occurred in superficial deposits and resulted from the seismic shaking. In this chapter only those faults produced directly by the earthquake of the 14th October will be described.

OBSERVATION AND MEASUREMENT OF FAULT MOVEMENT

The Meckering district is relatively flat and is intensively farmed; consequently much of the faulting was readily accessible. The displacement of numerous property boundaries, fences, roads, pipelines, and railways enabled accurate measurements, which provided a framework for the detailed analysis of the earth movements, to be made. By the same token, agricultural activity and seasonal rainfall rapidly modified, or even destroyed, part of the fault traces.

Owing to the sandy nature of most of the local soils, the fault plane was rarely sufficiently well exposed to enable direct measurement of the direction and amount of dip. Most of the small faults were considered to be reverse or normal solely on whether the ground displacement was compressional or tensional. For the purposes of measurement, ground displacement was resolved into three components, two horizontal and one vertical. One horizontal component—the strike-slip is parallel to the strike of the fault, and is either dextral or sinistral. The other horizontal component—the heave—is normal to the strike of the fault and is either compressional or tensional. Compressional heave is shown by bulging of the ground surface and is more difficult to measure than tensional heave, which is shown by openings in the ground surface. The vertical component—the throw of the fault—is the height difference across the fault between originally adjacent points.

Simple openings, in which there is no shearing, that is dip-slip or strike-slip displacement, are not faults as strictly defined. However, for convenience of description they are considered to be faults in this account and are named 'tension faults'.

The accuracy to which displacement could be measured was determined by local ground conditions and by amount of total displacement. The smallest measurable displacement, under ideal conditions, was about 1 mm, and most measured displacements have an accuracy of about ten per cent.

NOMENCLATURE OF THE FAULTS

Prior to 1968 no faults were either known or inferred in the Meckering area, thus all the fault names have originated with the present investigation. The main fault scarp, formed at the time of the earthquake, consists of two arcuate faults, named the Meckering Fault, and a short radial fault named the Burges Fault. Other faults, such as the Splinter Fault and Chordal Fault have been named with reference to their inferred relationship to the Meckering Fault while others, such as the Robinson and Sudholz Faults have been named after local features, roads or landowners. The location and names of the faults are given in Plate 2. and this chapter will consider in detail the Meckering, Burges, Robinson, Splinter and Sudholz Faults.

THE MECKERING FAULT

GENERAL FEATURES

The scarp of the Meckering Fault can be traced as a continuous feature for 37 km, and is bisected by the Great Eastern Highway at a point 4.4 km southwest of Meckering townsite. The trace is arcuate, concave to the east, and approximates a quadrant of a circle of radius about 13 km. The displaced southern section of the fault, together with the Splinter Fault, fit a circle of radius 14.5 km. Both extremities of the main scarp terminate in areas of low-lying, sandy soil, where recognition of faulting is difficult. However, discontinuous small displacements on the trend of the northern section have been traced for a further 6.5 km to the northeast. Similar extensions were not discovered at the southern end of the fault scarp.

The main scarp was formed by thrusting and dextral strike-slip movement along the plane of the Meckering Fault as the mobile eastern, or upper, block enclosed by the fault, moved westward. Displacements were at a maximum near the most westerly portion of the arc, about 1.6 km south of the Great Eastern Highway, where approximate measurements indicated a westward heave of 2.44 m, a southerly dextral slip of 1.54 m and a vertical throw of 1.98 m. The calculated total net slip was thus 3.49 m and the calculated dip of the fault plane 39°.

North and south from the point of maximum displacement, the crustal shortening, and the lateral and vertical movements, all decrease in magnitude along the fault scarp. Observations on minor faults to the east of the scarp showed that the dextral component of displacement decreased sharply to the east, whereas the vertical component, or throw, decreased at a regular rate of about 10 cm per km, or 1 second of arc. This decrease in uplift continued into a depressed zone of normal faulting, known as the 'backscarp', where the ground surface is actually below its pre-earthquake level. The former ground level is resumed at the eastern edge of the backscarp zone, about 12 km east of the centre of the arc formed by the Meckering Fault.

It is difficult to determine the absolute sense of vertical movement relative to sea level, but third order levelling from Fremantle on the coast, to Merredin, showed no large difference from the first order observations of 1961. The levelling profiles indicated that, at the eastward dipping fault plane of the Meckering Fault, the eastern plate had moved upwards, and had thrust over the static, lower or western plate.

The regular, arcuate shape of the fault scarp is disrupted by five dextral offsets, at right angles to the strike of the fault. The largest offset, known as the Burges Fault, is 2.4 km long. Only two small sinistral offsets of the fault scarp were found. It is considered probable that the offsets mark the line of pre-existing radial faults, and there is evidence to show that much of the Meckering and Splinter Faults are reactivated features (Chapter 8).

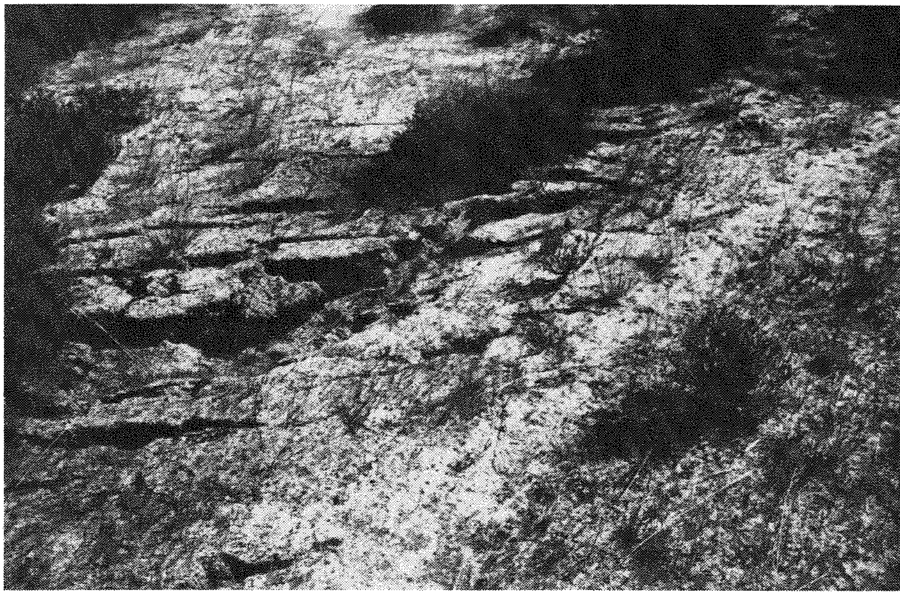
DETAILED DESCRIPTION OF THE FAULT TRACE

THE NORTHERN SECTION

At its northern end, the Meckering Fault was initiated as a narrow zone of continuous, open, tension fractures, which were difficult to trace in the sandy soil. The fractures became more conspicuous as they passed into areas of lateritic soil, and assumed an *en echelon* pattern, forming a slightly raised welt 5-10 cm high. A small dextral displacement of about 5 cm could be seen on each of the open fractures. As the fault changed direction from a bearing of 250° to about 220°, the main fault was paralleled on either side for a distance of 300 m by two narrow zones of *en echelon* tension fractures. These fractures, with only minor dextral displacement, appeared to have no connection with the main fault, and perhaps represented limited movement at a superficial level.

The fault continued for a further 2.2 km as a series of *en echelon* fractures until it crossed a salt flat and curved round to a trend of 242°. At the western margin of the salt flats, the fault was still a strong feature (Fig. 28), but as it continued through unconsolidated sandy soil it formed a low assymetric ridge, which was sometimes difficult to follow. A displaced fence line in this section (point 233, Fig. 39) showed a dextral displacement of about 30 cm and a throw of 40 cm for the fault, while 1.2 km further on, at point 147, the dextral displacement had increased to 76 cm and the throw to 53 cm.

The remainder of this northern section of the Meckering Fault had a variable surface expression, depending on the soil type, but it was commonly sinuous. In competent soil, or in pisolitic laterite soils, the fault pattern was often a well-defined alternate thrust and wrench (Fig. 42c), with the wrench sections up to 90 m long. Where sandy soil supported a tough grass mat, localised sections of the fault scarp consisted of alternate suprathrust and subthrust scarps, giving a meandering trace, and across a gravel road at point 146 (Fig. 39) the vertical displacement of 53 cm was made up of a number of small wedges formed by a series of minor stepped reverse faults.



28. The northern end of the Meckering Fault. The *en echelon* fracture pattern indicates dextral displacement, but without appreciable vertical movement.

The northern section terminated at a small drainage channel which flows southward to the Mortlock River. As it approached the channel, the fault scarp consisted of four *en echelon* fractures, stepped right, and without visible connecting wrenches. As it crossed the channel, the scarp rapidly decreased in height, and could only be traced beyond it for a further 60 m as a series of parallel tension fractures.

At this point, the first major dextral translation of the Meckering Fault was encountered. The original fault trace had died out, and 650 m north a new fault trace began as superficial cracking in a stream bed, but rapidly rose to a ridge 42 cm high as it was traced southwestward. The ends of each section of the fault were joined by a wide zone of discontinuous tension fractures along the stream channels. On a gravel road, the fracture zone was seen to consist of two major fractures, downthrown 4-5 cm to the east, and a number of minor fractures spaced out over a distance of 120 m. The probability that this dextral offset in the Meckering Fault was caused by a pre-existing radial fracture will be discussed later in the chapter.

DOWERIN ROAD SECTOR

For the next 5.5 km, the fault runs southeast and approximately parallel to the Dowerin Road until the next major dextral step is reached in the vicinity of Wilston St. Between points 142 and 141 (Fig. 39) the fault was fairly straight and usually formed a steep-faced scarp about 50 cm high, particularly in lateritic soils and in the distinctive red-brown loam over a dolerite dyke. In sandy sections the scarp was sinuous, with alternating suprathrust and subthrust sections (Fig. 29a). The scarplets sometimes appeared as flowage tongues, similar to the toe of a landslide.

West of point 141, the fault scarp consisted of an undulating, weakly flexured ridge in unconsolidated sand, which after 350 m suddenly turned southward for 150 m before resuming a southwesterly path. This small sinistral step in the Meckering Fault was on line with the Sudholz Fault, a radial fracture with a small sinistral displacement.

Southwest to point 133, the fault scarp consisted of *en echelon* ridges with interconnecting wrenches, and in the blocky soil, the front of the scarp was often underthrust while the back was overthrust. However, as the fault passed into a field with a clay horizon between the sandy loam and underlying weathered rock the nature of the scarp changed. On a series of four *en echelon* thrust scarps (Fig. 42a), the scarp was of the compressional arch type (Fig. 41), and reached a maximum height of 1.8 m, whereas the measured uplift was only 1 m. The presence of the clay and a tough mat of vegetation held the scarp material together, and only longitudinal tension fractures formed along its crest. Both the dextral displacement and heave of the fault at this point were measured as 1.0 m.

From point 132 to the intersection of the fault with the Dowerin Road, 1.1 km southwest, the fault scarp was linear, and became increasingly sharp in outline as the depth to the underlying rock decreased. In places, the main fault was accompanied by parallel, minor branch thrusts 6-12 m in front of, or to the rear of the scarp. The branch faults had a similar sense of movement to the main fault, with a maximum of 23 cm uplift near the main scarp. At point 130 the fault plane was well exposed (Fig. 37) to a depth of 5 m and dipped at 52°. A thin layer of soil and about 38 cm of pisolitic laterite gravel covered the weathered rock, which showed a polished surface in the fault plane but no slickensides.

The fault plane was again exposed 630 m further along the scarp, and between the two exposures, the fault plane was either masked by the collapsed toe of the upthrown block, or completely obscured in a few sandy areas.

Throughout this section, the vertical uplift of the eastern block was a little over 1 m, and there was a noticeable association of the fault scarp with areas of quartz pebbles.

As the scarp continued along the verge of the Dowerin Road, it became convex in outline with longitudinal tension fractures along the compression ridge (Fig. 29b). After crossing the road a diffuse scarp with two parallel thrusts developed in a sandy loam overlying a clay subsoil and massive laterite. The fault scarp then became complex (Fig. 30a) as it approached the major dextral offset in the vicinity of Wilson Street. This offset, which contained features similar to the Burges Fault Complex to the south, will be described later in this chapter.

WILSON STREET TO THE MECKERING QUARRY

Between the Wilson Street offset and the next major dextral step north of Meckering quarry, the fault traversed cultivated land, and although the throw of the fault was commonly greater than 1 m, the scarp was often diffuse. South of Stewart Road, the fault trended 218°, and the scarp front was lobate and convex towards the northwest (Fig. 31). Large tension fractures about 20 m to the rear of the scarp were common in this area.

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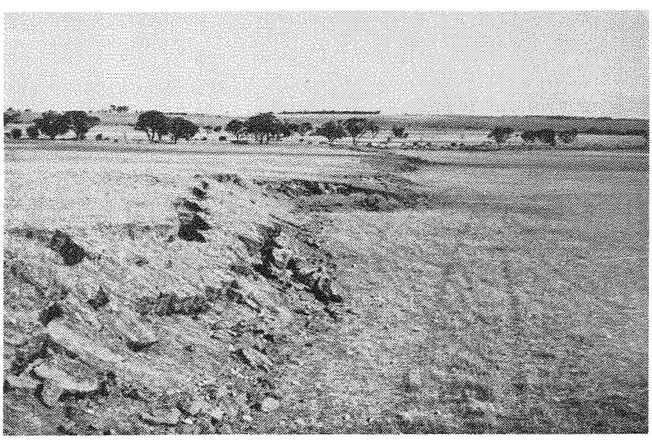
B



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29. The Meckering Fault:
   (a) Alternating suprathrusts and subthrusts in lateritic soil, 4 km north of Meckering.
   (b) The main fault scarp near the Dowerin Road-Wilson Street intersection north of Meckering. A convex scarp ridge with longitudinal tension fissures.
   (c) Rock overhanging scarp, fallen under its own weight. Note the presence of plentiful quartz pebbles. Meckering Fault, 450 m north of railway intersection.

A

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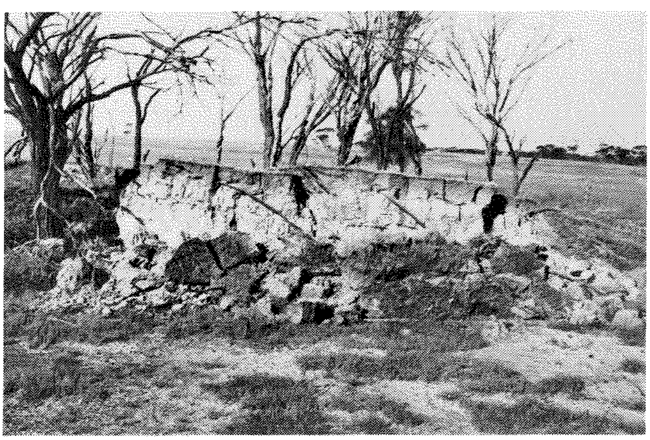

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30. The Meckering Fault:
 (a) Complex pattern of ground fracturing in cohesive lateritic soil near the Dowerin Road-Wilson Street intersection. Both suprathrusts and subthrusts are common.
 (b) Dermal subthrusts in laterite near the Goomalling Road-Wilson Street intersection. The main scarp is visible in the background, and the plane of the subthrust dips at 22°.
 (c) Dermal suprathrust in laterite, 500 m south of Koolbunine Road.

31. The Meckering Fault, looking north to the junction of Stewart Road and Moore Road, 2.4 km west of Meckering. The fault scarp is lobate and there are large tension fractures to the rear. (Photo: B.M.R.)

Farther south the fault scarp became very wide and developed into a mildly convex monocline, although the displacements measured on a fence line were 1.22 m of dextral slip and 1.22 m vertical throw. The diffuse scarp in this section probably resulted from a thick soil horizon and a strong mat of vegetation.

Five hundred metres north of the Meckering quarry the main fault scarp was offset 300 m in a dextral sense. Just south of point 107 (Fig. 39), the Meckering Fault sent off a minor, westerly trending thrust scarp which developed into a wrench. South from this point, the main scarp diminished in height until it terminated in a series of west trending wrenches. The offset portion of the Meckering Fault began as a low thrust scarp at the termination of the northern wrench fault, and increased in strength (Fig. 32b) until its vertical uplift exceeded 1.5 m near the southern wrench faults, and a strong compressional arch type scarp was formed. As with other dextral offsets, this sudden change in the fault trace was probably connected with a radial fracture in the mobile block.

MECKERING QUARRY TO THE MORTLOCK RIVER

In this, the most westerly section of the Meckering Fault, the fault trace curved from a trend of about 210° at its northern end to about 155° at the Mortlock River. Displacements along the fault were at a maximum in this section, and included the intersection with the railway (Fig. 11) and Great Eastern Highway (Fig. 1).

Half a kilometre north of the railway, the zone of fracturing at the fault scarp was narrow, but the fault plane was usually hidden by the collapse of the toe of the upthrown block (Fig. 29c). However, three readings of the dip of the fault plane were possible in the 30 m section where 30 cm of soil and laterite overlaid a wine-brown ferruginised weathered rock. The dip readings were 42°, 44° and 47°, and the relative vertical displacement on the fault was 1.52 m with a similar amount of dextral strike slip. A little farther south, a dip of 48° was measured, and slickensides plunging 57° to the north were visible on the polished fault plane.

In the vicinity of the railway, because of increasing depth to underlying rock and the presence of clay in the soil, the fault scarp changed from a sharp outline to a strongly convex ridge with a subthrust at the rear and overthrust in front. Between the railway and the Great Eastern Highway, the fault pattern was often complex (Figs. 1 and 15); the fault branched and rejoined in a zone up to 75 m wide. The fault crossed the highway as a single convex ridge 2 m high but the throw of the fault was measured as 1.3 m. North and south of the highway, the scarp was more complex, sometimes asymetric, and had a prominent subthrust backscarp and a gently sloping forescarp (Fig. 1, lower part of photograph). This wide zone of faulting was typical of areas with a sandy soil underlain by laterite.

A similar fault pattern continued up the hill south of the Great Eastern Highway until laterite came closer to the surface; the fault zone then became narrower and a single scarp developed with longitudinal tension fractures along the strongly convex face. At a fence line (point 1), a dextral displacement of 2.13 m and a throw of 1.83 m was measured. A soil section exposed by the fault showed kaolinized and ferruginized weathered rock overlain by cream and brown clay and a red-brown soil. The fault continued as a single strong feature for a further 1.3 km, until it reached an area of deep sandy soil, where it developed into a wide zone of multiple thrusts, giving rise to a broad humped scarp. For the next 600 m, up to three parallel thrust ridges were present until at point 309 (Fig. 39) the scarps rejoined to form a single scarp.

For nearly 1 km south of point 309, the fault scarp consisted of a high, featureless, sandy ridge marked by superficial warping rather than fracturing, and, although the throw of the fault, as measured on several fence lines, varied only between 1.5 m and 1.6 m, the ridge was usually 2 m high.

As the fault approached the Mortlock River, it developed forms typical of areas with deep soil and plastic clay. The scarp commonly developed a conspicuous underthrust, backscarp ridge with no overthrusting or fracturing of the front of the scarp. Where clay was near the surface, a strongly convex, bulbous, compressional arch type scarp was formed, and in salt flats, the fault became a zone of parallel scarp ridges (Fig. 32c).

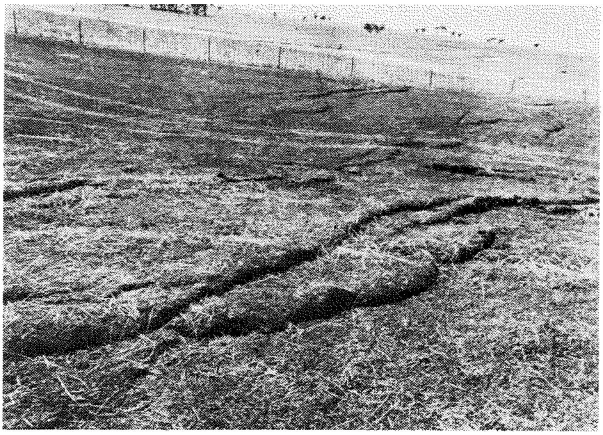
Near the Mortlock River, the soil changed from sandy to a red-brown loam overlying weathered rock, and the thrust scarp, 1.5 m high, had a steep front face and prominent longitudinal tension fractures. For 200 m this well-defined scarp ran parallel to, and 60 m west of, the Mortlock River, but it then changed direction to run due east to intersect the river. The scarp was then joined by a series of continuous tension fractures which orginated from the back of the main scarp further north and ran southwards along the west bank of the river. The fault 'nicked' the main river channel at this point, but again changed course and did not cross: instead, it continued due south as a featureless sandy ridge. It was not until 300 m further south that the fault crossed the Mortlock River, uplifting its sandy bed by 1.32 m (Fig. 14).

MORTLOCK RIVER TO THE BURGES FAULT COMPLEX

South of the Mortlock River, the fault continued its trend of 155° for several hundred metres, but then swung gradually to a due south trend until the Burges Fault Complex was reached. Initially, the fault scarp was in sandy soil, and relatively subdued; but farther south, where clay and laterite underlie the soil horizon, there was a comparatively wide zone of complex underthrusting and frontscarp overthrusting.

In the area where the Meckering Fault curved southward, the fault scarp bifurcated into two parallel branches about 40 m apart, and at one point the block between the two faults showed evidence of rotation. A fence crossing the traces at right angles showed a sinistral displacement of 0.38 m at the westerly fault intersection, and further sinistral displacement of 0.46 m at the easterly break (Fig. 33). A cadastral resurvey by the Lands and Surveys Department established that there had been an overall dextral movement of 52 cm. It is evident that the block between the two fault scarps had been rotated clockwise by about 2°. Rotation was suspected at a few other points, but this was the only instance where it could be confirmed.

The fault branch which gave rise to the rotation died out after a hundred metres, and for a short distance the fault scarp was a simple feature which gradually changed from a strongly convex arch scarp to a more angular thrust feature as laterite and weathered rock



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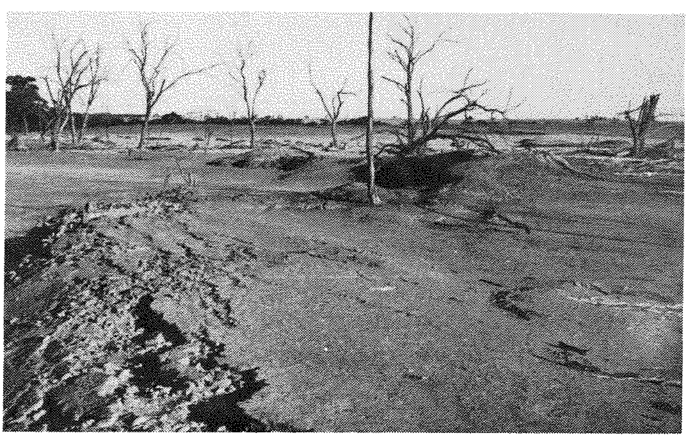

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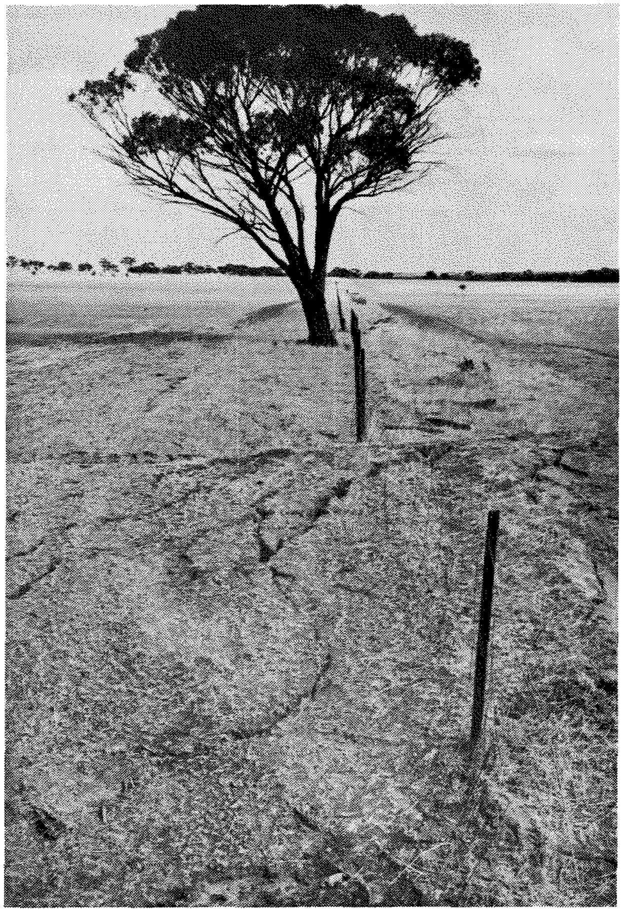
32. The Meckering Fault:
    (a) Small lobate suprathrusts slumped forward, 2.5 km west of Meckering.
    (b) Compressional arch scarp, 0.8 km north of the railway. Note the scatter of quartz fragments associated with the fault.
    (c) Sinuous pressure ridge in salt flats, 6.5 km southwest of Meckering. The ridge is parallel to and 15 m to the west of the main ridge which is seen in the centre of the photograph.

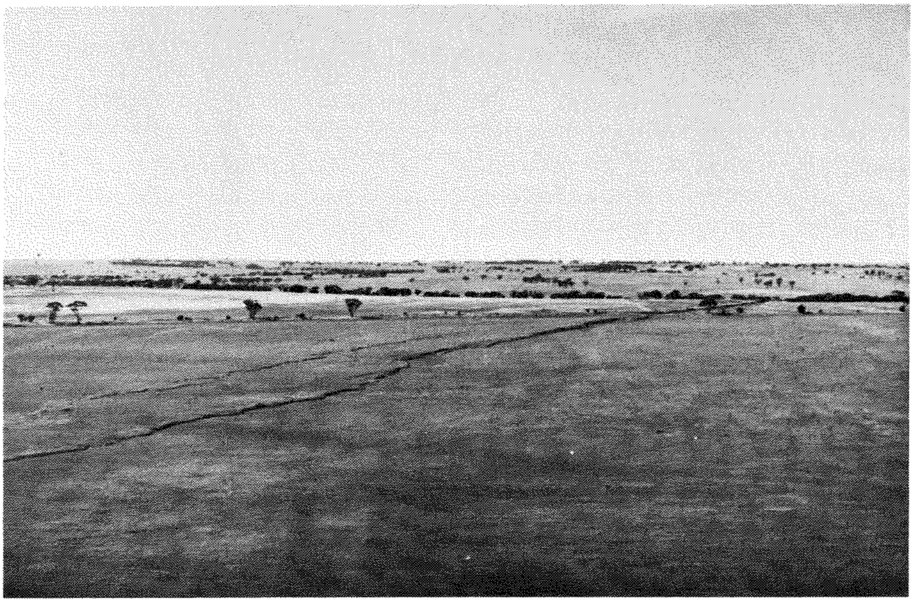


33. Rotation between parallel fault scarps, 700 m north of Koolbunine Road. Overall surveyed displacement was 0.52 m dextral, but the apparent displacement was sinistral.

approached the surface. The surface soil in this area was strewn with abundant quartz fragments. For the 400 m until the Koolbunine Road was reached, however, the fault again divided into two parallel thrusts (Fig. 34) and the vertical displacement of 1.5 m was divided between them.

At Koolbunine Road, the fault scarp was 1.52 m high (Fig. 12), and, as the fence lines and road were parallel to the local resultant of movement, there were no obvious lateral displacements. However, a small water pipeline serving a cattle trough was pushed past its original position, and indicated a crustal shortening of 1.6 m. Calculations based on these measurements showed a dextral displacement of 92 cm and a dip of 44° on the fault plane (point 35, Table 10).

South of Koolbunine Road, the Meckering Fault continued for a further 750 m as a single, strong, fault scarp about 1.5 m high (Fig. 35). For the most part the scarp was of the compressional arch type with the scarp ridge somewhat higher than the vertical displacement on the fault. The scarp was strongly convex with longitudinal tension



34. Meckering Fault north of Koolbunine Road. Two parallel thrust scarps, approximately 40 m apart. The small easterly (left) scarp dies out southward and the fault continues as a simple thrust (Photo: B.M.R.).

fractures and a few fissures oblique to, and at the rear of the fault trace. As the depth to underlying weathered rock decreased, however, the scarp outline became sharper, and large blocks of laterite were uplifted by the fault (Fig. 30c).

Where the fault intersected an unexposed basic dyke 300 m south of Koolbunine Road, there was a change in soil from grey and sandy to a deep red-brown loam. In the centre of this 60-m-wide zone, there was an exposure of the fault plane in ferruginized and deeply weathered rock, which dipped at 42° and was visible to a depth of 2.5 m. Slickensides on the fault plane plunged steeply, almost parallel to the dip of the fault.

In the vicinity of the Burges Fault Complex, the fault trace became complex because of the stresses imposed by the major dextral offset, and the last section of the Meckering Fault will be described together with the Burges and related faults.

SOUTHERN SECTION

The southern section of the Meckering Fault, nearly 9 km long, extends in an arc from the western end of the Burges Fault to the termination of the Meckering Fault just north of the Southern Mortlock River. The fault trend at its northern end is about 155°, and at its southern termination about 130°. Throughout its length both the vertical throw and the dextral displacement decrease to zero.

North and south of Hardy Road, the fault was fairly straight, and the fault scarp consisted of a collapsed rock overhang without backscarp features. There was abundant superficial quartz along this section of the fault, and weathered rock was always close to the surface. Two exposures of the fault plane were found, one with a dip of only 28°

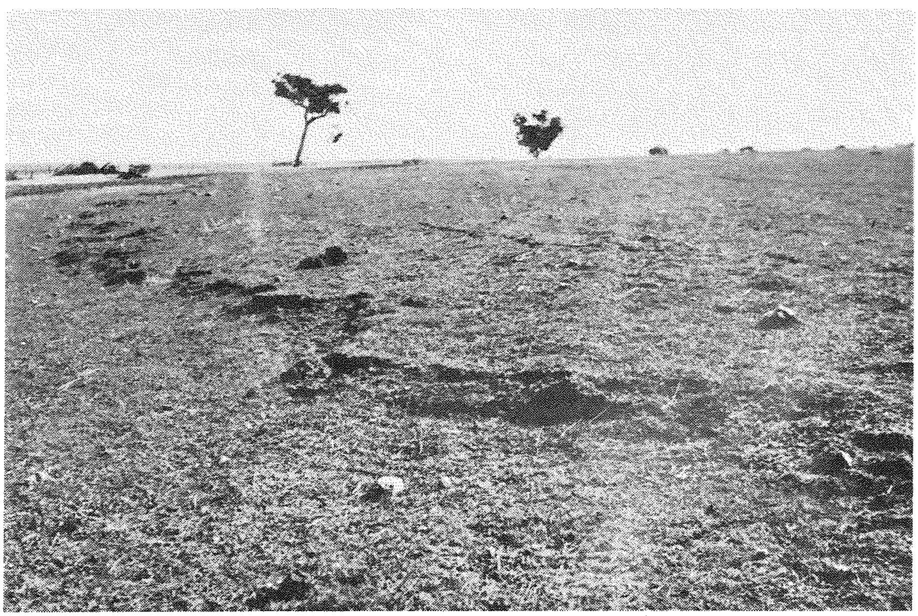
35. The Meckering Fault south of Koolbunine Road (Photo: B.M.R.).

located 30 m north of Hardy Road. The second exposure, 500 m south of the road, showed a dip of 54° and a superficial cover of only 25 cm of soil and laterite over weathered rock (Fig. 37b).

Approximately 750 m south of Hardy Road, the main fault scarp turned abruptly westward for about 100 m, then curved round to its former southwesterly trend. The westerly trending section was dominantly a dextral strike-slip fault with a lateral movement of about 1.8 m and a vertical displacement of about 60 cm upward on the southern side of the fault. The thrust scarp south of this dextral step had a sharp outline with a strongly convex front face, but died out after about 250 m, being replaced by a thrust scarp of increasing height, located 50 m to the east. The angle between the wrench section and the thrust scarp was traversed by a large tension fracture, which was open 45 cm, and the ground between it and the thrust fault appeared to have sagged.

South of this relatively complex area, the Meckering Fault was continued for a further 1 km by a well-defined scarp ridge, a little less than 1 m high, and with a strongly convex front face. There were strong tension fractures 2-3 m behind the scarp and the depth of soil was not great. As the soil became more sandy, the scarp became a gently convex ridge which divided into three *en echelon* scarps offsetting the fault trace a total of 200 m to the southwest. The southernmost of these scarps continued on a trend of 140° to become the main fault.

The final 5 km of the Meckering Fault showed a steadily diminishing fault scarp, from a ridge of 90 cm high, to superficial fracturing at its termination 750 m north of the Southern Mortlock River. Throughout much of the distance, the soil was lateritic and the scarp sharply defined even when the throw was no more than a few centimetres (Fig. 36). Quartz fragments were commonly found in the vicinity of the fault trace. The scarp itself



36. Southern end of the Meckering Fault. The well defined blocky scarp has a throw of 15 cm, dextral strike slip of 23 cm and a heave of 18 cm.

was often blocky, and sometimes the superficial blocks had been forced up over the elevated east block leaving the frontscarp intact. In areas of thicker soil, the surface scarp appeared as a small monocline without any surface fracturing. Throughout this section, tension fractures were common 2-3 m to the rear of the scarp. Fault planes excavated near the southern end of the fault showed dips of only 15-18°, but this was probably superficial as the dip calculated from the measurement of heave and throw was about 40°. The dextral slip measured on a fence line only a few hundred metres from the termination of the fault was only 4 cm.

RELATION OF FAULTING TO GEOLOGY AND TOPOGRAPHY

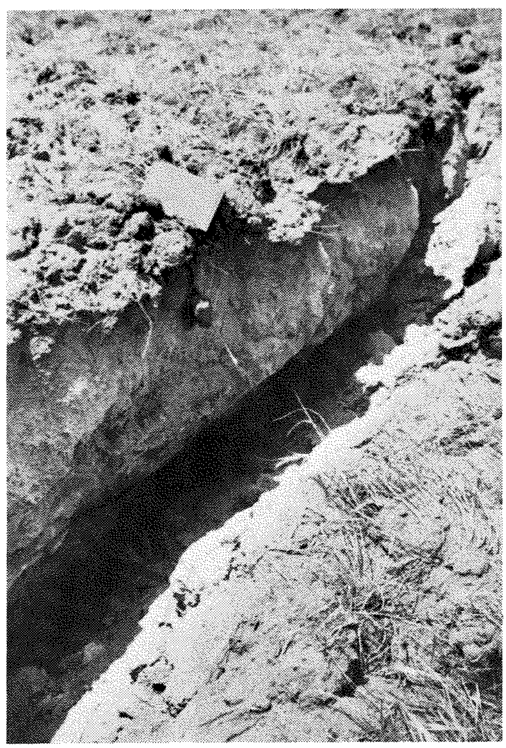
As outlined in Chapter 1, there were no known geological features which could account for the location of the Meckering Fault, although the stress field, which has evidently been active over a long period, could assist in understanding the Southwest Seismic Zone (Chapter 7). Throughout its length, the fault traverses all major rock types and cuts across the regional foliation. North of Meckering townsite, the fault is straight rather than arcuate, and follows the dominant dyke trend. But the dykes and shears in this area are vertical, and can have exercised only minor control on the shallow-dipping thrust fault.

With respect to the relationship of the Meckering Fault to the topography, the fault can be divided into two sections, a southern section between the East and the South Mortlock rivers, and a northern section along the valley of the East Mortlock River. In the south, the fault scarp cuts across the topography and reaches its highest and lowest points approximately 260 m above sea level near Warding, and 205 m at the East Mortlock River intersection 10.5 km south-southwest of Meckering. The central and northern sections of the fault, however, being situated on the right-hand flank of the river valley, are generally parallel to local topographic features. The fault follows the river in its curving course around Meckering township, a course which is possibly governed by older faulting.

FAULT PLANE EXPOSURES

The scarp of the Meckering Fault did not cut through a solid outcrop of fresh rock at any point, although it traversed areas of scattered exposure. However, the soil and weathered rock profile was of minimal thickness in several areas, and the fault plane was well exposed in moderately weathered rock in at least 23 locations (Fig. 37b). At each exposure, brecciation, shearing, and signs of previous movement were visible. It was rather surprising that so many fault-plane exposures were visible, because crustal shortening tended to roll up surplus ground at the scarp front and obscure structural details. Where exposed, the fault plane was often well defined, but the large overhang formed by the thrusting was sometimes unstable, and tended to break and collapse as a rock fall under its own weight (Fig. 37a). In some locations, a tension crack appeared to the east of the fault, and the overhanging wedge of rock and soil tilted, thus decreasing the apparent dip of the fault plane.

A



B

37. The Meckering Fault plane:
   (a) Exposure in weathered rock overlain by 38 cm of pisolitic laterite, 2.5 km north of Meckering (point 130, Fig. 39). The dip was 52°.
   (b) Soil and laterite 25 cm thick over slightly weathered granite, 14.5 km south of Meckering (point 79, fig. 39). Dip 54°, throw 76 cm.

A further complication to the direct measurement of the dip of the fault plane was that in certain exposures there was an opening of up to 30 cm between the two sides of the fault. At these locations, no slickensides were visible on the exposed fault surfaces, and it is thought probable that the fault plane became less steep near the surface.

In a few localities, where the fault scarp was not high, it was possible to expose the fault plane by digging. This was valuable at the extremities of the Meckering Fault and along the Splinter Fault, where rock was reasonably near the surface. In soils, the dip of the fault plane flattens, but in weathered rock the measurements were probably reasonably accurate.

The measurements made are plotted on Plate 2 and vary from 28° to 55°, but an exceptional 15° dip was exposed by digging near the southern end of the fault. Considering that the fault plane is not smooth, that only small exposures were available, and that the overhanging thrust scarp was unstable, the measurements are probably as representative as can be expected. The average dip of the fault plane appeared to be about 40-45° and to be constant throughout the length of the fault.

MEASURED FAULT DISPLACEMENTS

CADASTRALLY DETERMINED DISPLACEMENTS

As a result of agricultural activity in the Meckering area, numerous fence lines and cadastral boundaries, established since 1900, were disrupted by the fault. With the cooperation of the Lands and Surveys Department, it was possible to re-survey these boundaries and determine the values of resultant displacements with some precision. An endeavour was made to obtain measurements at reasonably spaced intervals along the fault scarp, but in certain areas this was not possible, as the original property boundaries were old and the lines could not be re-established. However, ten cadastral lines were resurveyed across the fault, and these were tied in to the second order triangulation of the State. The locations of the observations are shown in Plate 2, which also shows a vector representing the resultant horizontal shift. The results are set out in Table 9, which shows

TABLE 9. SURVEYED DISPLACEMENTS OF THE MECKERING FAULT

Location	Surveyed displacement: distance (m) A	Surveyed displacement: distance (m) B	Surveyed displacement: Azimuth	Azimuth of fault dip	Azimuth difference (a)	Movement Vectors: Heave B Cos a (m)	Movement Vectors: Dextral slip B Sin a (m)	Movement Vectors: Observed throw (m)	Calc. dip of fault	Net slip (m)	Plunge
1	—	0.63	278°	135°	37°	0.50	0.38	0.50	45°	0.80	38°
2	1.41	1.32	270°	123°	33°	1.11	0.72	1.23	48°	1.81	43°
3	—	2.14	265°	118°	33°	1.80	1.17	1.54	41°	2.64	36°
4	2.13	1.77	264°	096°	12°	1.73	0.37	1.44	40°	2.28	39°
5	—	2.46	256°	093°	17°	2.36	0.72	1.85	38°	3.08	37°
6	—	1.41	248°	080°	12°	1.38	0.29	1.45	46°	2.02	46°
7	1.17	0.90	235°	087°	32°	0.76	0.48	0.56	36°	1.06	32°
8	—	1.65	229°	084°	35°	1.35	0.95	1.55	49°	2.26	43°
9	—	1.32	217°	061°	24°	1.20	0.54	0.86	36°	1.57	33°
10	—	0.45	211°	037°	6°	0.45	0.05	0.46	46°	0.65	46°

the change in length and azimuth of the surveyed lines and the calculated movement vectors—assuming the eastern block to have moved. Also shown are the observed uplift of the eastern side, the calculated dip of the fault, and plunge of the movement vector.

Line 3 was surveyed along the Eastern Goldfields Water Supply pipeline, but the remainder of the displacements were determined by the resurvey of pegs and fences on cadastral lines. The azimuth of displacement is given for the upper side of the fault plane relative to the lower part, which is assumed fixed, while the azimuth of the fault dip is assumed to be normal to the strike of the fault. The disruption, involving crustal shortening and lateral displacement, is expressed as a local resultant vector rather than with respect to the principal horizontal stress which cannot be used unless the orientation of the strain ellipsoid is known (Means, 1963).

The displacements listed in column B, from which all subsequent calculations were made, were determined from the survey of pegs more than 300 m from the fault scarp; they thus represent the movement over a wide zone and avoid local anomalies.

Column A gives comparative displacements for three sets of pegs near the fault scarp. In each case, the A measurement was greater than B, the difference corresponding to the width of tensional openings between the two sets of pegs. The larger figures possibly represent the initial movement along the fault whereas column B represents the final displacement after minor ground adjustments had taken place in the weeks following the earthquake.

The measured displacements, and the calculated movement vectors, show that the fault can be divided into two sectors, approximately north and south of the large dextral translation known as the Burges Fault. This is well shown by the calculation of the net slip of the fault block, which combines both the surveyed horizontal displacement and the less accurately measured throw of the fault. A net slip of 3.08 m is recorded at the western extremity of the northern arc of the fault, and this decreases northwards to 0.80 m a few kilometres from the fault termination, and southwards to 1.06 m at the termination of the northern arc. At this point, the southwest trending Chordal Fault, which appears to form a hinge line, can be traced to within a few hundred metres of the Meckering Fault, which abruptly changes direction from a southeasterly to a southerly course. At location 8, in the immediate vicinity of the Burges Fault, the net slip of the Meckering Fault rises to 2.26 m then decreases along the southern arc to only 0.65 m near the termination of the fault.

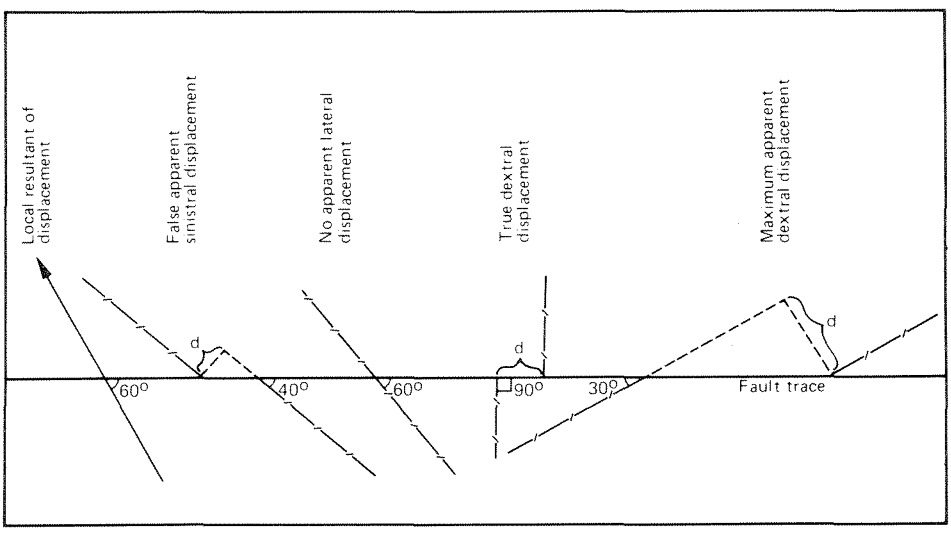
All movement vectors follow the pattern outlined above, but the dip of the fault, calculated from the vectors, shows no similar pattern and averages 42°. As might be expected, the calculated dips, being representative of the fault plane over several hundred metres, are more consistent than the measured surface dips. As the displacement vectors are not at right angles to the fault, their plunge is, in consequence, slightly less than the dip of the fault, being most nearly coincident where the dextral slip is smallest.

If the fault dips are projected back to the east, they converge in a small area about 8 km southwest of Meckering (Fig. 56). A projection of the fault plane to this point indicates a depth of about 10 km, but as the shape of the mobile block is probably spherical rather than conical (Chap. 10), the fault plane probably flattens at depth reducing the maxium thickness of the mobile block to about 4.5 km.

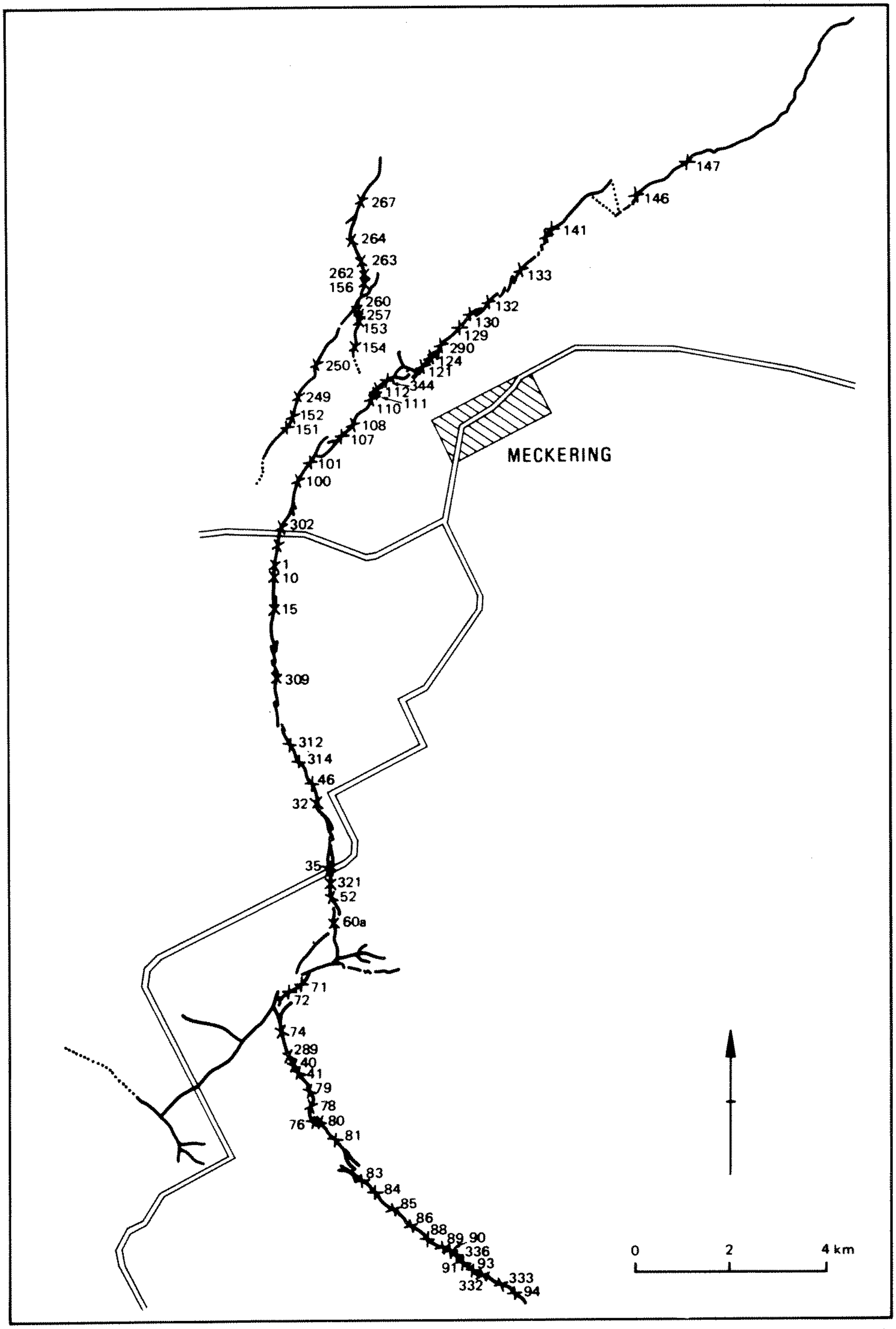
UNSURVEYED DISPLACEMENT OF FENCE LINES

The displacements surveyed by the Lands and Surveys Department provided a framework within which measurements made by less accurate procedures could be made with some confidence. Relative horizontal movement can be obtained at many places along the fault scarp by measuring the displacement of fence lines and pipelines, and vertical throw can be measured by hand instruments, after taking into consideration any extra compressional bulge. While the throw of the fault can be measured with reasonable confidence, the lateral displacement of a fence or pipeline will depend on the angle at which it cuts the fault. A fence at right angles to the fault will be displaced laterally by the absolute amount of slip, and in the same sense, either dextral or sinistral, but at other angles both the amount and sense of the slip may be changed. A fence which crosses the fault parallel to the local resultant of movement will not be laterally displaced at all, but if it crosses in the obtuse angle between the resultant and the strike of the fault then the apparent displacement will be in the correct sense and will increase until it is at a maximum when the fence is perpendicular to the resultant. Conversely, if the fence crosses the fault in the acute angle between the resultant and the strike, the sense of apparent displacement will be reversed and will increase to a maximum when the fence is nearly parallel to the fault. These various situations are illustrated in Figure 38.

From the measurement of fence line displacements alone, it is not possible to determine the absolute movement of the fault, but for fences at right angles to the fault the lateral shift is measurable, although sometimes allowance must be made for the effects of *en echelon* faulting. At a few points, the local crustal shortening could be estimated from surplus fence wire, after making allowance for the stretching involved in lateral shift and the compression roll on the fault scarp. In such cases the absolute lateral shift and the dip of the fault could also be calculated.



38. **The effect of angle of interception on the apparent displacement of fence lines crossing a dextral thrust fault.**



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39. Observation points for fence line displacements on the Meckering Fault.

TABLE 10. DISPLACEMENT OF FENCE LINES BY THE MECKERING FAULT

Locality No.	Lateral displacement (uncorrected) (m)	Vertical displacement (m)	Heave (m)	Angle between fence and scarp	Calculated Lateral displacement (m)	Calculated Dip of fault
233	D 0.30	0.40		60°		
147	D 0.76	0.53		60°		
146		0.53				
141		0.51	0.15			73°
133	D 0.55	0.55	0.61	85°	D 0.50	42°
132	D 0.71	0.99	0.99	80°	D 0.55	45°
130		1.02				
129		1.16				
290		1.10				
124			1.07	55°		
121	D 1.32	0.69		65°		
344		0.76				
112	D 0.76	1.22	1.98	90°	D 0.76	32°
111	D 0.91	1.22		70°		
110			0.99	60°		
108	D 1.22	1.22		60°		
107	D 1.16	0.69		60°		
101	D 1.52	1.52				
100		1.60				
302		1.30				
1	D 2.13	1.83		35°		
10	D 1.52	1.98		50°		
15	S 0.69	1.63		150°		
309		1.68				
312		1.52				
314		1.37				
46		1.37				
32		1.37				
35	0.00	1.52	1.60	120°	D 0.92	44°
321		1.45				
52	D 1.83	1.52		15°		
60a	D 0.91	1.52				
71a	D 1.52	0.43		75°	(D 1.5)	(80°)
71	D 1.52	1.07		65°	(D 1.5)	(80°)
74	D 0.41	0.91		80°		
289		0.67				
40	D 0.30	0.85		85°		
41	D 1.37			25°		
79		1.22				
78		0.61	1.83			18°
76	D 0.61	0.61		90°	D 0.61	
80	D 0.30	0.46		90°	D 0.30	
81		0.91				
83	D 0.61	0.91		55°		
84	D 0:69	0.61		18°		
85	D 0.61	0.46		70°		
86	D 0.30	0.41		70°		
88		0.46				
89	D 0.30	0.30		90°	D 0.30	
90	D 0.30	0.30		28°		
336	S 0.23	1.26		120°		
91			0.20	90°		
93	D 0.23	0.20		45°		
332	S 0.08	0.20		150°		
333		0.15				
94	D 0.06	0.04				

NOTE: D = Dextral Movement. S = sinistral movement

Table 10 lists the displacement of fences, but, except in a few cases, the measurements have not been corrected for the angle between the fence and the scarp. The location of the observation points is given in Figure 39. The observations confirm the concept obtained from the surveyed lines that the fault movement was at a maximum in the westerly parts of the arcuate fault trace, and decreased in magnitude to the north and to the south.

SLICKENSIDES

Although the fault plane was observed in over twenty localities, apparently reliable slickensides were seen in only four. As explained earlier, this is probably because the fault plane became less steep near the surface, and the upper plate moved away from the lower plate instead of moving over it in close contact during fault movement. The most northerly slickenside was in the plane of the Meckering Fault near the surveyed line no. 3 along the Eastern Goldfields Water Supply pipe line (Plate 2, and Table 9). A second set was seen in an exposure 300 m south of Koolbunine Road, and the remaining two were in two of the faults which make up the Burges Fault complex, where the fault is marked as dipping at 75° and 80°.

Slickensides indicate the direction of relative movement of adjoining rock masses, and thus should parallel the relative displacements determined by the resurvey of cadastral points. At the Eastern Goldfields Water Supply pipeline, the cadastrally determined fault displacement plunged at 36° towards 085°, while the plunge of the slickensides nearby was 36° towards 072°. The Burges Fault is situated between two of the surveyed displacements, positions 8 and 9, where the movement plunges at 43° towards 049°, and 33° towards 037° respectively. Where the fault plane dips at 80°, the slickensides plunge at 32° towards 050° (Fig. 40) and at the 75° dip they plunge at 19° towards 093°. Agreement between the first slickenside measurement and the surveyed displacements is good, but the other is anomalous. This is probably the result of the fault plane locally consisting of two separate fractures of different displacements, so that the slickensides represent only part of the total movement. At the fault plane exposure 300 m south of Koolbunine Road, the slickensides plunged directly down the fault plane at 42° towards 090° whereas the cadastrally determined displacement at the road was a plunge of 32° towards 055°. The probable explanation for this difference is that movement along the Meckering Fault took place in two stages, an initial thrust movement produced the observed slickensides, followed by dextral displacement which was not recorded because the fault plane was open.

THE MORPHOLOGY OF THE FAULT SCARP

Although the forms of normal fault scarps have been previously catalogued, consistent scarp forms resulting from reverse or thrust faulting have not been defined, both because of scarcity and the lack of clear cut structures because of poor soil conditions. Henderson's (1933, p. 51-52) account of the reverse faulting that accompanied the Hawkes Bay N.Z. earthquake of 1931 described the fault scarps thus:

> . . . the ridges . . . resemble the pressure ridges formed at the toe of a surface slump . . . Ocassionally the tough dry turf is folded into broken recumbent folds, or masses of turf override the ground in front for several feet . . .

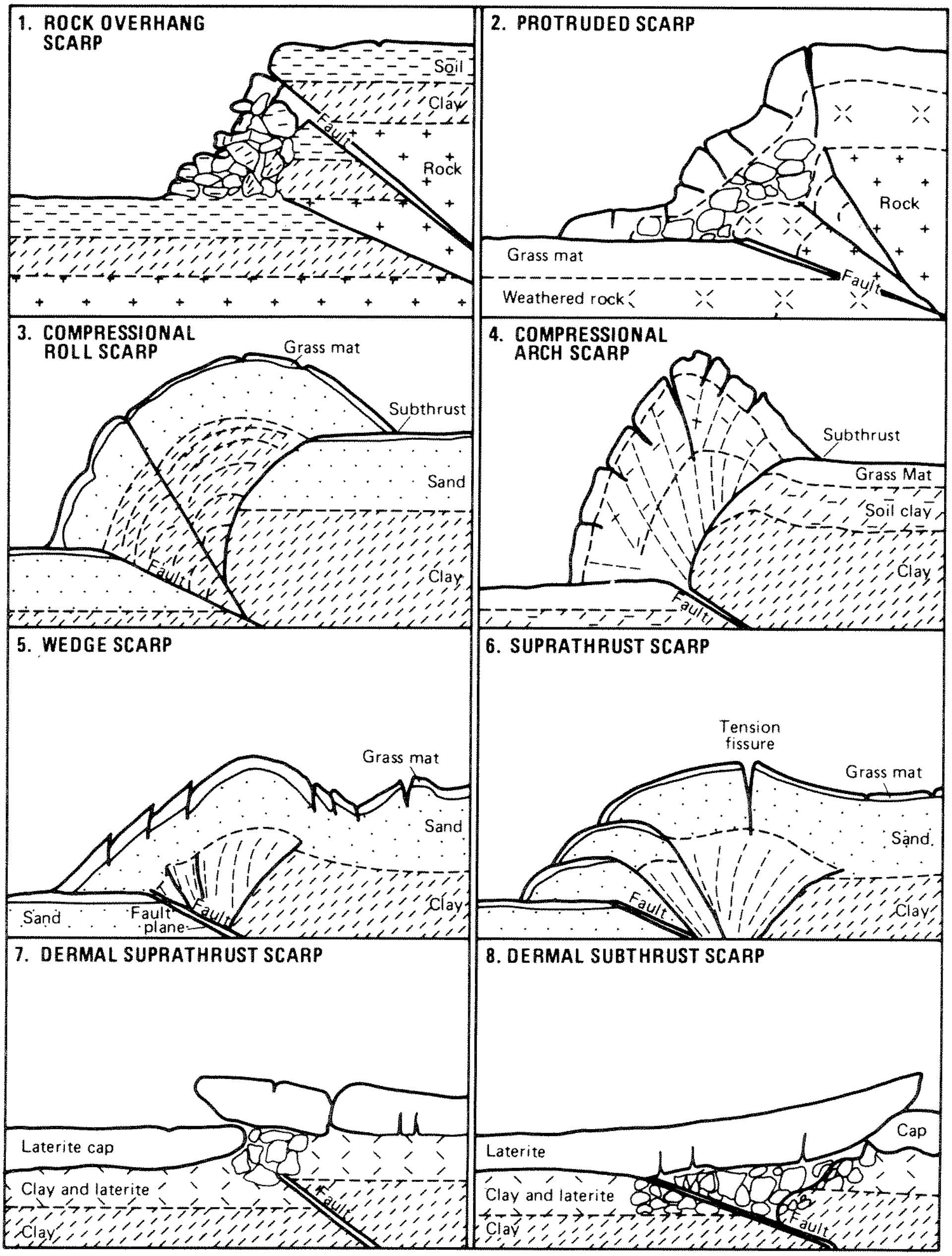
40. Slickensides on the plane of the Burges Fault. The fault plane dips at 80 degrees to the southeast, and the slickensides plunge at 32 degrees to the northeast.

Similarly the fault scarps which formed in unconsolidated landslide material after movement on the White Wolf Fault, California, in 1951, showed little variation in form and were described as pressure ridges, or 'mole tracks' (Bulwada & St Amand, 1955). Again, in a preliminary report on the faulting accompanying the Inangahua Earthquake, Lensen and Suggate (1968) have described the two scarps as showing minor reversed faulting, with compressional rolls and tension cracks. The faults were in alluvial river terraces and displayed no significant variety of form.

An experimental approach to low-angle thrusting has been provided by Link (1928). In experiments on the lateral compression of alternating layers of various materials, he was able to produce overthrusts and underthrusts with many of the characteristics of the scarp of the Meckering Fault.

The Meckering Fault produced a variety of simple structures at the scarp which were capable of being studied and classified. The clarity of the forms produced was directly related to the shallow nature of the soil and the nearness to the surface of firm rock. The form of the scarp was also controlled by the local trend of the scarp front and by the principal stress directions, and variations in these resulted in a large diversity of form. This variety can be reduced to at least eight distinct types of thrust scarp, which are illustrated in Figure 41.

The various scarp forms were the result of compression on a variety of soils, but, where there was a considerable thickness of residual or alluvial sand, the scarp was generally quite formless, and the only variation was provided by the thickness and coherence of the grass mat. This type of scarp has not been included in Figure 41, but an example is shown in Figure 29 where clay was present in the upper layers of the soil. The



41. Thrust scarp morphology and classification.

compressional movement has, in this case, caused the clay to deform plastically into an anticlinal bulge which resulted in the immediate scarp front rising up to 1 m higher than the uplifted ground to the east. This clay bulge was also shown by the forms named the compressional roll scarp, the compressional arch scarp and the wedge scarp.

Where the upper soil layers were firm and dry, instead of deforming plastically they often sheared. This sometimes resulted in an overhanging scarp in which the fault plane was visible, or if laterite capping was present to a suprathrust or subthrust scarp. The suprathrust, or overthrust scarp was formed where the compressional heave forced the upper soil layers of the mobile block up and over those of the stable block, and had the appearance of a normal thrust fault. More rarely an ancillary superficial fault was formed, at right angles to, and in advance of, the true fault plane, and the mobile block underthrust the laterite capping to form a subthrust scarp.

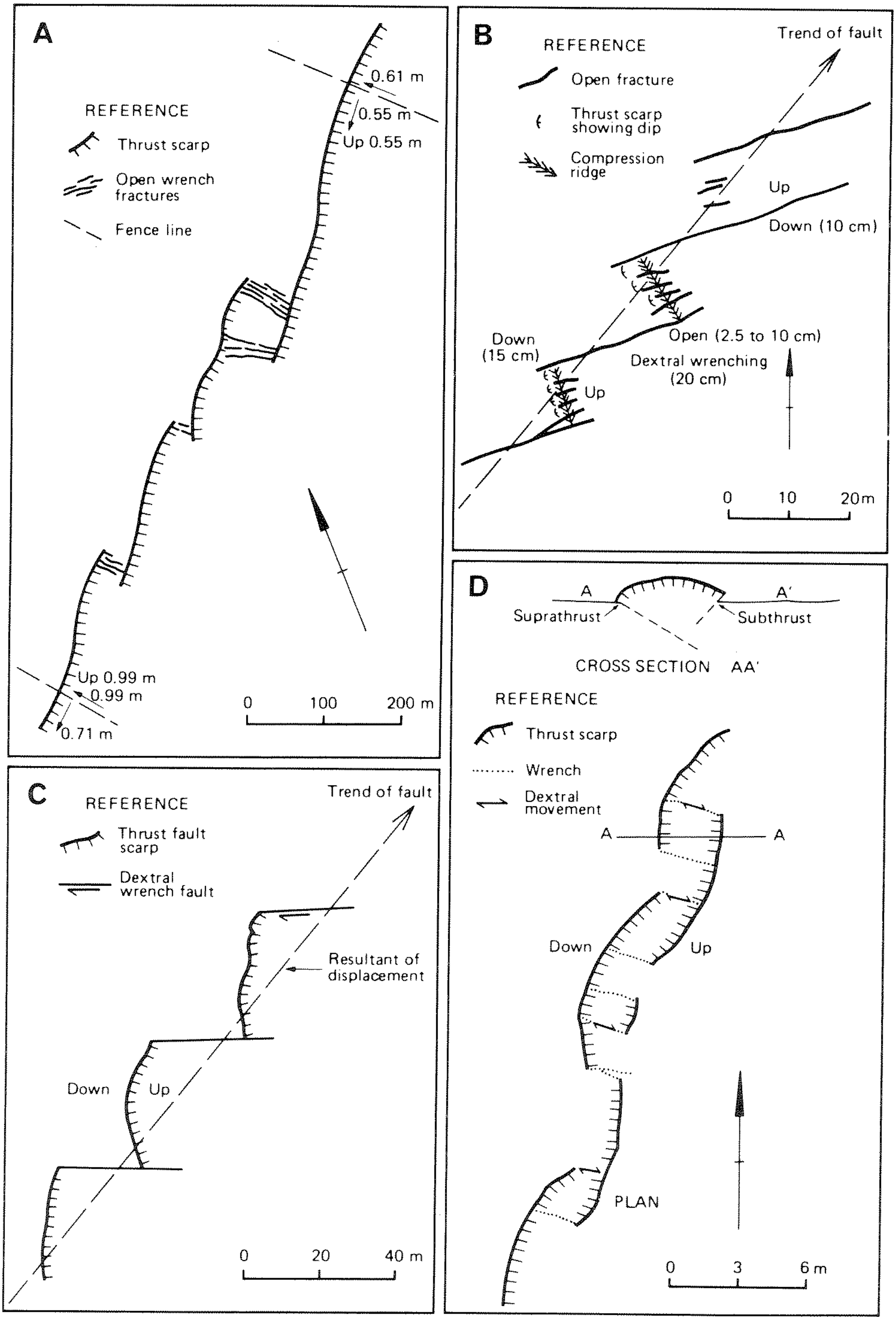
In general, the Meckering Fault scarp consisted of a single, compressional and wrench feature, with associated tension openings up to 30 m from the main front of the scarp. The definition and magnitude of the scarp was a reflection of the nearness of rock or hard laterite capping to the surface. The surplus soil and weathered rock was often rolled up in the form of a pile in front of the advancing upper plate, but sometimes, when there was a strong grass mat, the surplus ground was preserved integrally, with tension breaks where the overhang fell under its own weight.

TYPICAL FAULT PATTERNS

For much of its length, the Meckering Fault consisted of a single scarp with only minor associated tensional cracking parallel to the strike. With all movement taken up along a single fault plane, these stretches preserved the fault in its most spectacular aspect. However, commonly the soil conditions would not support a single fault plane at the surface, or the fault itself was divided along closely spaced slices of rock, so that the fault scarp became a zone within which were developed patterns of minor superficial faulting. Several such patterns are described (Fig. 42).

EN ECHELON FAULTING

In all the primary faults of the area, *en echelon* faulting was common. Usually the individual fault scarps were at about 30° to the trend of the scarp front and rotated anticlockwise from it, but the angle could be as little as 10° in some areas. The length of the individual faults making up the pattern ranged from a few metres to several hundred metres, and in the larger examples, the faults were often connected by tension fractures and wrenches at right angles to the trend of the fault (Fig. 42a). At the northern end of the Meckering Fault and the southern end of the Chordal Fault, where the rotation was clockwise, there was often a raised compressional ridge or 'mole track', up to 1 m high. On the Chordal Fault tension openings, trending at 30° obliquely to the ridge, divided it into narrow rectangular blocks which at either end of the fault were thrust out beyond the zone of dislocation (Fig. 42b).



42. Typical fault patterns:
(a) *En echelon* faulting on the Meckering Fault.
(b) *En echelon* faulting at the southern end of the Chordal Fault.
(c) Alternative thrust and wrench faulting.
(d) Alternate suprathrust and subthrust faulting.

ALTERNATING THRUST AND WRENCH FAULTS

A characteristic fault pattern consisted of alternate short thrust faults and connecting strike-slip faults at right angles to the thrusts (Fig. 42c). The trace of the scarp thus became zig-zag or sinuous. The wrench faults were usually vertical planes, along which there has been a small transcurrent movement and minor tensional parting of the walls. These wrench sections could be as long as 30 m, and this type of faulting could persist for over 1 km. This pattern was essentially a variation of *en echelon* faulting in which the thrust faults and interconnecting wrenches were of equal length. An example of this pattern of faulting is shown in Figures 42c and 49.

SUPRATHRUST AND SUBTHRUST FAULTING

In sections of the fault trace exhibiting alternate thrusting and wrenching, it was quite usual to have alternate suprathrusting and subthrusting. The effect was to give a composite trace of arcuate pressure ridges, alternately facing east and west, and interconnecting wrenches (Figs. 29a and 42d). The resulting ridge was thus wedge-shaped in cross-section, with the westerly facing fault plane not extending to the surface as a fracture or suprathrust for short distances. Occasionally there was subthrusting at the western face of the wedge and suprathrusting at the eastern, thus reversing the normal situation.

PARALLEL FAULT SCARPS

Double or multiple fault traces were common along the scarp of the Meckering Fault; the parallel faults sometimes forming a zone up to 60 m wide. These were considered to be part of the main fault rather than branch faults, and were often connected to the main scarp by short wrench faults. The total displacement shown by a series of parallel faults was invariably the displacement of adjacent single fault scarps. Where several parallel faults were present, the individual scarps sometimes displayed suprathrust scarps, giving a broad humped profile.

Another form of parallel scarp arrangement occurred when the main scarp diminished, and another, parallel to it, increased in magnitude until it became the main scarp, and the original scarp disappeared without visible connection or continuation. This form was shown 2.6 km south of Hardy Road, where the west, and main, scarp diminishes over a distance of 50 m; and a new scarp, 55 m to the east, gains in vertical displacement as it continues southward.

DEXTRAL NORMAL FAULTING

A feature of the Meckering Fault scarp, particularly the central section of the fault, was the occasional presence of dextral normal faulting to the east of the main scarp. The faults, with a small downthrow to the west, were parallel to, and within 40 m of, the main fault scarp. These openings modified the amount of crustal shortening achieved at the main scarp, and displayed the same dextral movement. Because of the lateral movement of these faults, their characteristic surface expression was a 'mole track', or line of disturbed earth, as if the ground had been turned by a plough. Typical cross sections of these faults are given on Plate 4.

The presence of dextral strike-slip faulting immediately to the rear of the main scarp is considered to be the result of lateral movement following the thrusting movement in time. After the initial thrust movement, accompanied by some dextral strike slip, had been completed, the broken ground at the scarp front effectively resisted further lateral movement; this resulted in the formation of longitudinal cracks at the rear of the scarp. The time sequence would partially explain the notable absence of slickensides on the exposed portions of the fault plane. A similar sequence of events has been established for the Burges Fault.

CREVASSE OPENINGS PARALLEL TO THE MAIN SCARP

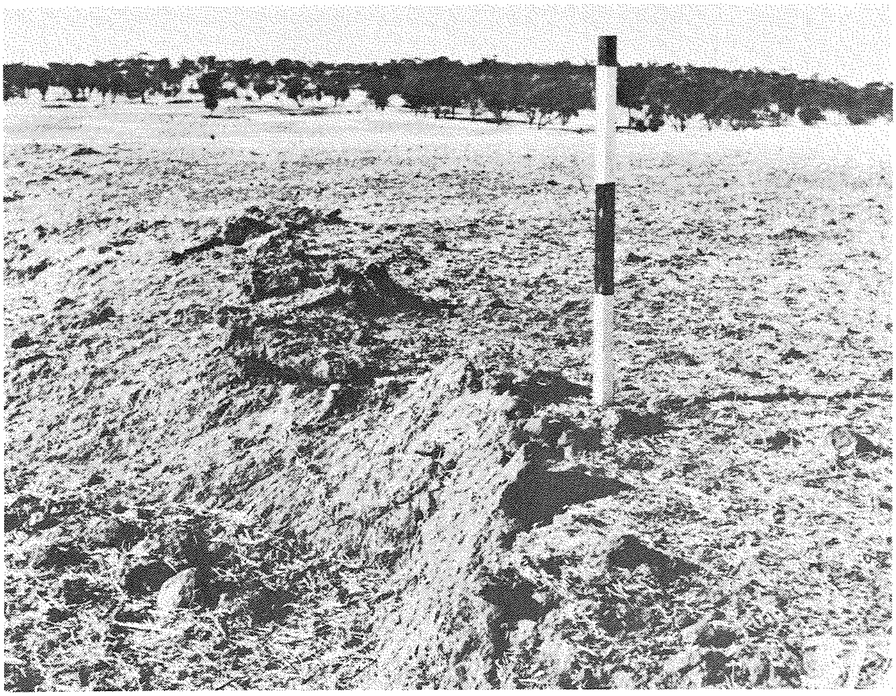
In areas of thick soil cover, linear cracks and openings were a feature of the fault scarp. The short open cracks were usually parallel, or only slightly oblique, to the strike of the fault, and occurred to the east and within 10 m of it. The openings varied from a centimetre or so up to about 40 cm wide, and from a few metres to 50 m or more long, and had the appearance of crevasses (Fig. 31). Vertical displacement across the crevasses was invariably present; the west side was downthrown, but the vertical movement was always less than the width of the opening. It is clear that these features were caused by the dip of the fault plane flattening in soil and completely weathered rock at the surface, and the collapse of the overhanging fault scarp. This type of fracture is clearly different from the dextral normal faults described in the previous section.

THE SPLINTER FAULT

The Splinter Fault is a dextral thrust fault, 9 km long, trending north-northeast, and situated about 1.5 km northwest of the northern part of the Meckering Fault (Plate 2). In general, the Splinter Fault parallels the Meckering Fault but its surface trace is complex. From a short central strand, the fault bifurcates both north and south. To the south, the main branch trends southwest for 4 km while a minor branch trends southerly towards the Meckering Fault. Beyond this southern branch, a series of southerly trending ground fractures almost provides a surface connection with the Meckering Fault, but the Splinter Fault is probably best considered as a secondary fault, rather than a branch of the Meckering Fault.

Nowhere was the fault plane of the Splinter Fault exposed naturally, but at three localities where weathered rock was present near the surface it was exposed by digging (Fig. 43b). The measured dips varied from 25° to 32° and averaged 27° eastwards. On the Meckering Fault, 1.6 km to the east, the fault plane dips easterly at angles of between 35° and 52°, with an average dip of 42°. It is possible, therefore, that the two faults may merge at a depth of about 1.6 km, at a position about 2 km to the east of the scarp of the Meckering Fault.

The maximum displacements were shown in the central portion of the fault (Fig. 43a) where it was estimated that there was a maximum crustal shortening of 61 cm, a dextral movement of 30 cm and a vertical displacement of about 33 cm. The total net slip, calculated from these figures was therefore 74 cm and the fault dipped at 28°. The



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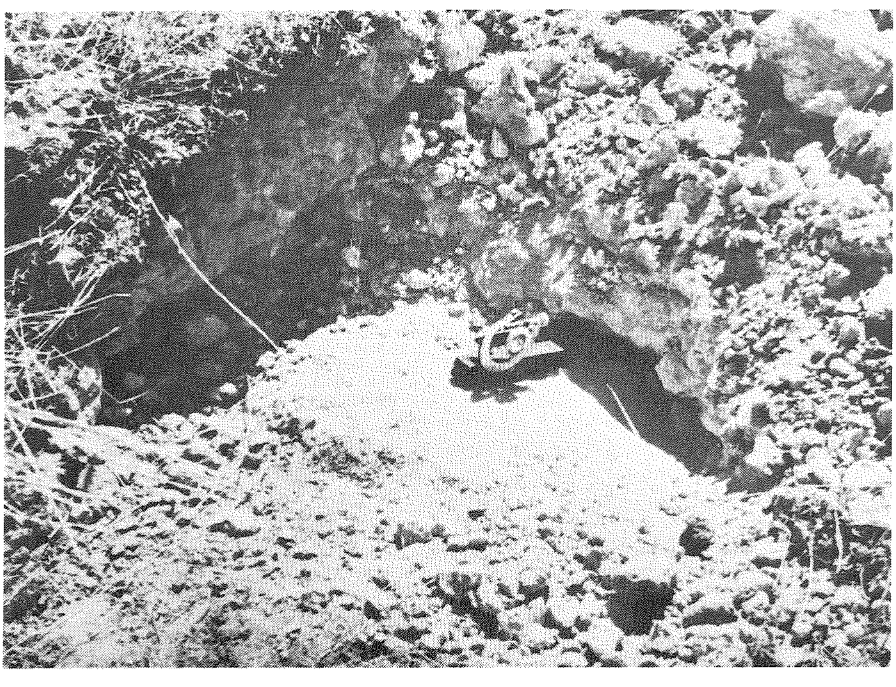


B

43. (a) The Splinter Fault at its point of maximum uplift of 33cm.
(b) Excavation of the Splinter Fault plane in moderately weathered rock. The fault dipped at 30° to the east.

maximum movement on the Splinter Fault was thus only about half that surveyed at the adjacent location 2 on the Meckering Fault (Table 9), and less than one-quarter of the maximum movement of the Meckering Fault.

In the two fault branches at the northern end of the Splinter Fault, the type of faulting was quite different. The main scarp to the north showed dominant thrusting with only a small dextral slip component, but the northeasterly branch was characterized by tension openings and strong dextral movement. This separation of the compressional and strike-slip movements along two distinct faults is further evidence that the two movements were separated in time.

The southern bifurcation of the Splinter Fault consists of a southerly trending fault, which persists for only 400 m before disappearing, and a southwest trending branch which continues for about 4 km. The main scarp shows dominant thrusting, with decreasing vertical displacement along its length from a maximum of 25 cm at the centre. The thrust front varies from a slumped, diffuse, protruded scarp, to a sharp roll, and there was an open fracture immediately behind and parallel to the thrust toe.

As in the case of the Meckering Fault, the displacement of fence lines by the Splinter Fault was measured. The location of the observation points is shown in Figure 39 and the measurements in Table 11. The lateral displacements were all dextral and are given uncorrected for the angle at which the fence crossed the fault.

TABLE 11. DISPLACEMENT OF FENCE LINES BY THE SPLINTER FAULT

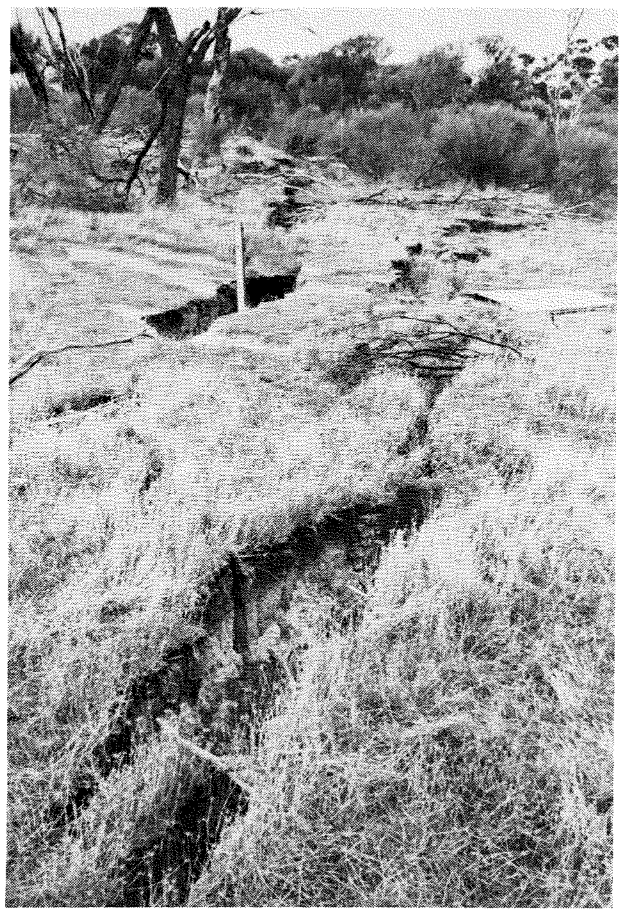
Locality No.	*Lateral displacement (uncorrected) (m)*	*Vertical displacement (m)*	*Heave (m)*	*Angle between fence and scarp*
267	D 0.30	0.30		80°
264		0.37		
263		0.67		
262		0.41		
156	D 0.30	0.46		40°
260		0.24		
257			0.26	40°
153		0.15		
154	D 0.10	0.15		40°
250		0.20		
249		0.10		
152			0.23	40°
151	D 0.20	0.10		60°

THE BURGES FAULT COMPLEX

Twelve kilometres south of Meckering township, the Meckering Fault is abruptly terminated by an east-west fault complex, but resumes its southward course after a 1.6 km westward translation. As a topographic feature, this dextral translation is part of the main scarp of the Meckering Fault complex, and has been named the Burges Fault. Minor branch faults associated with the Burges Fault, have been named the Anterior Fault and the Posterior Fault, and the southwestward continuation of the Burges Fault has been separately named the Robinson Fault. This complex of faulting occurs at the largest of the several dextral translations that offset the trace of the Meckering Fault. A detailed plan of the faulting is given in Plate 3.

THE BURGES FAULT

South of Koolbunine Road, the southward trending Meckering Fault formed a single thrust fault having a well defined west-facing scarp and a subthrust eastern boundary (Fig. 35). As it crossed the corner of location 2119 (Plate 3), however, the fault branched to form a zone about 100 m wide containing north-south trending thrust scarps and numerous east-west trending tension fractures (Fig. 44). These dextral wrenches and tension openings were common within the zone as far as the point where the Anterior Fault branches off to the southwest. Beyond this point, the main scarp continued as a series of anastomosing thrust scarps in a zone about 40 m wide. The end of the southerly trend of the Meckering Fault was marked by a branching to the southeast and southwest, forming a triangular shaped area which was completed by westerly faulting across the base. This triangular zone contained complex thrust and dextral faulting, and from its



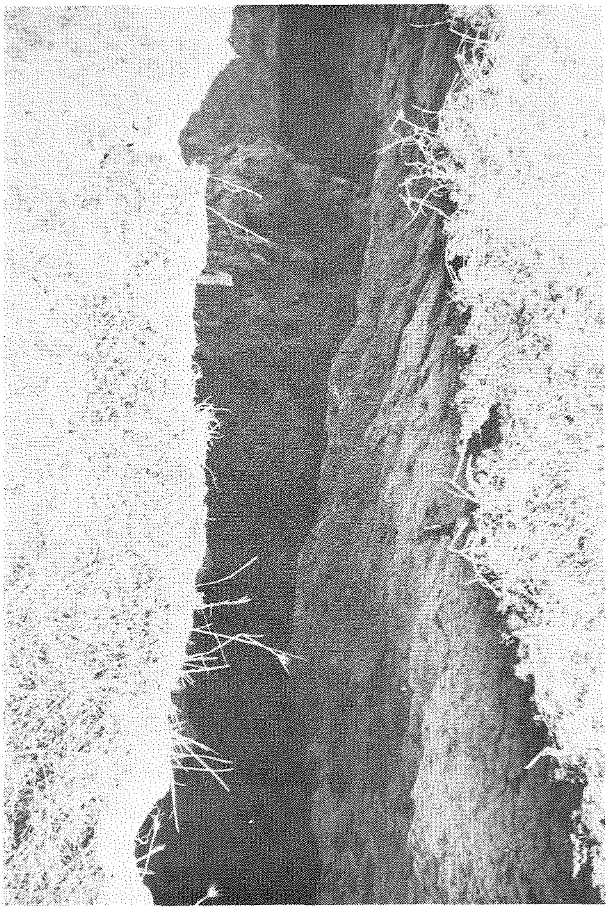
44. Open wrench fractures 880m south of Koolbunine Road. The blocks between the fractures were tilted, with the north side up 30 cm at the eastern end and south side up 45 cm at the western end. Dextral movement along the fractures was about 50 cm.

45. The Meckering and Burges Faults. The smooth scarp of the Meckering Fault in the left centre of the photograph is terminated by the normal Dextral shear of the Burges Fault which shows a broken scarp.

southeast corner the Posterior Fault trended to the east-southeast. The base of the triangle, trending westward, formed the main scarp of the dextral strike-slip fault named the Burges Fault (Fig. 45).

Westward, from the end of the Meckering Fault to Reynolds Brook, the Burges Fault was complex, having two major parallel branches. The southern branch was predominantly a dextral strike-slip fault with only a minor thrust component, whereas the northern branch was predominantly a thrust fault. Westward from Reynolds Brook, there are no branches, and the scarp form indicated a dextral reverse fault. Beyond the point where an extension of the Anterior Fault would meet the Burges Fault, the zone of faulting broadens to about 100 m wide and continues to the most westerly extension of the Burges Fault. From here the 220° trend of the Burges Fault is continued as the Robinson Fault, but the main thrust scarp of the Meckering Fault resumes a south-southeasterly course towards 165°.

The fault plane of the Burges Fault was exposed at two points on the southerly branch of the fault, 107 m northeast of Reynolds Brook, and in the bank of the brook itself. At the first location, the branch fault was a dextral reverse fault having a vertical throw of 20 cm, strike slip of 90 cm, and a fault plane dipping at 75° south (Fig. 46). The fault plane was open, and formed a crevasse 0.46 m wide and at least 3 m deep. Slickensides measured on the south wall of the fault pitched 20° east which, with the fault plane striking at 087° gives a resultant displacement of the fault plunging at 19° towards 093°. At Reynolds Brook, the northern and southern branches form a single fault with the fault plane dipping south at 80° and showing dextral movement of 1.52 m and a vertical displacement of 1.01 m. Slickensides measured at this point showed a resultant displacement plunging at 32° towards 050°. This latter measurement accords well with the cadastrally determined displacement directions along lines 8 and 9 — 43° plunge towards 049°, and 33° plunge towards 037° respectively. The earlier measurements, however, are completely at variance, not only with the overall movement along the Burges Fault, but also with the total movement on the fault at the point where the slickensides were observed. Fault movement at this point appears to have had two separate components, an initial strike-slip movement, which produced the slickensides, followed by vertical movement, which produced the observed configuration of the ground and opened the fault plane. In addition, these observations can be reconciled with the total movement on the fault when they are combined with the movement of the northern branch of the Burges Fault, which was predominantly a thrust fault with minor dextral slip. This situation was rather similar to that observed in the Splinter Fault where the two northern branches also had different types of movement, and is further evidence that fault displacement took place in separate stages.



46. The Burges Fault plane, showing a opening of 45 cm to a depth of about 3 m and a dextral strike slip 90 cm on the broken tree root.

A

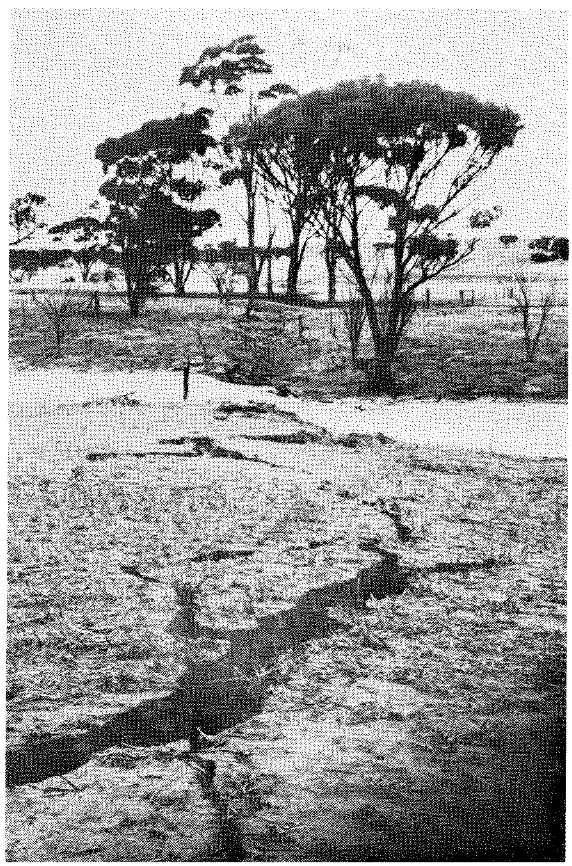
B

47. The Burges Fault:
(a) Displacement of the fence line between locations 2180 and 1479, showing a dextral strike slip of 1.52 m and a throw of 1.03 m.
(b) Main scarp of the Burges Fault west of Reynolds Brook.

This example shows the need for caution when using slickensides as indicators of fault displacement. Unless it is certain that the fault involved is the principal fault, and that all movement took place along it, then slickensides may be misleading.

DETAILED FAULT DESCRIPTION

Plate 3 provides a detailed plan of the surface expression of the Burges Fault. Throughout most of its length, the fault is complex, and no single measurement will give the total movement along the fault. However, the principal movement was a dextral strike-slip of about 1.52 m, as shown by fence displacements at the sections numbered 71 and 71a (Fig. 47a). Westward from the termination of the Meckering Fault, the principal branch of the Burges Fault was a well-defined dextral strike-slip fault; this fault, however, died out about 250 m to the west, and the 1.5 m displacement, measured at 71a was taken up by a series of short tension fractures. The subsidiary fault branch to the north, which joins the end of the strike-slip section to a point about 200 m north along the Meckering Fault, is predominantly a thrust fault with only a minor dextral-slip component and a maximum throw of only 0.4 m. It appears to have formed in the angle between the Meckering and Burges Faults in response to the different styles of displacement along the two faults.



48. The Burges Fault as it crosses Reynolds Brook.

Between Reynolds Brook and the termination of the first strike-slip section of the fault, there are again two branches of the Burges Fault. The southern branch is a high-angle reverse fault with a maximum throw of 56 cm and a small dextral slip of the order of 7 cm. The northern branch, in contrast, is a low-angle thrust fault with an irregular trace and a maximum vertical displacement of 61 cm. The two fault branches join at Reynolds Brook (Fig. 48), but for the final 120 m dextral strike-slip movement in the area between the two faults is indicated by an anastomosing series of open tension fractures.

From the Reynolds Brook to its western tributary, the fault scarp is remarkably straight and is obviously governed by a pre-existing structure which shows as a lineament on air-photos. The scarp form indicated a dextral, high-angle reverse fault having about 1.5 m of dextral movement and 1.0 m of vertical movement of the south side, along a fault plane which dips 80° to the south. The fault trended 043°, and there were numerous oblique tension openings at 065°. The fractures showed small dextral movements of about 3 cm, vertical displacements of about 10 cm, and were often open up to 10 cm (Fig. 47b).

For the remainder of the Burges Fault, beyond the western tributary of Reynolds Brook, the general direction of the fault swung to 065° and its nature changed considerably. The fault consisted of large *en echelon* tension fractures, trending 110°, and interconnecting pressure ridges, trending 035°. The tension fractures were open as much as 50 cm, and, when first observed, some were over 3 m deep. Dextral movements up to 1.0 m were measured on some fractures. Perhaps because of the sudden change in fault direction at West Reynolds Brook, the vertical movement on the tension fractures for the first 150 m beyond the stream were in the opposite sense to that usually observed, and displacements, south side down, of up to 23 cm were measured. Thereafter the normal situation resumed, and the south side was elevated up to 61 cm.

STRUCTURAL INTERPRETATION OF THE FAULT

Throughout the length of the Burges Fault its most prominent surface expression was a series of *en echelon* shears and it was impossible, on field evidence alone, to integrate these into an account of the development of the fault. Tchalenko (1970), however, has shown that the fracture pattern produced by strike-slip faults is similar to that produced experimentally when clay is deformed in a shear box or similar experiment. The order of events can be observed experimentally, and by analogy have been shown to give a good account of the formation of shear zones during faulting (Tchalenko and Ambraseys, 1970).

Experimentally the earliest fractures formed are 'Riedel shears', *en echelon* planes lying at a small angle to the direction of movement, with the acute angle pointing against the relative movement. Tension fractures, at about 45° to the movement, may also develop. After the peak strength of the material has been overcome P-shears are developed, symmetrical to the Riedel shears but with the acute angle pointing along the relative movement. At this point the material has only residual strength and the main displacement becomes concentrated on principal displacement shears which develop parallel to the overall movement and isolate elongate lenses of essentially passive material between them.

Rose diagrams of the fracture pattern of sectors of the Burges Fault, and a key to the nomenclature of the fractures have been included on Plate 3. The simplest pattern, and the one which conforms most closely with experimental data, is obtained for the section between the two arms of the Reynolds Brook. The main movement of the fault has taken place along a single principal displacement shear and the bulk of the minor fractures are seen to be early formed Riedel shears at about 20° to the direction of displacement. A small number of conjugate Riedel shears trending at 150° and P-shears at 070° are also present.

The most complex fracture pattern is present in the eastern part of the fault. The dominant pattern is a pre-residual structure of principal displacement shears enclosing lenses of material which contain earlier formed fractures. In the field it was noted that many of these fractures were tension fractures, without appreciable strike-slip movement, while others were dextral strike-slip fractures. Both groups plot together and trend 120° to 130°, or 30° to 40° from the direction of principal displacement. This angle is too large for Riedel shears, and at 30° too low for normal tension fractures. However, displacement along the main fault was large and it is possible that early formed Riedel shears were rotated to their present position while the pure tension fractures formed later at about 40° to the displacement. P-shears, symmetrical with Riedel shears but formed just prior to the major displacement shears, are present in their expected orientation and trend at 070°, and there are a few pressure ridges, conjugate to the tension fractures, which trend at 050°.

The western section of the Burges Fault, between Reynolds Brook and the southern section of the Meckering Fault, shows an apparently simple pattern of open dextral shears trending at 120° to 130° and pressure ridges at 030° to 050°. The dextral shear fractures are at too steep an angle to be Riedel shears, yet many of them show displacements of up to 0.9 m. There are few fractures parallel to the direction of principal displacement and all movement has been taken up by these *en echelon* fractures. It appears probable that the fractures represent rotated Riedel shears and later formed tension fractures.

For the Dasht-e Bay̅az (Iran) faults analysed by Tchalenko and Ambraseys (1970) the main fractures formed, other than principal displacement shears, were Riedel and P-shears. However, in several respects the fault was different from the Burges Fault. Displacement along the Dasht-e Bay̅az Fault was predominantly strike-slip, the section of the fault studied excluded the fault terminations, and for the most part the fault was covered by thick alluvium. At Meckering the displacement on the Burges Fault was a complex combination of strike-slip and reverse faulting, the Meckering Fault partly determined the fracture at its eastern and western ends, and for the most part hard lateritic sub-soil overlying rock was present within a metre or so of the surface. Only in the valley of the Reynolds Brook was there an appreciable thickness of soil and it was in this section that the fracture pattern conformed most closely to that formed experimentally in clays and naturally in Iran. Nevertheless, the experimental model does suggest an order of formation of the minor fractures which make up the Burges Fault. Riedel shears, at a low angle to the displacement direction, were the first to be formed, and as these were rotated by progressive deformation tension fractures and pressure ridges were formed at about 40° to the displacement. A small number of P-shears, symmetrical to the original direction of the Riedel shears, were then formed, followed by the principal displacement shears along which most movement took place.

THE ANTERIOR FAULT

The Anterior Fault (Plate 3) was the name given to a minor branch fault which cuts across the angle between the northern section of the Meckering Fault and the southwest trending Burges Fault. It was a dextral thrust fault with a maximum strike-slip in the order of 30 cm and a vertical displacement of about 40 cm. The fault commenced at the front of the Meckering Fault scarp, 500 m north of its termination against the Burges Fault, and trended 225° for about 1 km until it reached Reynolds Brook. Throughout its length, it displayed alternate thrust and wrench fault scarps, each about 20 m long; suprathrust and subthrust scarps were common (Fig. 49).

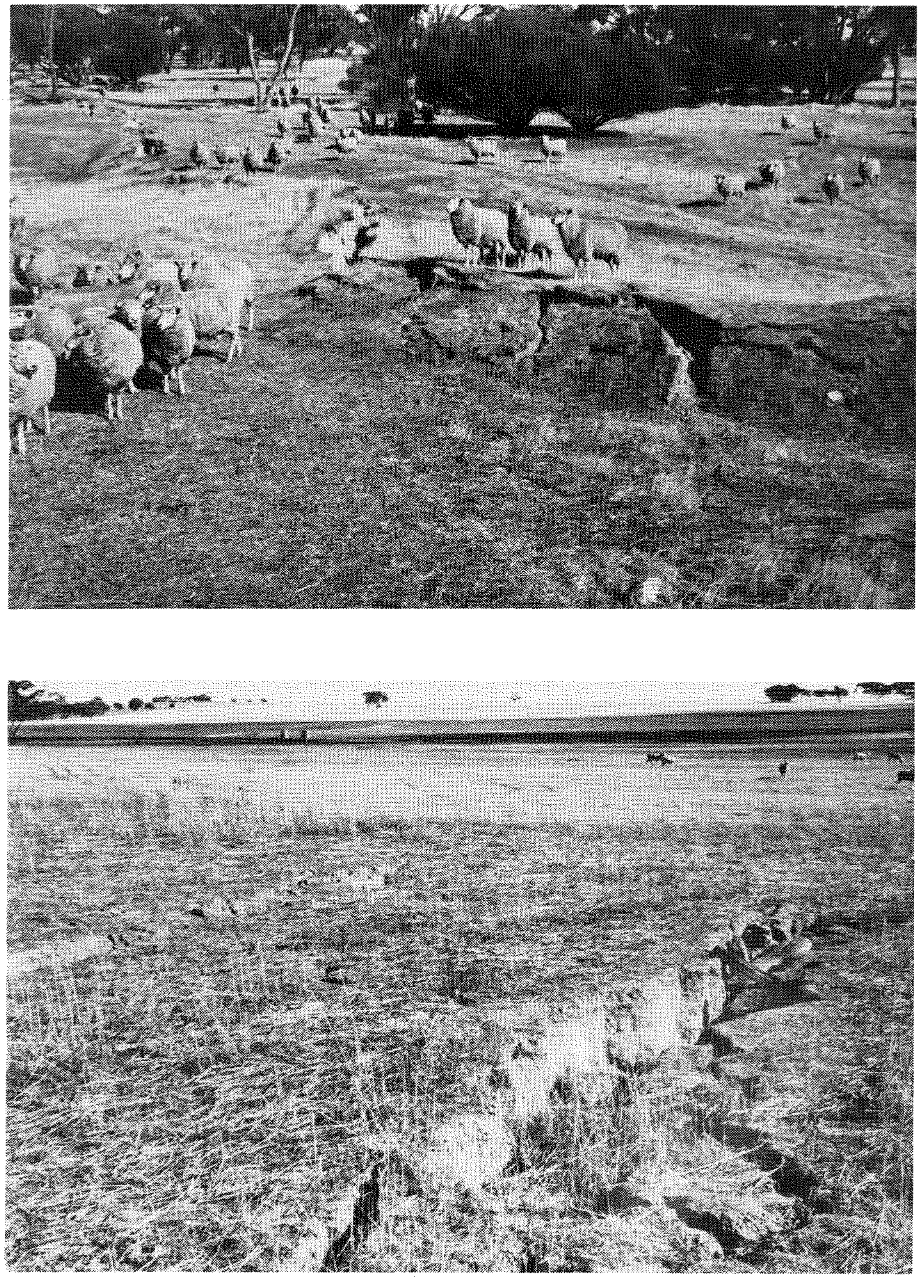
To the southwest, from Reynolds Brook to the angle between the Burges Fault and the southern continuation of the Meckering Fault, the Anterior Fault degenerated into a series of subparallel, transverse tension fractures ranging from a few metres to 250 m long, and separated from each other by about 25 m. The fractures were often open from 2-3 cm and sometimes showed a similar vertical displacement—south side elevated. The fractures near Reynolds Brook, and those adjacent to the Burges Fault showed no lateral displacement, but a central group showed a consistent sinistral displacement of about 3 cm.

The Anterior Fault was probably caused by the differential movement between the northern Meckering Fault and the Burges Fault. The direction of the fault is parallel to the resultant displacement of the Meckering Fault and its movement was probably largely strike-slip and vertical, with only a small northwesterly thrust component. The fracture pattern (see rose diagram on Plate 3) shows that the surface fractures consist of Riedel shears and tension fractures with a conjugate set of compression ridges, and no development of principal displacement shears.

THE POSTERIOR FAULT

The Posterior Fault is the east-northeasterly continuation of the Burges Fault to the east of the Meckering Fault. For the first 250 m it continued the 060° trend of the Burges Fault, but then it bifurcated to form an easterly trending sub-parallel branch. A third sub-parallel branch of the Posterior Fault originated from the point where the Meckering Fault terminates against the Burges Fault. A fourth fault, possibly related to the Posterior Fault, was a remarkable thrust, trending 150° and situated 200 m to the east of the Posterior Fault.

The most northerly fault was a dextral thrust fault, which formed a scarp about 30 cm high and showed a dextral slip of about 8 cm (Fig. 50). The thrust scarp faced north, and, therefore, moved in an opposite sense to that of resultant of the Meckering Fault. To the south of the scarp and parallel with it, were a series of tension fractures, showing minor dextral movement. The middle branch of the Posterior Fault was generally similar to the northern, consisting of a northerly directed thrust scarp with a dextral tension fracture immediately behind it.



A

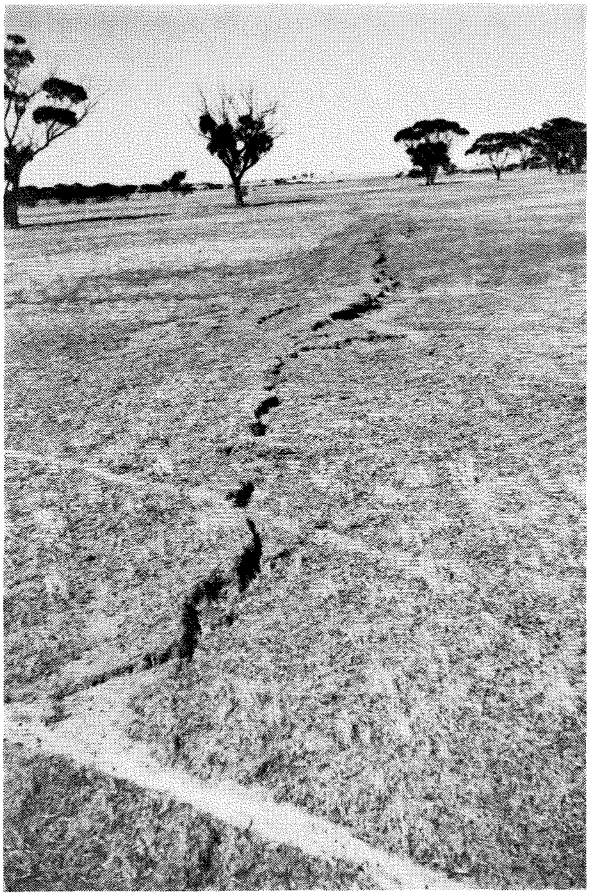
B

49. The Anterior Fault:
(a) Alternating thrust and wrench faulting, giving a zig-zag pattern.
(b) Close-up of a wrench section with dextral displacement of 15 cm, throw of 40 cm to the northwest and the fracture open 12 cm.

The most southerly of the three brances of the Posterior Fault had a variable surface expression. From its junction with the Burges Fault, it appeared as a series of *en echelon* tension fractures each 100 m long and having a small sinistral strike-slip movement; it then became a thrust fault for a further 120 m, overthrust to the north. This was followed by a 200 m-long section of alternate wrench and thrust scarps, with dextral movement and the thrusting directed southward. The fault then continued for a further 1.1 km as a series of tension fractures and short stretches of dextral strike-slip faults of small magnitude (Fig. 51).

The southeasterly trending fault to the east of the Posterior Fault proper was composed of a straight thrust scarp 550 m long and one or two sinistral tension fractures immediately behind the scarp to the southwest. The thrust scarp faced predominantly northeast but certain segments had thrust to the southwest. The maximum vertical movement on the fault was about 23 cm and the sinistral slip about 5 cm. The relationship of this fault to the Posterior Fault is not known.

50. Posterior Fault: The main thrust scarp is in the background, the large fractures to the rear of the scarp were at least 4 m deep, open 30 cm and showed dextral movement of 40 cm and downthrow to the south of 25 cm.

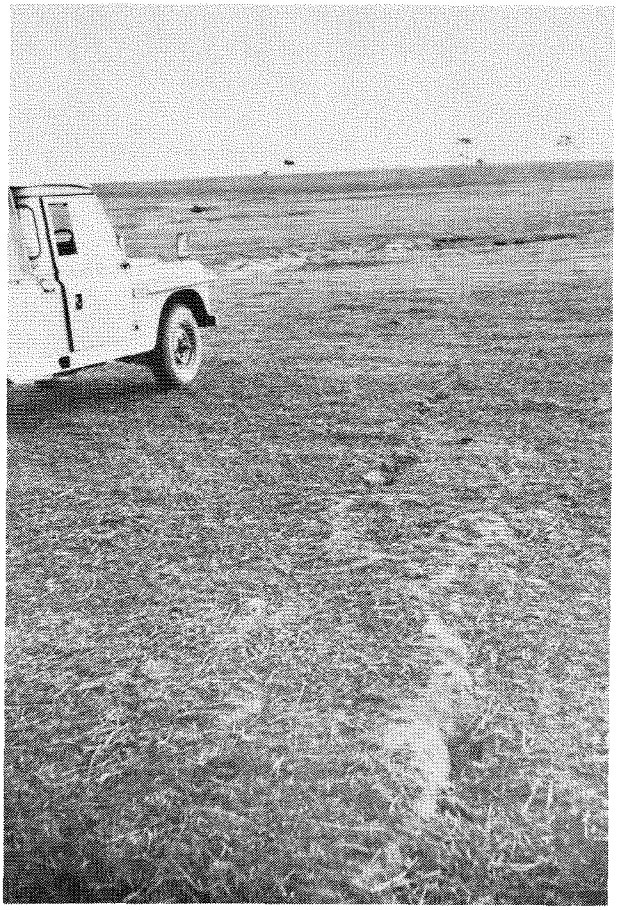


51. Posterior Fault: The most southerly offshoot, showing dextral movement of 7.5 cm, downthrow of 10 cm to the north and a fault opening of 15 cm.

THE ROBINSON FAULT

The Robinson Fault commenced at the western end of the Burges Fault, where the Meckering Fault continues its southerly trend. It continued the trend of the Burges Fault for 3.3 km until it was terminated by branches to the northwest and southeast.

At the scarp of the Meckering Fault, the Robinson Fault was actually a little south of, and parallel to, the Burges Fault, and was possibly related to the tension fractures found in the angle between the two major faults (Plate 3) and which trended 065°. The main section of the Robinson Fault consisted of *en echelon* dextral tension fractures, at an angle of 20° to the fault, and interconnecting pressure ridges at right angles to the fractures (Fig. 52). Movement along the fault was minor, but where it crossed the York Road a pipeline was ruptured during faulting and required an additional 23 cm to repair it.

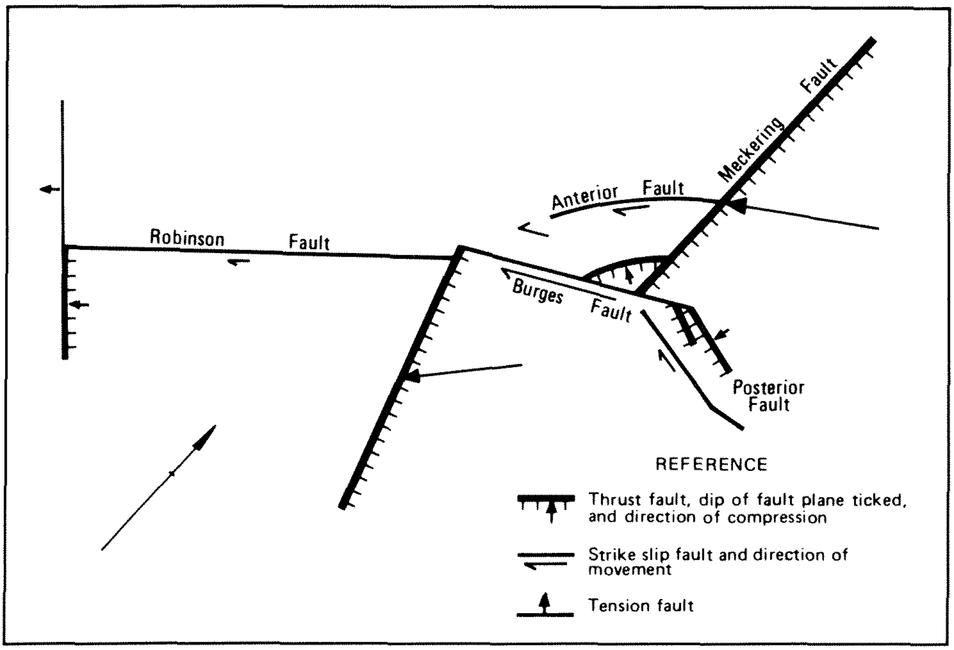


52. The Robinson Fault 400 m west of the Meckering Fault. *En echelon* fractures at 20° to the fault trend and showing minor dextral strike slip.

The cross fracture which terminated the Robinson Fault was different north and south of the fault. To the northwest, *en echelon* tension fractures continued for 2.4 km; they showed no lateral displacement, but were open about 5 cm and their northsides were elevated about 4 cm. The southeast branch, however, developed into a thrust scarp whose north block was 6-9 cm higher than the south block. This sinuous thrust scarp followed a ridge mantled with abundant quartz fragments for 1.6 km before branching into smaller thrusts.

BLOCK MOVEMENTS IN THE BURGES FAULT COMPLEX

A complete analysis of the movement of the various blocks outlined by the Meckering and Burges Fault was not possible without the resurvey of a more detailed series of cadastral points than was available. Nevertheless, by consideration of the lines that were surveyed across the Meckering Fault, and the approximate relative movements



53. Schematic block movement in the Burges Fault Complex.

known for the Burges Fault, some idea of the overall movements can be obtained. Figure 53 is a diagrammatic representation of the faults, on which the relative movements are marked. It is evident from this, that the Burges Fault is more than just an offset of the Meckering Fault: it is an independent fault and a controlling factor in ground movements in the vicinity.

The mobile block to the east of the northern section of the Meckering Fault moved along 229° to form a dextral thrust fault. South of the Burges Fault, the movement was along 217° to form a similar fault. The Burges Fault, however, was a dextral strike-slip fault which trended along 244°. Had the fault been merely parasitic upon the main Meckering Fault, then its trend could be expected to lie between 229° and 217°. The fact that it cuts across the main trend of movement, and is continued into the Posterior Fault to the east and possibly the Robinson Fault to the west, suggests that the Burges Fault is a separate structure which probably existed before the earthquake of 1968. This suggestion is supported by the observation on earlier air-photos of a weak lineament along the trace of the fault.

The differential movement between the northern section of the Meckering Fault and the Burges Fault was probably directly responsible for the formation of the Anterior Fault and the northern branch of the Burges Fault. The Anterior Fault is primarily a dextral strike-slip fault of small displacement, and its trace is parallel to the local resultant of the Meckering Fault. The dextral movement of this fault appears to have been compensated for by the series of sinistral tension fractures between its termination and the Burges Fault. The small thrust fault that forms the northern branch of the Burges Fault is probably only a superficial slice squeezed out between the two major faults. The relative southward movement of the northeast block would also account for the apparent northward overthrusting of the Posterior Fault, which becomes an underthrust rather than overthrust fault.

South of the Burges Fault, the block enclosed between it and the southern extension of the Meckering Fault is seen to contain much less fracturing than the block to the north. This is again consistent with the direction of movement along the Meckering Fault, which would put tension rather than compression on the Burges Fault. It has been noted that the Meckering Fault indicates that movement took place first as a thrust and later as a dextral strike-slip and this, if rotated through a right angle, would be equivalent to a strike-slip movement followed by tensional opening along the Burges Fault. This is, in fact, the condition noted at several points along the Burges Fault and is confirmed by slickensides.

FAULTING IN THE VICINITY OF WILSON STREET

Of the five major dextral translations of the trace of the Meckering Fault, the Burges Fault complex, described in the previous section, is the largest. It is not typical, however, in that a series of prominent faults are associated with it, and because of the size of the offset—1.6 km. More typical is the 300 m offset in the vicinity of Wilson Street, 1.5 km northwest of Meckering townsite (Plate 4).

54. *En echelon* section of the Meckering Fault in the vicinity of Wilson Street. (Photo: B.M.R.)

From the north, the main fault scarp trended 215° until it was displaced 323 m to the northwest, at right angles to its trend, before resuming a southwesterly direction of 225°. Between the two parallel scarps there were two dominantly tensional and strike-slip features, a Frontal branch fault, with a trend of 295° and an Intermediate branch fault with a trend of 257°.

The northern portion of the Meckering Fault scarp consisted of two parallel features 7.5 m to 15 m apart, outlining a compressional arch scarp (Figure 41). To the rear of the scarp there were a few small tensional fractures, only one of which showed any displacement. However, the displacement on this fracture suggested that the fault movement had been a two-stage process. The fault scarp consisted of a normal overthrust toe immediately backed by a subthrust which forced up a wedge of material to form a hummocky ridge. The maximum vertical displacement was not reached until about 5 m behind this ridge, where a tension fracture, open 30 cm and at least 2.5 m deep, was found. A dextral displacement of 40 cm and a downthrow to the west of 40 cm was measured on the fracture. It appears that an initial compressive thrust movement was followed by withdrawal and dextral strike-slip, the collapsed toe of the overthrust block remaining anchored to the lower or western block. This two-stage movement was similar to that deduced from slickensides found on the plane of the Burges Fault.

The estimate of total movements along this section of the Meckering Fault, being a composite of measurements along a 300 m section, were a vertical displacement of the southeast block of 0.69 m upwards, a dextral strike-slip of 1.32 m and a heave towards the northwest of 1.07 m. From these a net displacement of 1.83 m towards 254° can be calculated, the fault plane dipping at 33° and the displacement vector plunging at 22°. This section of the fault graded imperceptibly into the Intermediate branch fault.

The westerly, displaced section of the Meckering Fault commenced at the end of the Frontal branch fault, opposite the termination of the northern section, as a single thrust scarp with a vertical displacement of 13 cm. From Wilson Street to Moore Road, the fault trace was complicated by interaction with the Intermediate branch fault, but beyond Moore Road the Meckering Fault again became a large, single, dextral thrust scarp. Displacement of cadastral boundries at the junction of Moore and Stewart Roads showed that the throw of the fault was 1.22 m, the heave to the northwest was 1.36 m and the dextral strike slip was 0.91 m, giving a net displacement of 2.04 m towards 281° and plunging at 36°, the fault plane dipping at 42°.

The Frontal branch fault joined the two sections of the Meckering Fault and trended at 295°. Although total movement was small, the fault appeared to be a dextral strike-slip fault, and the fault scarp was largely made up of dextral tension fractures, trending 330°, alternating with minor thrust scarps at 260°. The thrust scarps were often coupled in pairs about 3 m apart, one superthrust and one subthrust scarp. The pair was often joined internally by a tension fracture.

The Intermediate branch fault commenced at the termination of the northern section of the Meckering Fault as a series of alternating thrust faults and tension fractures. The general trend of the fault was 257°, coincident with the resultant of movement on the Meckering Fault. The short thrust scarps, which had a small dextral displacement and were sometimes coupled as superthrust and subthrust scarps, trended about 220°; the longer tension fractures ran at right angles to them. Several of the tension fractures showed an *en echelon* pattern, with a sinistral offset between each section. Movement on the Intermediate fault was dextral with tension fractures open up to 8 cm the south side elevated up to 9 cm, and a strike-slip displacement of 15 cm.

For 220 m, the Intermediate fault was well defined, but as it approached the southern section of the Meckering Fault, the fault zone widened to about 250 m to form a triangular area of tension fracturing. Between the end of the Intermediate fault and the Meckering Fault a series of tension fractures trended 310°. These were up to 100 m long, and open about 8 cm; the south side was elevated about 5 cm, and showed a small sinistral strike-slip displacement of up to 15 cm. To the rear of the Meckering Fault scarp, there was a series of short dextral tension fractures, and these were succeeded eastward by six tension fractures up to 240 m long, trending 100°, which made up the remainder of the triangle. Four of these fractures commenced at dextral tension fractures at the rear of the main scarp, and showed dextral-offset *en echelon* faulting, which died out to the east. The most northerly two were more intimately associated with the Intermediate fault and showed sinistral-offset faulting with openings up to 4 cm wide.

The form and pattern of the faulting in the vicinity of Wilson Street was probably the result of the interaction of a pre-existing structural weakness in the form of a radial strike-slip fault, and the resultant direction of movement of the Meckering Fault, oblique to it. There was thus similarity, though on a smaller scale, between the Wilson Street area and the Burges Fault Complex. The Frontal fault was equivalent to the Burges Fault, and like it, shows an extension to the west of the Meckering Fault in the form of a line of *en echelon* fractures, whereas the Intermediate fault was similar to the Anterior Fault as both were parallel to the local resultant of movement along the major fault. In general, the pattern of faulting at Wilson Street was repeated at each of the major dextral translations of the Meckering Fault, which suggests that a similar situation was responsible for each.

THE SUDHOLZ FAULT

The large dextral offsets in the trace of the Meckering Fault, along the Burges Fault, and in the vicinity of Wilson Street, both suggested the presence of radial fractures which governed the trace of the main fault. In both examples small faults were found radiating west from the Meckering Fault, but only the Posterior Fault was known to extend to the west of the fault. The Sudholz Fault was later found adjacent to a small sinistral step in the main fault, and proved to be the largest radial fault within the arc of the Meckering Fault.

Shortly after the earthquake, a series of fractures crossing the Great Eastern Highway about 2.5 km east of Meckering were mapped as tension fractures. Similarly, near a small sinistral step in the trace of the Meckering Fault, 4 km northeast of the town, small tension fractures perpendicular to the fault trace had been mapped, both inside and outside the fault arc. After the main phase of mapping, a study of the morphology of the Mortlock River suggested that the sudden change from salt flats to a narrow channel northeast of Meckering was governed by faulting, and that the channel had been possibly displaced in a dextral sense. An examination of the area in May 1969, seven months after the earthquake, revealed a strong tension fracture about 400 m long which crossed the Mortlock River in the predicted position, and formed a discontinuous feature 4 km long with the fractures already mapped to the northwest and southeast. The fault trended 335°, and was named after Mr F. Sudholz, whose farm it traversed.

Although the fracture was discontinuous, it was sufficiently strong at the Mortlock River to have survived several stream flows that had tended to erode and fill it (Fig. 55). The erosion had obscured the nature of the fault displacements, but there were indications that the movement had been largely sinistral normal, with the west side up and the fracture open up to 4 cm.

The possible importance of the Sudholz Fault is shown by the fact that epicentres of the foreshocks of 29th September and 3rd October 1968 were located in this area, and were strongly felt and caused damage at Mr. Sudholz's farm. The possible relationship of the fault to the mechanism of the Meckering earthquake will be considered further in Chapter 9.

55. The Sudholz Fault in the bed of the Mortlock River. The fracture had been partly eroded and filled in by river flows.

RADIAL FEATURES OF THE MECKERING FAULT

It has been shown earlier that the cause of the sudden dextral translation of the Meckering Fault at Wilson Street and the Burges Fault Complex was a strike-slip fault, radial to the arcuate major fault. It can be surmized that all translations of the fault are similarly caused and several are sufficiently well defined to be able to project the line of radial faulting to the east, where they meet at a point to the southeast of Meckering, and in the Backscarp Zone (Plate 2). Lines used for this purpose were drawn from the Wilson Street and Burges Faults, the northern extremity of the Meckering Fault, the unnamed most northerly dextral translation, and the Sudholz Fault. These lines met above the area of coincidence of projections of the fault-plane dips, 1.7 km southwest of the geometric centre of the arcuate fault.

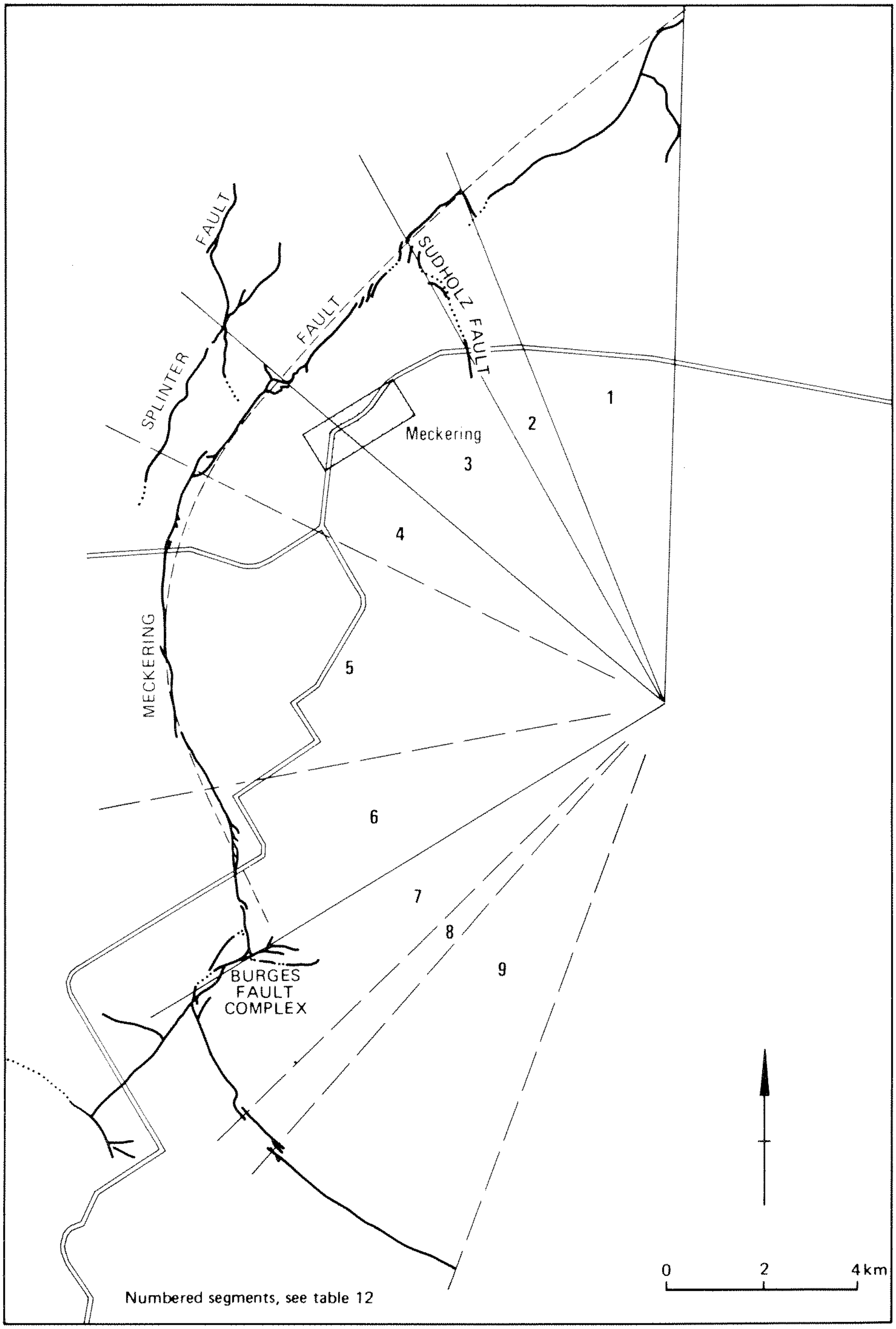
By joining the southern extremity of the fault and all other fault translations to this centre the mobile block of the Meckering Fault is divided into nine segments numbered as in Figure 56. Table 12 lists the diameters of each segment, and it will be seen that the radial distance decreases from north to south until the major dislocation of the Burges Fault is encountered.

TABLE 12.—MEDIAN RADIUS OF SEGMENTS OF THE MECKERING FAULT

Segment	*Radius (km)*
Northern terminal	13.68
Segment 1, median	12.39
2	11.75
3	10.94
4	11.02
5	10.86
6	9.98
----Burges Fault----	
7	12.47
8	12.71
9	12.87
Southern terminal	13.11

South of the Burges Fault, the radius immediately increases by 2.5 km and continues to increase throughout the southern section of the fault. If the Burges Fault is 'removed', the resultant trace of the Meckering Fault would appear to be parabolic. However, the best fit that could be obtained was for the northern section of the fault, and this conformed well to an exponential curve of the form $Y = ae^{bx}$ (Fig. 56).

At Wilson Street and the Burges Fault complex, the radial faults extend outside the arc of the Meckering Fault. Elsewhere, there are a few radial tension fractures outside the arc which are not related to offsets in the main fault scarp. Within the arc, only the Posterior Fault of the Burges complex and the Sudholz Fault were definitely radial, but the other steps in the Meckering Fault were occasionally expressed in the form of discontinuous radial tension openings. These could more readily be called radial cracks rather than faults. Radial breaks of this nature are to be expected on mechanical grounds, as the arcuate mobile block was compressed, sheared off, and expanded westward. It is rather surprising that the maximum expansive movement of over 2 m is not shown by radial expansion cracks along the scarp front itself. The dominant tensional openings associated with the scarp were parallel to it, not at right angles.



56. Radial features of the Meckering Fault.

The radial nature of these faults and fractures implies that they are intrinsic to the mobile block, as pre-existing faults would be unlikely to have a radial pattern. However, in certain localities it is evident that radial faulting has guided the Meckering Fault and therefore must have been present before the earthquake of 1968. An explanation lies in the possibility that the whole of the Meckering Fault complex is a reactivated feature. Formed originally as a secondary fault at the first movement of the Meckering Fault, the radial faults have since acted as guides for further movement.

HISTORIC THRUSTS AND REVERSE FAULTS

Low-angle thrust faults are not uncommon in the geological record of tectonic fold belts, and they are inferred in the deep seated structure below island arcs which provide the most seismically active zones at present. Nevertheless, surface faulting associated with modern earthquakes is almost entirely strike-slip or normal faulting, thrust faulting is decidedly rare. Well exposed thrust faults are even rarer, and in 1958, Richter (p.182) could write that "Except for Tsuya's report on the Japanese earthquake of 1945, there is no good account of a large earthquake producing a surface trace along a low angle thrust".

Reverse or thrust faulting, with some degree of surface expression, has been described from the following earthquakes: Hawkes Bay (N.Z.), 1931 (Henderson, 1933); Mikawa, (Japan), 1945 (Tsuya, 1946); Kern County (California, U.S.A.), 1952 (Bulwada and St Amand, 1955); Gobi-Altai, (Mongolia), 1957 (Florensov and Soloneko, 1965); Montague Island (Alaska, U.S.A.), 1964 (Plafker, 1967); Inangahua, (N.Z.), 1968 (Lensen and Suggate, 1968).

HAWKES BAY, NEW ZEALAND, 1931

The Hawkes Bay Earthquake of 3rd February 1931 was New Zealand's most damaging earthquake, causing enormous loss of property and 256 deaths (Callaghan, 1933). The earthquake had a magnitude of 7.9 and caused a northeast trending block 96 km long by 16 km wide to be uplifted as much as 2.4 m. At the southern end of this block, a few kilometres southwest of Hastings, thrust faulting was observed in the Poukawa Valley, The main thrust faults, trending northeast, were 5.6 km and 1.6 km long and were joined by an east-trending wrench fault 1.6 km long. Although movements along the faults were of the order of 2 m the fault plane was nowhere observed, and it was believed that the movement was along bedding planes which locally dip 20° to the northwest. Henderson's (1933) description of the surface expression of the faults has already been given.

MIKAWA, JAPAN, 1945

The thrust fault formed after the Mikawa Earthquake of 13th January 1945 was named the Fukozu Fault by Tsuya (1946). It consisted of an east-west section about 5 km long and a southerly trending section about 4 km long. The earthquake appeared to have reactivated an older thrust fault dipping at 50° to 70°. Total movement was in excess of 2 m, and at several points the fault plane was exposed and could be measured directly. Where the fault cut subsoil or Quaternary deposits the dip was reduced to 15° to 20°.

KERN COUNTY, CALIFORNIA, 1952

The earthquake of 21st July 1952 in Kern County, California, was of interest not only because of its widespread destructive effects, but because it proved that the 51 km long White Wolf Fault was active, and unlike other major Californian faults was a reverse fault. At depth the northeast-trending fault is straight, and shows an uplift to the southeast of about 3 000 m. Faulting after the earthquake was complex, and mainly confined to a 19 km section in poorly consolidated landslide material at the foot of Bear Mountain. Relevelling showed that the Bear Mountain block had been uplifted about 60 cm and that there had been some sinistral movement along the fault (Whitten, 1955), which disposes of the possibility that the observed faults were reactivated slides. The fault trace was often curved, indicating a low-angle thrust, and there were numerous oblique strike-slip faults. Nowhere was the main fault plane exposed at the surface, but the photographs of thrust scarps, tension fractures, and offset fence lines presented by Bulwada and St Amand (1955) are very similar to those taken by the present authors after the Meckering earthquake.

The White Wolf Fault disrupted several tunnels of the Southern Pacific Railroad (Kupfer et al., 1955), and revealed a thrust fault in diorite that dipped at 30° to the southeast. The seismic evidence, however, indicates that the fault plane dips about 63° (Gutenberg, 1955). It is possible that the observed faulting represents only a superficial slice of quartz diorite, detached because of differential movement between the White Wolf Fault and the nearby Edison Fault, or by the general north-south crustal shortening in the region. In a generalized map of the area, Hill (1955, Figs. 1 & 2) shows a number of low-angle thrust faults with traces similar to that of the Meckering Fault, which represent superficial slices produced by differential movements along the major transcurrent faults of Southern California.

GOBI-ALTAI, MONGOLIA, 1957

Perhaps the largest earthquake associated with reverse faulting has been the Gobi-Altai earthquake of 4th December 1957. Situated in southwestern Mongolia it had a magnitude of 8.6, and resulted in 850 km of faulting, the longest being the Bogdo Fault of 265 km. The area was previously thought to be seismically inactive but the investigations of Florensov and Soloneko (1965) suggests that the area is subject to periodic large earthquakes rather than a larger number of moderate events. Reverse strike-slip faults characterized the activated structure of the 1957 earthquake. Vertical displacements of about 3 m and sinistral strike-slip of 6 m were common along much of the Bogdo Fault, reaching a maximum of 8.85 m at one point. The plane of the major fault dipped at about 65°-70°, but several thrust structures which formed obliquely to the main fault showed fault planes dipping as little as 30°. The form of the fault scarp of these low-angle thrusts was often similar to those at Meckering. In unconsolidated recent sediments, a structureless 'roll' with parallel tension fractures to the rear, was formed, and where bedrock was near the surface the overhanging part of the thrust often collapsed. Florensov and Soloneko (1965, p. 295) also note that, in places, clay material was squeezed out from below by the thrusting movement.

ALASKA, 1964

The Alaska Earthquake of 27th March 1964 had a magnitude of 8.4, and was centred at the head of Prince William Sound, 130 km east of Anchorage. The earthquake affected an area of 260 000 km^2, and the associated landslides and seismic sea waves caused the loss of 114 lives, and at least $US 310 million of damage (Hansen and others, 1966). A northwest-trending zone at the head of the Gulf of Alaska, 950 km long and and up to 400 km wide, underwent uplift or subsidence. The average uplift was about 2 m, but in places was as large as 11.6 m; maximum subsidence was about 2.5 m. Horizontal displacements were more uniform throughout the area, and were directed towards the southwest; the maximum measured displacement near the centre of the zone was 19.62 m.

Despite the fact that vertical and horizontal movements were more extensive than any known to have been related to a single tectonic event (Plafker, 1969, p. 8), surface faulting was small. Superficial fractures, landslides, and clastic extrusions were common throughout the area (Foster and Karlstrom, 1967), but faulting was confined to two small reverse faults on Montague Island, on the axis of the tectonized zone (Plafker, 1967). The Patton Bay Fault was about 35 km long, had a strike of 037° and a maximum uplift of the northwestern block of about 7 m. The fault plane commonly dipped 60°-85° to the northwest, but in places the dip was as low as 50°. Movement was almost entirely dip slip, with a maximum sinistral strike slip of 0.6 m. The Hanning Bay Fault, 10 km northwest of and parallel to the Patton Bay Fault, was only 6.4 km long, and showed similar characteristics to the larger fault. The maximum uplift along the steeply dipping thrust fault was about 5 m, and there was a small sinistral strike slip of 0.3 m or less.

The similarity of the geology on either side of the Montague Island faults suggests that they are not the primary faults along which the earthquake originated. Focal plane studies of the earthquake suggest that it was generated on a major thrust fault dipping at only 14° and striking 061°. The model adopted by Plafker (1969, pp. 63 ff.) relegates the Patton and Hanning Bay reverse faults to the status of secondary fractures caused by a major underthrust from the Aleutian Trench.

INANGAHUA, NEW ZEALAND, 1968

The northern portion of the South Island of New Zealand has been the site of the formation of two reverse fault scarps. The West Nelson (Murchison) Earthquake of 1929 produced an uplift of about 4.9 m and sinistral strike slip of 2.4 m along a reverse fault dipping about 64° (Henderson 1937). The fault had been previously mapped, and named the White Creek Fault. On 23rd May, 1968 a second earthquake occurred 20 km west of the White Creek Fault, at Inangahua Junction. The earthquake had a magnitude of 7.0 and a focal depth of about 12 km (Adams and others, 1968), and regional surveys showed that an area of about 1 000 km^2 had been uplifted by an average of 1 m (Boyes, 1971; Lensen and Otway, 1971). Two small fault traces were produced, at Inangahua, and 9 km south at Rotokuhu (Lensen and Suggate, 1968). The Inangahua Fault was 1 km long and showed a maximum vertical displacement of 40 cm, a crustal shortening of 10 cm, and a sinistral strike slip of 19 cm. This fault was tentatively identified as a reactivation of the Glasgow Fault, a major fault of the region. The Rotokuhu fault trace extended over 1.5 km, and was associated with a crustal shortening of about 50 cm and vertical and dextral displacements of about 1 m, and appeared to be a conjugate shear of the Inangahua Fault along the bedding planes of sedimentary rocks. The calculated dip of the faults was 76° and 63° respectively, and their main surface expression, in thick soil with a tough grass mat, was a compressional roll. The larger Rotokuhu trace also showed tension cracks perpendicular to the fault.

SUMMARY AND COMPARISON WITH MECKERING 1968

Faulting described in the previous paragraphs has been largely high-angle reverse faulting. The Mongolian fault was a surface expression of a major structural element of the region; and the New Zealand, Japanese, and Californian examples were all due to the reactivation of major faults. In each case, the fault trace was linear, and the fault plane dipped at angles of 50°-85°, usually near the higher value. The only faulting connected with a low-angle thrust was that on Montague Island, Alaska. The visible faults conformed to the previous examples, but it was inferred that they were secondary features related to a low-angle megathrust beneath the Aleutian Island arc.

In contrast, the Meckering Fault trace was arcuate, dipped only 43° and was connected with no known major fault. The mobile block could be outlined with some degree of presision, bounded as it was by the Meckering Fault to the west, and the Backscarp Zone to the east (Chap. 6), and limited in depth by the fault plane to a superficial saucer shaped segment. In the other examples cited, the mobile block was not limited in this way, and the three-dimensional shape of the deformed block could not be simply determined.

The Meckering Fault, however, did have certain similarities to some of the secondary features of the previously recorded reverse faulting. The Poukawa thrust, a secondary bedding-plane fault activated by the Hawke's Bay earthquake, showed a curved trace, and its two sections were joined by a transcurrent fault equivalent to the Burges Fault. In California, the steeply dipping White Wolf Fault appeared to become shallower near the surface, to give a fault trace similar to that at Meckering, and following the Gobi-Altai earthquake, some minor branches of the Bogdo Fault were low-angle thrusts which formed scarps similar to those at Meckering.

Thus, the Meckering Fault is not unique except that it cannot be correlated with a known major fault in the region. However, this point will be considered later when discussing possible mechanisms for the earthquake (Chap. 10) where it will be shown that a reasonable explanation is a deep seated fault or shear zone.

CHAPTER 6

Primary effects on terrain—earthquake generated faults

The previous chapter described the major thrust faults that were caused by the earthquake of 14th October. The faults were characterized by their large movements and the formation of prominent fault scarps; and were caused by the release of elastic strain. In contrast, the group of faults considered in this chapter, although often of great extent, were characterized by small movements, and a lack of prominent topographic expression; they developed either immediately following or over a period of weeks and months following the principal earthquake. One fault was shown to have extended itself over a period of 22 months, and in other faults this development was suspected, but could not be proved. This secondary faulting was undoubtedly caused by elastic creep in the mobile block and was connected with the aftershock sequence. However, the lack of precision in the determination of the aftershock epicentres did not allow individual shocks to be tied to the development of particular faults.

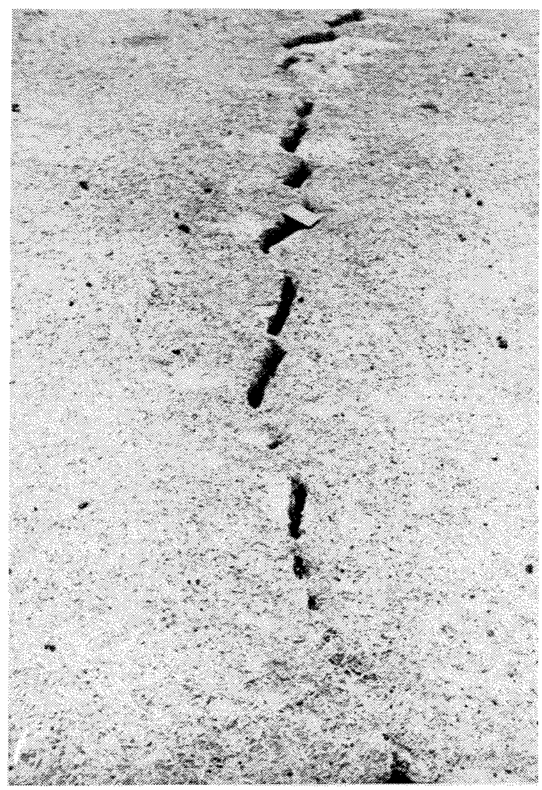
Secondary faulting as a result of elastic creep is probably common in the vicinity of any major fault that has been activated by an earthquake, but because most faults are relatively straight their presence may be obscured by their closeness to the major fault, and when recognized their relationship to the major fault may not be determinable. At Meckering, the major faulting was distinctive in having an arcuate trace and a shallow-dipping fault plane, with the result that secondary faults were separated from the main fault, and their relationship to it could be determined.

Although some secondary faulting could have occurred in the stable block to the west of the Meckering Fault, all the observed faults were in the mobile block, and were enclosed by the extremities of the major fault.

THE CHORDAL FAULT

A fault having a small dextral and normal displacement was traced for over 13 km from a point near the Meckering Fault, 9 km south-southwest of the township, to where it disappeared in salt flats 4 km northeast of Meckering. It trended, with few deviations, 030°, and thus formed an almost complete chord across the arc of the main fault trace. The fault was named the Chordal Fault from its superficial geometric relationship to the Meckering Fault.

A



B

57. The Chordal Fault:
   (a) *En echelon* faulting at the southern end, with raised scarp and uplifted fingers of material between the fractures.
   (b) Close-up of one of the fractures.

FAULT DESCRIPTION

The Chordal Fault was divided into two sections having slightly different characteristics, a southern, continuous section, which was dominantly dextral strike slip faulting with a lesser tensional or normal component, and a discontinuous northern section with dominant tensional fractures and only minor dextral strike slip movement.

The southern section of the fault could be traced for 6.5 km northwest from the York Road, adjacent to the point where the Meckering Fault changed direction from its arcuate course to follow a southerly path. There was a gap of about 250 m between the southern termination of the Chordal Fault and the trace of the Meckering Fault, but in the area between the two faults there were numerous minor tension fractures. Displacements along this section of the fault were up to 23 cm of dextral strike slip and 15 cm of normal dip slip, with the west block down relative to the east.

Farther to the north, in the central portion of the Chordal Fault, the displacements remain dextral normal, but the fault had 'scissored', and the west side was now elevated up to 5 cm with respect to the east. In this section, the type of faulting changed to become characteristically *en echelon* stepped left, and with a dextral movement up to 8 cm showing clearly in the individual wrenches. Individual wrenches were from 18 m to 45 m long and trended 30° to the east of the fault direction; they were connected by strong compression ridges up to 9 m long and 23 cm high (Fig. 42b and 57a). The compression ridges were at right angles to the wrench faults, and their fault planes generally dipped to the east. The Chordal Fault in this section therefore had a characteristic zig-zag pattern and a general trend of 040°. As a result of the lateral displacement, the wrench sections were open fractures from 2.5 cm to 10 cm wide, and often displayed a minor zig-zag pattern themselves.

The northern section of the Chordal Fault was a discontinuous series of tensional fractures, open up to 13cm, with only a minor dextral strike slip movement. Often there were two parallel or diverging fractures in a narrow zone up to 10 m wide, which had sometimes subsided to form a graben-like depression. At its northern end, the Chordal Fault curved northwards towards the Meckering Fault, and lost its surface expression in an area of salt flats. At its termination, the Chordal Fault is on line with, and only 2.5 km from, a major dextral translation of the Meckering Fault. It is possible that a radial fault connected with this translation caused the termination of the Chordal Fault, but it should also be noted that 6 km to the northeast, and on line with the main trend of the Chordal Fault, the Meckering Fault changes abruptly to an 030° course for its final 3 km. It was noted earlier that the southern end of the Chordal Fault was adjacent to a change of course of the Meckering Fault trace, and it appears possible that the presence of the Chordal Fault was major determinant of the course of the main fault.

Throughout most of its length, the Chordal Fault consisted of a single feature, but there were a few short fault branches at 90° or 60° to its trend, particularly towards its southern end. There were also several minor, secondary faults, parallel to it and up to 1.2 km long.

DEVELOPMENT OF THE FAULT

The Chordal Fault was the first of the secondary faults which indicated that fault movements continued after the main earthquake of 14 October. The fault was first noted six weeks after the appearance of the Meckering Fault scarp when a report was received of a considerable length of tension cracking in fields 6.5 km south of Meckering and to the east of the York Road. The fields had been visited regularly by a farmer who believed that he would have seen the rather conspicuous faulting if the openings had appeared at the time of the main earthquake. However, the fault trace was on line, although not continuous, with tension fractures across the Great Eastern Highway. This particular feature, consisting of two tension openings, had been repaired by the Main Roads Department maintenance crew a week after the earthquake. A week later, this fresh seal has been broken and a third fresh crack had appeared, all within a distance of 10 m. A further observation of this feature, ten days later, revealed subsidence between the two outside openings forming a graben-like depression. The new fractures showed openings up to 1 cm wide and normal faulting with a small dextral component.

The agricultural area is moderately well populated, and at the time, farmers were keen observers of earthquake damage, and ready to report all occurrences to the authorities. The fact that the main section of Chordal Fault was not observed for six weeks does not prove that it did not exist. Continuing movement along the fault could be demonstrated from periodic observations of the highway intersection, and it is possible that the fault extended itself southwards over a five or six week period.

MAJOR TENSION FAULTS

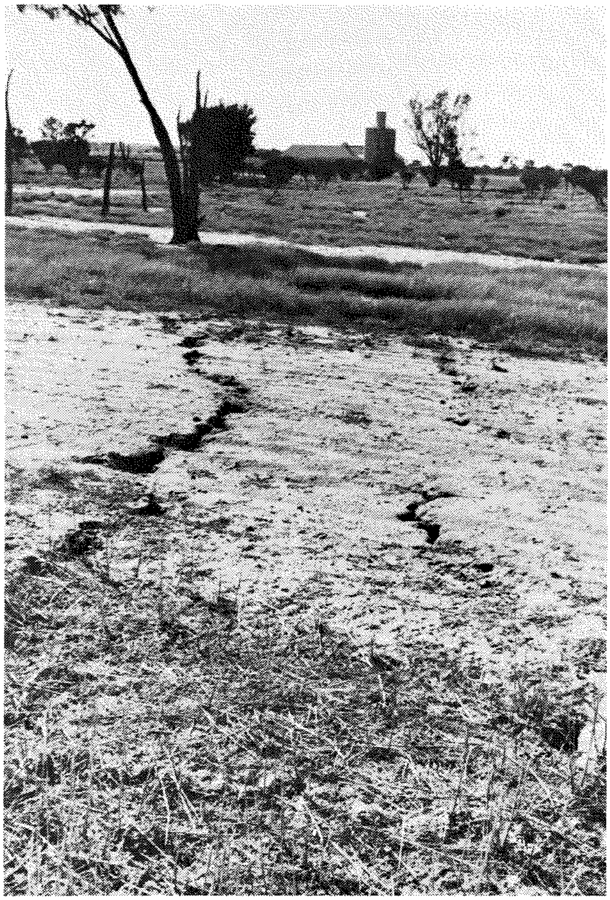
The Chordal Fault isolated a segment, up to 5 km wide, of the mobile cap, and contained a number of major tension fractures. The tension faults were generally parallel to the Meckering or Chordal Faults and varied from 10 m to 5 km long.

The larger faults consisted of up to three open *en echelon* fractures, with dextral offsets between the fractures, and small vertical displacements. Another characteristic pattern was that of a subsided block or graben between two parallel fractures which opened up to 5 cm and were about 2.5 m apart leaving the central area depressed about 7.5 cm. Single fractures might be open as much as 7.5 cm, and the west side was generally elevated about 3 cm.

Small tension faults were quite common throughout the segment, and were quite unlike the 'crevasses' which formed immediately behind the main fault scarp as a result of the flattening of the dip of the Meckering Fault in poorly consolidated soils. The tension faults were particularly well seen on tar-sealed roads.

At least one of these major tension faults was apparently formed during an aftershock on the day following the principal earthquake. The opening of the fracture disrupted a pipeline, distorted the new concrete horizontal grain silo northwest of the township, and cracked its floor.

The aftershock occurred about 5 am on the morning of 15th October, and a tension fault 5 km long, parallel to the Meckering Fault, and 1.4 km east of it, appeared. The surface expression of the fault generally consisted of two or three parallel openings up to 3 m



58. Subsidence graben 2 m wide and 5 cm deep on a major tension fault 2.5 km west of Meckering. The continuation of this fracture disrupted the floor and walls of the horizontal grain silo in the background.

apart with a depression or graben between them (Fig. 58). The fractures were open 4 cm, the graben depressed about 13 cm, and there was no lateral movement. In some areas, the graben structure was replaced by a single strong continuous feature, downthrown 4 cm to the east, and in places by a set of *en echelon* fractures up to 2.5 m long and stepped right.

THE BACKSCARP ZONE OF FAULTING

On each of four dirt roads eastward from Meckering, a zone of normal faulting and slumping was encountered 9 km to 12 km from the town. On each road the clay surface was broken by up to fifty individual fault fractures occupying a distance of up to 3 km. On the Great Eastern Highway, 11 km east of Meckering near Waeel, and within a 4-km-wide zone which was later shown to be depressed up to 8.9 cm below its pre-earthquake level, the bitumen seal was broken in two places. At the northern extremity of the Meckering Fault, a zone of slump-like, but linear, faulting extended for over 2 km in a southerly direction. Unfortunately, the area between the roads was underlain by residual sand and covered by natural vegetation or crops, and only occasional slump-like depressions were visible at the surface. Nevertheless, the features outline an ill-defined zone of normal faulting and slumping which joins the two extremities of the Meckering Fault (Plate 2) and probably marks the extent of the depressed area which was discovered east of the fault during the relevelling of the region by the Lands and Surveys Department. The zone marks the eastern limit of observed faulting and the eastern margin of the mobile block of rock which gave rise to the Meckering Fault, it has, in consequence been named the Backscarp Zone.

No overall account of the Backscarp Zone can be given because of its poor surface expression. However, the individual groups of faults can be described, leaving a detailed consideration of the levelling profile along the Great Eastern Highway to a later chapter.

SLUMP FAULTING AT THE NORTHERN END OF THE MECKERING FAULT

Towards its northern end, the Meckering Fault curved northwards and trended 030°. About 1.5 km before the fault scarp terminated, an arcuate fault, concave to the west, branched southward along a trend of 165°. The branch fault, 1.8 km long, appeared as a zone of fracturing about 2.5 m wide containing six to ten sub-parallel cracks. The fractures formed a series of alternating concave and convex curves giving a sinuous southerly trace, whose west side was almost always down with respect to the east. The zone of fracturing often formed a shallow trough of minor graben-like subsidence between adjacent cracks which were open as much as 2.5 cm. A fence line was displaced a few centimetres in a sinistral sense by the fault zone. To the east of the fault just described, and, between it and the Great Eastern Highway 9 km to the southeast, there were at least ten areas of discontinuous, minor normal faulting. As many as sixteen separate faults in each area trended northerly over a total length of about 200 m, each having its west side down. The faults appeared to be vertical, and there were often alternating compression ridges and tension openings in each group. The individual faults trended about 030°, and the groups of fractures had a general trend of about 340°.

DEPRESSED AREA ALONG THE GREAT EASTERN HIGHWAY

About 12 km east of Meckering, on the Great Eastern Highway opposite Waeel railway station, a pronounced dip in the road and a break across the bitumen seal appeared after the earthquake. This was on line with the trend of minor normal faulting to the north.

The levelling profile obtained by the Lands and Surveys Department (Fig. 69) showed that the uplift at the Meckering Fault scarp decreased regularly eastward until at 43.4 km from Northam the ground was depressed below its former level. The depression reached a maximum of 8.9 cm and the pre-earthquake level was not resumed until 49.8 km from Northam. The 43 km mark is on strike with the minor south-trending fault at the northern end of the Meckering Fault and coincides with two small cracks in the Great Eastern Highway, while the larger fracture at Waeel is 48 km from Northam.

Local residents were firmly convinced that the whole of the Great Eastern Highway east from Meckering to Cunderdin had been considerably altered by the earthquake. However, the tar seal had been disrupted in only six places, four of them to the west of the Chordal Fault and within a few kilometres of the town. In the months subsequent to the earthquake the seal failed by crazing and cracking in many areas but this probably resulted from secondary consolidation after the seismic shaking rather than tectonic movement.

FAULTING ALONG LEEMING ROAD

Continuing southward from the depressed zone of the Great Eastern Highway, there were many small faults which could only be seen on the compacted surfaces of dirt roads. Individual faults were small and generally trended between north and northeast. Movement along the faults was dominantly normal, the west side downthrown and the fault plane vertical or dipping steeply to the west. On one group of faults a small sinistral strike-slip displacement was noted.

Leeming Road, 7 km to 10 km southeast of Meckering provides an example of this type of faulting, and the faults are summarized in Table 13.

TABLE 13.—NORMAL FAULTING ON LEEMING ROAD, SOUTHEAST OF MECKERING

Cluster	*Distance from Meckering (km)*	*Trend*	*Width of cluster (m)*	*No. of faults*	*Total displacement (cm)*	*Fault opening (cm)*	*Apparent dip*	*Lateral movement*
1	7.08	020°	1	3	15		Vertical?	
2	9.23	018°	20	7	15	9.5	Vertical to steeply W	
3	9.25	030°	40	8	20		75° W	Sinistral
4	9.66	019°	1.8	3	13		Vertical to steeply W	
5	9.82	018°	2	6	30	7.6	Steeply W	
6	9.90	012°	1	3	15		80° W	

TOTAL: 30 normal faults, west side down 108 cm

The total apparent downthrow of over 1 m on 30 faults is considerably greater than that found by the relevelling of the Great Eastern Highway. However, it is probable that much of the apparent down throw to the west resulted from an easterly tilt of many of the small blocks separated by parallel faults.

Similar zones of largely parallel normal faults, west side down, were found on nearby Moore and Hardy Roads. It was expected that similar faulting would be found on Bulgin Road, between Leeming Road and the Great Eastern Highway, but the road was graded immediately after the earthquake and faulting was not discernible. The faulting in Moore Road provided the only example of structure directly affected by the Backscarp Zone of faulting—a farm house which was totally destroyed. Later, six small normal faults, trending 320°, the south side up 2.5 cm on each, were found crossing the road and cutting the foundations. Fault movement in this area was undoubtedly damaging, but the seismic shaking, so close to the source of the earthquake would also have been sufficient to overthrow the building.

59. The Backscarp Zone: minor faulting on road 12865, 14 km south-southeast of Meckering.

FAULTING ALONG ROADS 12865 and 13400

A prominent group of small normal and reverse faults was found on Roads 12865 and 13400, 4.8 km north of the southern end of the Meckering Fault (Fig. 59). The faults were dominantly northwest trending with subordinate northerly and westerly trends, they were usually normal faults dipping steeply to the west or vertically. As with the Leeming road faults, downthrow was usually to the west, and a few showed sinistral strike slip. The observed faulting extended for about 2.3 km southeast along Road 12865 and for 1.2 km southwest on Road 13400, and is summarized in Tables 14 and 15.

The net effect resulting from this zone of normal faulting was subsidence having a small sinistral strike-slip movement. Again, because of the slight rotation and easterly tilt of many small blocks separated by parallel faults, the total apparent throw of the faults was much greater than the real subsidence.

TABLE 14. FAULTING ON ROAD 12865, SOUTHEAST FROM JUNCTION WITH ROAD 13400

Distance (km)	*Number and type of fault*	*Trend*	*Displacements*
0.0	3 tension	360°	
0.2	8 reverse in 20 m	290°	West side up, 1.3 cm to 2.5 cm each
0.3	4 normal	290° to 320°	East side up 2.5 cm
	17 normal		East side up
0.5 to 0.6	normal faults diminish, tend to become reverse 16 normal	200° to 312°	Each open 1.3 cm, with 1.3 cm vertical displacement
0.8	10 normal (1 m apart)	220°	East side up
	4 normal sinistral	220°	East side down 5 cm each, 2.5 cm sinistral
	3 normal	300°	East side up 20 cm total, fence broken
1.4	1 long tension fracture	190°	
1.5	5 reverse	280°	Minor
1.6	10 normal (in 50 m)		Minor
1.9	1 tension	200°	
	1 normal	320°	
2.1	18 normal	247°	South side up, total about 25 cm, open 12 cm
2.2	15 sinistral	285°	Open 1.2 cm, cranked left
2.3	10 normal	285°	South side up, open to 1.3 cm

TABLE 15. FAULTING ON ROAD 13400, SOUTHWEST FROM JUNCTION WITH ROAD 12865

Distance (km)	*Number and type of fault*	*Trend*	*Displacements*
0.1	5 tension fractures	360°	Open 0.3 cm to 0.6
0.2 to 0.3	50 tension fractures	328°	Open 0.6 cm each
0.5	5 tension fractures	310°	
0.6	5 normal	350°	East side up
0.8	5 normal	322°	East side down
0.9	18 normal (two sets)	007° & 287°	East side down, some east side up
0.9 to 1.0	4 normal	350°	East side up
1.0 to 1.1	6 strong normal	310°	East side up, 1.2 cm each
	28 normal	350°	East side down, 0.3 cm each
	6 tension fractures	360°	

SIGNIFICANCE OF THE BACKSCARP ZONE

The Backscarp Zone of faulting marks the eastern limit of known ground breakage and movement. Joining the ends of the arcuate main fault scarp it marks out a mobile block of some 230 km^2. With most faulting, it is not possible to delimit the extent of ground movement, either relatively or absolutely, without an accurate resurvey of the area, and this is not always possible. At Meckering, however, the main thrust fault and the Backscarp Zone outline a segment which contains all the major faulting except the Splinter Fault. This suggests limitations on the ultimate extent of the Meckering Fault itself, the three dimensional shape of the mobile block, and the mechanism of the earthquake and faulting. The last point will be considered in detail in Chapter 9, but it would appear that movement on the shallow-dipping Meckering Fault was terminated at the Backscarp Zone which represented a major tension feature, and that the mobile block formed a superficial cap of rock which extended to no great depth. This is consistent with the shallow epicentral depth of 7 km or less.

If the Backscarp Zone is taken into account, then movement of the mobile block fits a relatively simple form. Elevation of the mobile block at the Meckering Fault is compensated by a depressed zone at the Backscarp about 4 km wide. Similarly, the compressional heave seen at the Meckering Fault is compensated by tensional normal faulting in the Backscarp Zone. Strike-slip movement, prominent at the Meckering Fault scarp, decreased eastward towards the geometric centre of the arcuate fault. At the Meckering Fault, the maximum strike-slip was a little over 1 m in a dextral sense, at the Chordal Fault the movement was a maximum of 23 cm and still dextral. In the Backscarp Zone, strike-slip movements were a maximum of a few centimetres and in a sinistral sense. The mobile cap thus appears to have moved southward and to have rotated about the geometric axis of the main fault trace. In total the overall movement of the mobile block can be described by two concurrent rotations, anti-clockwise in the horizontal plane and clockwise in the vertical plane when viewed from the south.

THE KOOLBUNINE FAULT

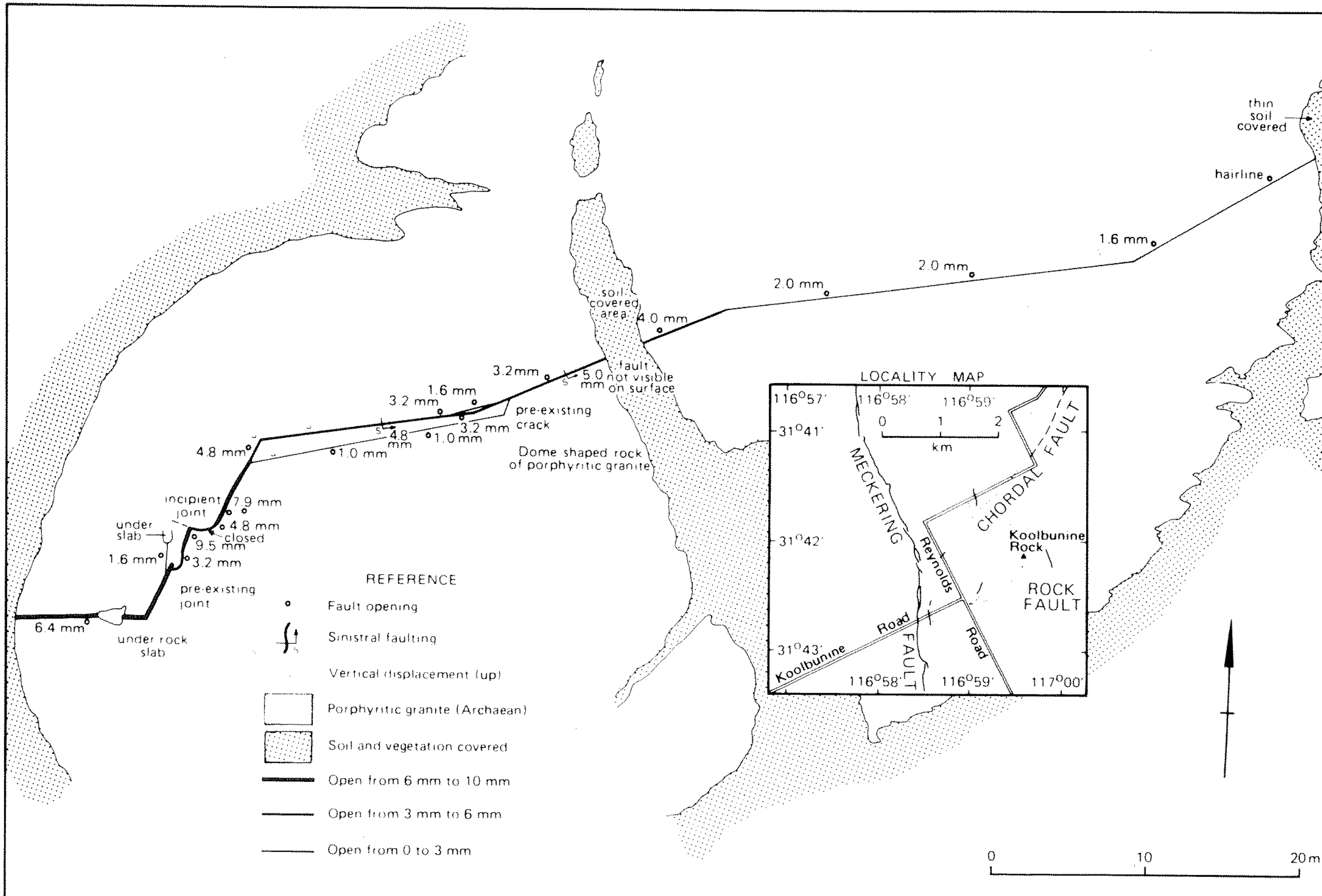
The Koolbunine Fault is a short fracture, about 100 m long, close to the intersection of Koolbunine and Reynolds Roads; its interest lies in the fact that it was the only fault observed in fresh granite, that it was a new fracture and that over a period of nearly two years it was observed to extend itself.

The fracture was first noticed during the regional geological mapping of the area on 5th November 1968, and was found to extend a little over half way across a granite outcrop 100 m wide. The maximum width of the opening was 0.6 cm, and there was no obvious lateral movement. The feature was re-examined three weeks later and it was found that the crack could be traced right across the outcrop, an extension of about 45 m, and that it had widened to a maximum of about 0.7 cm, with a sinistral strike slip of 0.2 to 0.3 cm. In September 1970, twenty-two months after the first examination the fault was mapped in detail (Fig. 60); it had widened to a maximum opening of 0.95 cm, and the maximum sinistral movement was about 0.5 cm. In addition, a fresh branch fault 18 m long with a maximum opening 0.15 cm and no obvious lateral movement (Fig. 61), was traced.

The fault occurred on the flanks of Koolbunine Rock, an oval shaped dome of rock elevated about 2.5 m above its surroundings. The granite is a melange of coarse-grained porphyritic and medium-grained equigranular phases, relatively free of joints other than sheet joints parallel to the rock surface. The rock is fresh, and the fault cut across the granite with a clean, fresh opening, in places breaking individual feldspar crystals.

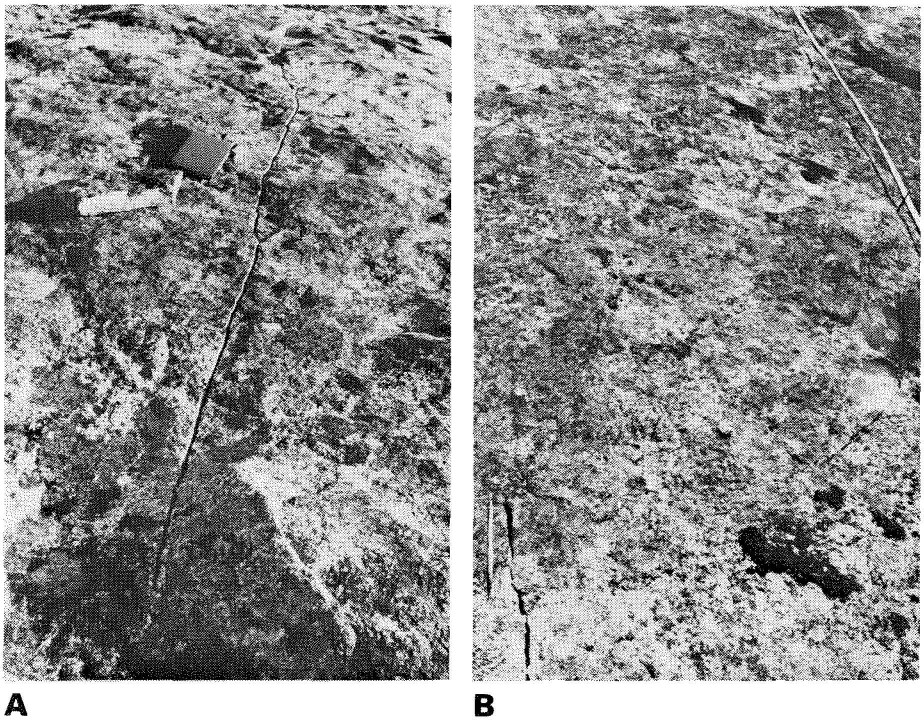
It is not known whether the extension and enlargement of the Koolbunine Fault fracture was a continuous process, unconnected with later seismeic events, or if there had been two or three separate increments resulting from local aftershocks. There were numerous aftershocks in the area, but the epicentres of these could not be located with sufficient accuracy to connect them with individual fault fractures, and observations of the fault were not at sufficiently close intervals.

The fault was located 0.8 km northeast of the Meckering Fault on Koolbunine Road, and trended 070°, at right angles to the main scarp. There was no obvious surface connection with the main scarp, but the fracture was located in a zone of complex



GSWA 17498

60. The Koolbunine Fault.



61. **The Koolbunine Fault:**
(a) **Close-up of part of the fracture in Sept. 1970, showing a small sinistral displacement.**
(b) **A dextral step in the fracture.**

discontinuous faulting, about 1 km wide and 1.5 km long, at the southern end of the Chordal Fault. In this area, there was clear evidence that the Chordal Fault was a partially reactivated feature and that the new fault was associated with an inactive portion of the Chordal Fault near its junction with the Meckering Fault. Thus the Koolbunine Fault could be either a new radial fracture, as its disposition to the Meckering Fault suggests, or a southern extension of the Chordal Fault.

CHAPTER 7

SECONDARY GROUND BREAKAGE

In addition to the faulting described in Chapters 5 and 6, seismic shaking following the Meckering Earthquake produced a number of secondary effects involving superficial ground failure. These include slumps, debris slides and clastic extrusions, all of which were mapped in the epicentral region, and slumps, which were detected as much as 60 km to the northwest of Meckering.

SLUMPS

Slumps are undeformed landslides in which movement takes place only along curved (concave upward) internal slip surfaces. The exposed fractures are concentric and concave towards the direction of movement. Many slumps in the Meckering area were in areas of high water table, and several wells were located within, or close to, extensive slumps. Slumping was often an isolated phenomenon, unrelated to any observed faulting, but there were several examples of a series of slumps in line with, and probably associated with, extensions of known faults. Although best developed in sloping ground slumps were also observed in very gently sloping or flat ground.

CIRCULAR PATTERN SLUMPING

A typical isolated circular slump was observed on Location 201, 3.2 km south of Meckering, and 400 m west of the York Road. The slump was on the south side of a hill sloping at about 20° towards an incised stream channel. The diameter of the slumped area was 23 m, and the scarp extended for about five-sixths of a circle; the unbroken portion was on its lowest side. On the upper edge, the slumped area was detached both horizontally and vertically about 5 cm to 8 cm from the undeformed ground. The slump was about 10 m above the stream, and was probably caused by the presence of a local high water table or potential spring.

LINEAR SLUMPING

The only structural damage attributable to slumping occurred 2.5 km east of Meckering. At this location, the Eastern Goldfields Water Supply pipeline was fractured at the time of the earthquake. The pipe line traversed the foot of hill slope of thin soil over granite, immediately above the salt-flats of the Mortlock River. At the pipe break, a small discontinuous scarp was traced westward for 45 m, and the downhill side was depressed 15 cm lower than the uphill side of the fracture. The scarp consisted of five separate arcuate scarplets, and was thus a linear slump. A month after the earthquake, probably due to aftershock activity, a further linear group of three scarplets, having downhill depressions of 3 cm, 5 cm, and 2.5 cm, and about 7 m long, had developed 3 m above the earlier feature. The linear nature of these slumps was probably due to the thin soil cover, and the damage was caused by lowering the pipeline supports about 10 cm.

SLUMPING AT BOLGART GOLF COURSE

The most distant slumping which could be attributed to the seismic shaking associated with the Meckering Earthquake occurred at Bolgart, 60 km northwest of Meckering. On the 11th green of the town golf course, a series of six concentric slump scarps, curving from 035° to 090°, formed on the downhill side near the hole. The maximum width of opening was 2.5 cm, and the total vertical displacement was about 30 cm. On line, and about 30 m distant, at 055°, was a freely running spring, indicating a high water table in the area. The significance of this slumping, at such a distance from the epicentre, will be considered further in the chapter on the Calingiri Earthquake.

SLUMPING AND THE SUDHOLZ FAULT

Three kilometres east of Meckering and immediately south of the Great Eastern Highway, six circular slumps were located on a northerly trending line 0.5 km long. The largest slump was 13 m in diameter, the smallest 2 m, and around the perimeter of each

62. Part of a circular slump feature, one of six online with the Sudholz Fault, and 3 km east of Meckering.

there was a small scarp up to 15 cm high (Fig. 62). The scarp height varied around the perimeter, and was as low as 0.5 cm. Inside the circular rim of each slump, the ground was depressed as much as 60 cm, or in the case of the smallest slump only 22 cm, and there were often other minor arcuate scarps within it, sometimes in the form of small thrusts. In the cases where there was a topographic low side to the slump, small lunette sub-thrusts, concave towards the centre of the slump, were often grouped on this side.

The line of slumps occupied a topographic depression across the foot of a hill slope, and were on line with the Sudholz Fault. The fault itself was part of the radial fracture pattern of the mobile block, and showed as persistent tension fractures with a small sinistral strike-slip. The slumps at its southern end appear to mark a continuation of the fault with only intermittent surface expression in unconsolidated overburden.

SLUMPING AND THE SPLINTER FAULT

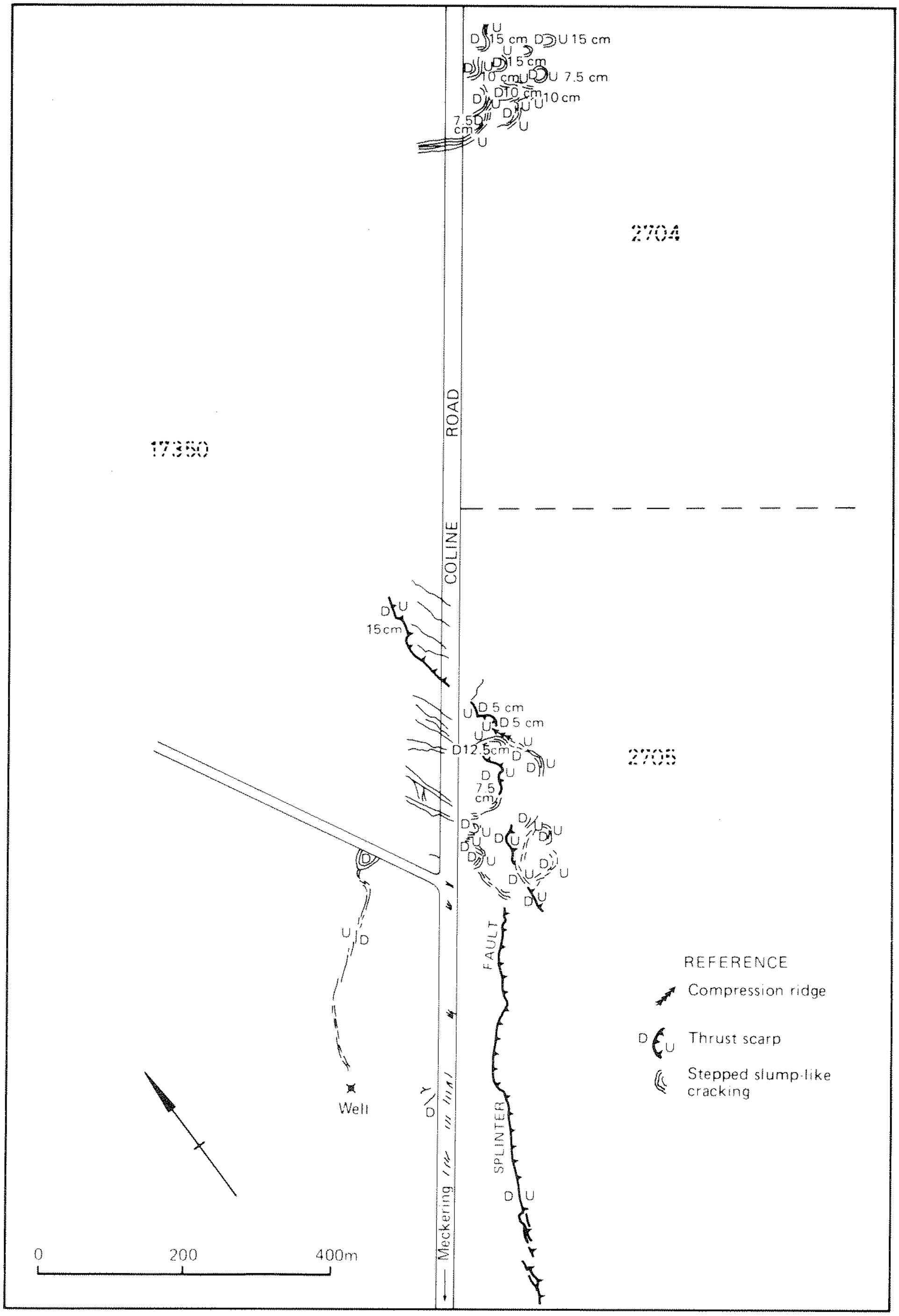
The most conspicuous connection between faulting and slumping was found near Coline Road, at the northern termination of the Splinter Fault (Fig. 63). Not only was there circular slumping on line with the fault, but the fault itself passed through an area of slumping.

The Splinter Fault commenced in Location 17350 as a narrow sinuous zone of four openings, each downthrown about 4 cm to the west. There was no lateral displacement of fence lines as the fault crossed Coline Road into Location 2705. In this field the fault swung to the southwest, and over the next 300 m was marked by a discontinuous thrust scarp having a throw of about 7.5 cm, the east side predominantly overthrust to the west. The fault then continued as a permanent feature, parallel to Coline Road, and with steadily increasing displacement. Numerous tension fractures at about 60° to the fault trace were found along the road.

In the area where thrust faulting was noted and for 75 m either side of the fault, there was a complex pattern of arcuate slumping. In addition to many small features there were six large arcuate slumps subtending angles between 90° and 180° and all facing west. Each slump consisted of several concentric fractures having a total downthrow of about 10 cm to the west.

Parallel to the Splinter Fault and 200 m west of it, in Location 17350, there was a fracture zone about 250 m long, the northwest side of which was elevated about 7.5 cm. The fracture zone died out southwards a few metres from a well, but its northern termination was in a semi-circular slump, open to the east.

About 750 m northeast along Coline Road from the point where it was crossed by the Splinter Fault there was an isolated area of slumping in the corner of Location 2704. The slumps were in an area about 100 m by 150 m, and on line with the projected trend of the Splinter Fault. Ten separate slumps were found, all open to the west. They varied from small, almost circular slumps, 20 m in diameter, to larger arcuate slumps 100 m in diameter and subtending an angle of about 90°. The number of concentric fractures varied from 2 to 5 and the central area was depressed from 7 cm to 15 cm.



63. Slumping near Coline Road at the northern end of the Splinter Fault.

LANDSLIDES

Because of the subdued nature of the topography, there were few landslides of any size. In the Perth Metropolitan area, old landslips in filled areas associated with road and bridge works were reactivated, and in the major cuttings of the standard gauge railway along the Avon Valley, there were several small rockfalls. These have been noted previously in Chapter 3. South of Cunderdin, where gullying is active, a number of small landslides developed.

CLASTIC EXTRUSIONS

Clastic extrusion is a name proposed by Lensen (1968) to replace the terms "mud volcano" and "sand volcanco", which have undesirable connotations. The name refers to the emission of water from the ground during seismic shaking, and the bringing up of quantities of sand or mud which are deposited around the orifice to form a small crater.

64. A small 'sand volcano' in the Mortlock River, 400 m west of Meckering. The 'vent' is 7.5 cm in diameter and emitted sand and salt water.

Several areas of clastic extrusion activity were found in the vicinity of Meckering, but all were in the low-lying salt flats of the Mortlock River, North of the railway yard in Meckering, there were several sand mounds resulting from water flow. These were associated with linear cracks trending 345° through the adjacent tar-sealed road. Water flowed for six hours after the main earthquake shock, and deposited mounds of fine white sand and silt up to 15 cm high.

South of the railway, and a little to the west of the town, more than twenty separate sand mounds were located in the salt flats (Fig. 64). In this area a graben-like depression had formed between two sub-parallel scarps trending at 360°. As the water table was only about 30 cm below the surface, this ground failure was probably the cause of the clastic extrusions. The sand mounds consisted of a clean yellow sand of remarkably even grain size, and the maximum height of the mounds was 15 cm. The sand, which had spread over a considerable area of the salt flats, was encrusted with salt, and a large pool of extremely saline water, still visible a month after the earthquake, collected in the lowest portion of the flats.

CHAPTER 8

Previous history of the Meckering and associated faults

One of the earliest questions asked, following the Meckering Earthquake, was whether the faults formed were new fractures or the reactivation of old faults. As outlined in previous chapters, the seismicity of the Meckering district was no greater than that of any other part of the South West Seismic Zone, and did not give cause to suspect the presence of active major faults in the area. Since the region had been settled there had been no faulting in the district, and regional mapping failed to reveal any older, potentially active, faults. Nevertheless, evidence of previous activity was sought, and several indications were found, each one inconclusive on its own, but in total strongly suggestive that faulting has happened before and that most of the major faulting of the Meckering area was reactivated older faulting. The nature of the evidence fell into three catagories; the presence of iron-stained fault breccia, the distinctive nature of soil and rock debris in the vicinity of faults, and the evidence of geomorphology. In addition there had previously been some effects of quarry blasting in the area which, although they could not be explained at the time, suggest now that the fault had been under stress some years prior to the earthquake.

FAULT BRECCIA

At most points where the plane of the Meckering Fault was exposed, the rock near the surface was a thoroughly kaolinized granite, and although fault breccia was reported from several locations, the rock was unsuitable for petrographic examination. In addition, where the fault was open, the material between the fault walls was largely blocks of kaolinized granite and overlying soil which had fallen from the hanging wall. However, 8 km southwest of Meckering, near the point where the fault cuts the York Road, several lensoid slabs of rock were retrieved which on examination proved to be fault breccia.

The lensoid slabs were up to 80 cm across and 5 cm thick, strongly iron stained with a slickensided surface. In thin section (15015), only quartz, microcline, 'clay minerals' and hydrated iron oxide could be seen, with a single fragment of oligoclase. The structure of the rock consisted of large 'eyes' of quartz or microcline, sometimes as strained individual crystals, more usually as granulated aggregates, with an interstitial very fine-grained quartz-'clay mineral' matrix. Hydrated iron oxide was found in discreet channels which formed a network throughout the rock and was obviously later than the cataclasis. In addition, superficial iron-staining covered the slickensides.

There is no evidence that the iron staining could have formed in the few weeks between the formation of the fault and the examination of this locality, and these specimens provide the only direct evidence of the previous existence of the Meckering Fault.

QUARTZ STREWN, AND RED SOIL AREAS

During the mapping of the fault scarps in the Meckering area, an association was noted between the fault trace and areas strewn with quartz fragments, or areas where the soil was a particular reddish colour. Where surface breakage was small or intermittent, a fault extension could often by located by following such indicators. In other cases, potential extension to a known fault could be postulated in the same way. As the quartz and red soil pre-date the earthquake of 1968, the obvious inference was that they were formed following earlier movements of the faults.

THE MECKERING FAULT

In those areas where rock was close enough to the surface to allow measurement of the fault plane, the rocks observed nearby were usually quartz-rich, either small quartz reefs or a quartz-rich gneissose granite. The southernmost 6 km of the Meckering Fault was located in an almost continuous zone of quartz scatter, and the few exposures of the fault plane were seen in a small, brecciated quartz reef. A particular example was seen about 2 km from the southern end of the fault where the scarp, about 3 cm high at this point, crossed an eroding creek bed. Quartz fragments were notable for 27 m upstream of the fault on its elevated side and for 20 m downstream. The fault plane was clearly seen in a quartz reef on the south bank of the stream. The southeasterly trending quartz reef was brecciated, and the fault plane dipped at 40° to the northeast. Upstream of the fault, there is an outcrop of sheared granite in the stream bed, whereas immediately downstream the medium grained porphyritic granite is unstrained.

The presence of quartz strew in the vicinity of the fault can probably be explained in terms of previous movement of the fault which caused elevation of the eastern block and locally accelerated erosion, leaving the brecciated quartz veins as residual pebbles. A similar effect was noted in several places where the fault scarp was bulldozed down in the following year to allow seeding operations. Resistant quartz veins and nodules were left exposed on the planed surface of the eastern block, and would obviously have presented a picture of quartz strew within a few years, when vegetation and soil formation had obscured the underlying weathered rock.

Areas of iron-rich red soil are a conspicuous feature along several sections of the fault trace. East and north of the railway quarry, 4 km southwest of Meckering, where the fault is well exposed, the clayey soil is strongly iron stained. The rock exposed nearby on the elevated block, consists of thin sheets of granite with iron-stained selvages. The sheets are parallel to the dip of the fault, and there is no evidence that they were produced by the earthquake of 1968

THE SPLINTER FAULT

The Splinter Fault showed a particularly close correspondence to quartz-strewn areas, and in several places where surface fractures were small, the position of the main fault could only be established by following such features. At one point, where the fault displaced a moderately weathered gneissose granite, there was a small quartz reef 45 cm wide immediately to the west of, and parallel to, the active fault scarp.

From the last visible surface fracture at the southern end of the Splinter Fault, an extension could be plotted by following several small quartz reefs and areas of quartz strewn soil. The line paralleled the scarp of the Meckering Fault and joined its southern part south of the 1.6 km westerly translation along the Burges Fault. It would appear that before the earthquake of 1968, there were at least two parallel arcuate faults in existence, and the scarp that appeared on 14 October contained elements of both. In the area closest to the epicentre, both existing faults were activated. The principal displacement near the epicentre was on the easterly of the two faults, the Meckering Fault, but south of the Burges Fault the displacement was transferred to the westerly fault. South of the Burges Fault there were no indications that the northern part of the Meckering Fault had had a former extension, and from a consideration of their dips, it is probable that the planes of the Meckering and Splinter Faults coalesce at depth.

DIFFERENCES IN SOIL PROFILE ACROSS THE FAULTS

In areas where solid rock was close to the surface, it was relatively simple to determine the soil profile on either side of the fault scarp. Digging at several points along the Meckering Fault showed that the soil on the eastern side of the scarp was invariably thinner and consisted of less layers than that on the western or downthrown side. This suggests that the fault has moved in comparatively recent times and that part of the soil profile has been stripped from the uplifted block. It is possible that a comparison of soil profiles across the fault might offer a means of dating the previous movement, but unfortunately the weathering profile for granitic rocks in the wheatbelt area had not been acurately dated.

GEOMORPHOLOGY

It has been mentioned previously that several of the faults in the Meckering district followed topographic lows across a hillside, or followed stream channels. The most reasonable explanation is that these morphologic features marked the site of older faulting and that erosion has removed crushed rock to form the feature. A particular example is the Chordal Fault. At its northern end, the fault followed a remarkably straight stream channel for 5.5 km. Farther south, the fault followed the crest of a small but prominent rise connected either with the fault or with a poorly exposed dolerite dyke.

THE MORTLOCK RIVER

One of the most striking features of the Mortlock River is the arcuate swing from a westerly to a southerly direction around Meckering. For about 12 km the river is parallel to, and about 1.5 km east of, the Meckering Fault scarp. Not until about 9 km south of the town does the river resume its westerly course and cross the fault scarp. Such areas are unusual features of the drainage pattern of the wheatbelt, as most of the river courses can be divided into short straight channels governed by jointing, foliation, or other geological controls.

The probable cause of the arcuate course is that the river has been guided by the raised and tilted edge of the mobile block or has eroded along the trace of an older fault.

The importance of stream morphology was demonstrated by the discovery of the Sudholz Fault. To the northeast of Meckering, the Mortlock River changes abruptly from a very wide valley filled with alluvium and containing salt flats to a relatively narrow incised channel. The possibility that this change might be fault governed led to an examination of the area and the discovery of a small but persistent radial fracture later named the Sudholz Fault.

Another morphological feature examined, without success, for signs of faulting, was a small stream to the southwest of Meckering which apparently exhibits reverse drainage. The stream rises north of Meenaar and flows south for about 3 km before turning abruptly eastward and following a straight course, 9 km long and parallel to the Great Eastern Highway, to the Mortlock River. The stream configuration is strongly suggestive of reverse drainage as a result of tilting of the block west of the Meckering Fault, with the stream following an east-west radial fracture. The possible reality of this tilting is increased when it is realised that a curve drawn parallel to the Meckering Fault and about 7 km to the east is entirely in low-lying country and includes the headwaters of the reversed stream, a long straight section of the Mortlock River and several other small tributary streams, some of which flow eastward.

Stream morphology studies of the whole of the South West Division of the State (Chapter 12), show the presence throughout the South West Seismic Zone of a number of circular or arcuate lineaments. The Meckering Fault follows one of these lineaments which suggests that the others may be the site of similar thrust faulting.

THE RELATIONSHIP BETWEEN FAULTING AND ROCK OUTCROP

At several locations there was evidence that weathered rock existed at no great depth along the trace of the Meckering Fault, but except for the minor fracture named the Koolbunine Fault, none of the faulting traversed fresh rock. If the Meckering Fault was a reactivated feature, this could be expected as faulting would crush the rock and lead to more rapid erosion and soil formation. However, an examination of the geological map of the area (Plate 1) does suggest a relationship between the fault trace and the outcrop of fresh rock, particularly south of the Great Eastern Highway. The fault itself lies entirely in alluvium or colluvium, and to the west, there are wide plains with little outcrop. Immediately to the east, however, there is an almost continuous line of granite outcrops, and the land surface slopes gently towards wide sandplains to the southeast of Meckering township. The land surface appears to be saucer shaped, with its outer rim along the Meckering Fault. It will also be noticed that as the Meckering Fault steps westward at the Burges Fault so does the line of granite outcrops. Elevation of the eastern block along the fault has allowed erosion to expose fresh rock while leaving it covered to the west of the fault. The only significant rock outcrop adjacent to and west of the fault is to the west of Koolbunine Rock, but the exposure is low lying and often strongly weathered compared with the dome of fresh granite exposed east of the fault.

North of Meckering township, the relationship between faulting and rock outcrop is complicated by the presence of the Splinter Fault. The Mortlock River runs between the Meckering Fault and the granite outcrop east of the town, which forms the rim of the 'saucer'; between the parallel Meckering and Splinter Faults, the Beeberring Hills rise 60 m above the plain to form a small horst.

Other outcrop patterns which may be significant for the history of faulting in the Meckering district are the arc of small hills from Meenaar Hill to Five Mile Hill to Little Bald rock, all west of Meckering, and the southeast trending line of outcrops and breakaways to the east of the town. The outcrops from Meenaar to Little Bald Rock are immediately to the east of a low-lying arc which may represent an arcuate fault parallel to the Meckering Fault; the rocks again represent the elevated side of the fault. The line of outcrops and breakaways from Meckering through Bulgin Rock to the southeast mark the 'Meckering Line', the eastern limit of rejuvenation of the river system (Mulcahy, 1967). If the Beeberring Hills are included in the outcrops which form the edge of the Meckering mobile block, then the Meckering Line forms a ridge which divides the saucer in two and may mark the trend of the deep seated structure responsible for the faulting (see Chapter 10).

DAMAGE FROM QUARRY BLASTING

The Meckering quarry, 3.5 km southwest of the town, is sited in a dome-shaped outcrop of porphyritic granite, and had been in periodic use for many years as a source of building stone, kerbing blocks and crushed rock. In 1965 the quarry was reopened to supply ballast for the standard gauge railway. The major quarry blasts were usually fired on Sunday morning, and immediately brought complaints from two farmers 10.5 km and 11.3 km south of the quarry. Strong ground vibrations were reported and one farmer complained that the walls of his house had been cracked, yet people living as near as 2 km east of the quarry reported nothing more than sound effects and a small concussion. The blasts had been carried out according to Mines Department regulations, and tests conducted in large quarries near Perth had indicated that significant damage should occur only within a radius of about 250 m of the explosion.

Following the earthquake of 1968 it was found that the Meckering Fault passed within 300 m of the quarry and the fault plane dipped beneath it. The farmhouses were also sited near the fault and were destroyed. One house, of concrete block construction, was 600 m west of the Meckering Fault and 440 m north of the Burges Fault, while the other, of clay brick construction, was 450 m east of the fault.

As the existence of the Meckering Fault was not suspected in 1965 no detailed examination was made of the possible damage caused by blasting, and after the earthquake none was possible. One explanation, however, is that stress had already built up three years before the earthquake and that the pre-existing fault plane channelled the shock waves from the quarry blasting.

CHAPTER 9

Regional Deformation of the Earthquake Area

After the Meckering Earthquake, the Western Australian Lands and Surveys Department commenced a check of measurements in the vicinity of the fault scarp. Geodetic measurements were made between stations previously established by the Australian Geodetic Survey and the Lands and Surveys Department. Levelling circuits were made both north and south of the Meckering area and along the Great Eastern Highway across the fault affected block. In addition, geodetic measurements across the area were also made available by the Australian Division of National Mapping.

GEODETIC OBSERVATIONS

LANDS AND SURVEYS DEPARTMENT

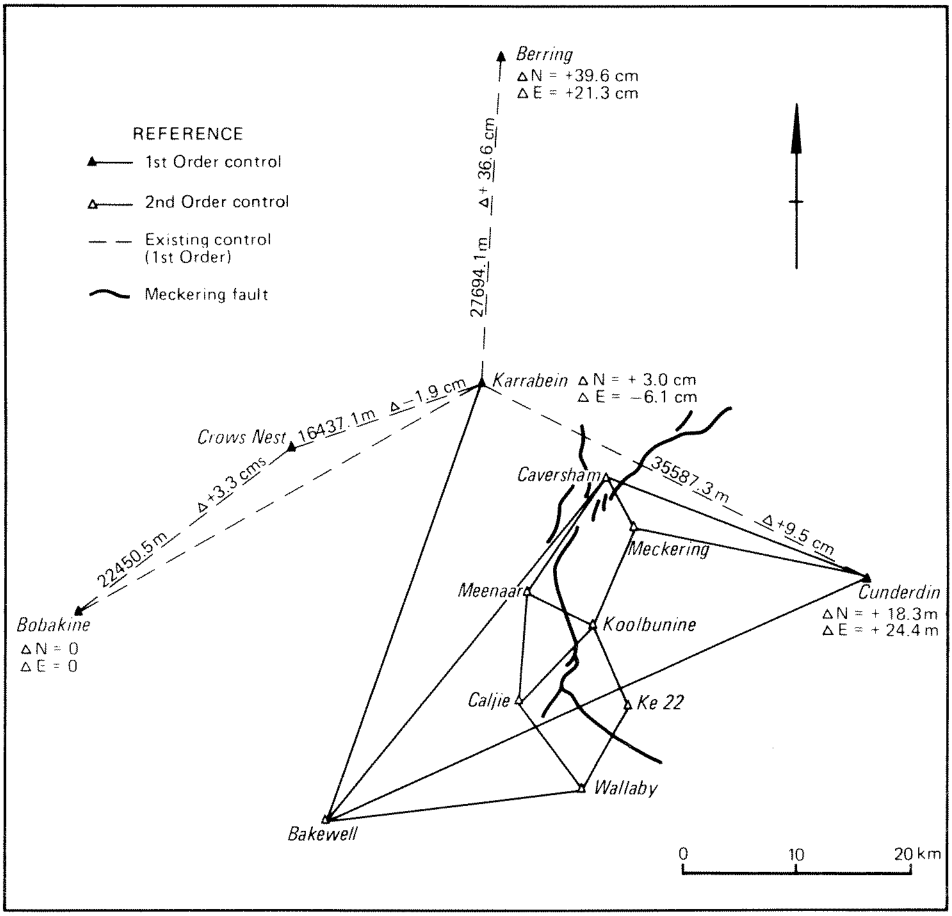
A network of stations was originally established in 1958 using an MRA-1 Tellurometer. In November 1968, following the earthquake, the stations at Bobakine, Karrabein, Berring and Cunderdin were reoccupied and the distances remeasured with an MRA-2 Tellurometer. The receipt of measurements made by the Division of National Mapping in 1969 showed certain discrepancies, and several of the distances were remeasured in May 1970 using a model 8 Geodimeter. In addition, because the original Bobakine-Karrabein distance was of doubtful value the intermediate station at Crows Nest was used in the second series. The position of the stations is shown in Figure 65, and the measurements obtained in Table 13.

TABLE 16. COMPARISON OF PRIMARY DISTANCE MEASUREMENT BY THE LANDS AND SURVEYS DEPARTMENT OF W.A.

Line	*1958 (MRA-1)*	*Nov. 1968 (MRA-2)*	*May 1970 (Mod. 8 Geodim.)*
Bobakine-Crows Nest	22 450.504 m	—	22 450.537 m
Crows Nest-Karrabein	16 437.129 m	—	16 437.110 m
Karrabein-Berring	27 694.114 m	27 694.499 m	27 694.462 m
Karrabein-Cunderdin	35 587.338 m	35 587.433 m	unsatisfactory
Bobakine-Karrabein	[1](38 310.235 m)	38 310.620 m	—

[1] Doubtful value

For the purpose of measurement, Bobakine Trig Station, 12 km south-southwest of Northam, was assumed to be unchanged. From the measurements the following changes were calculated.



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65. Lands and Surveys Department of Western Australia geodetic observations, including the second order network established to monitor future displacements in the vicinity of Meckering.

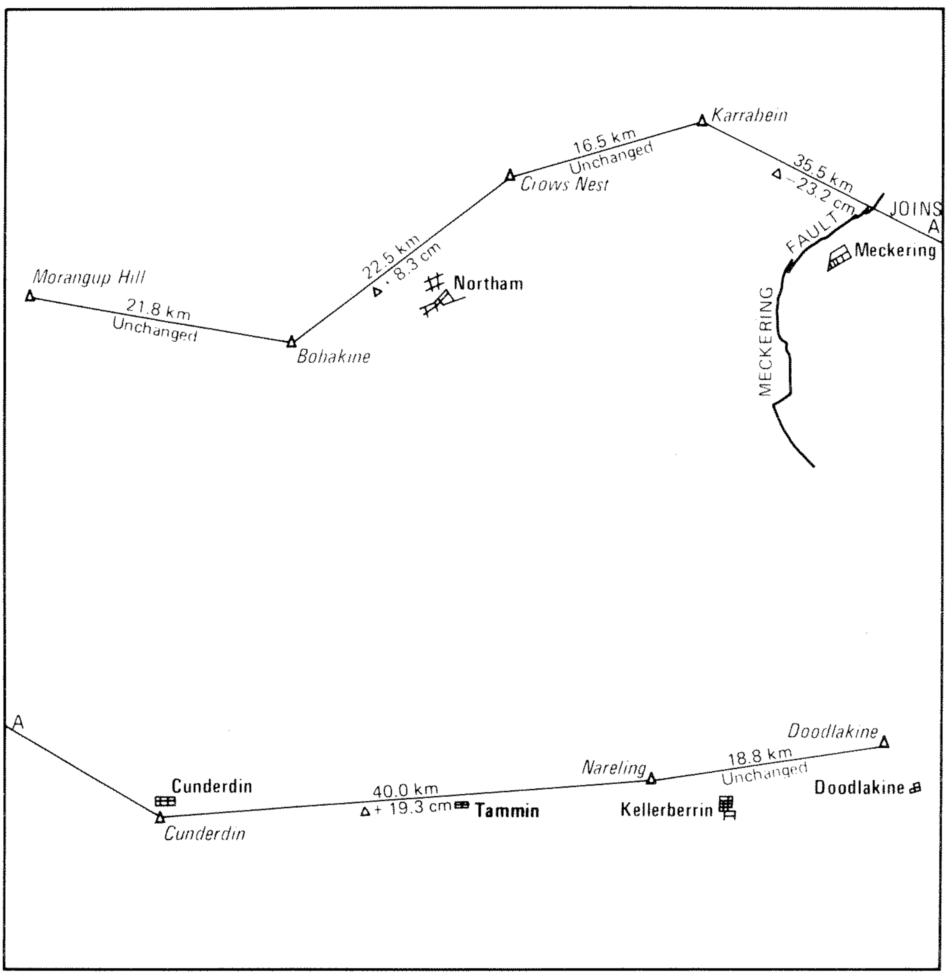
TABLE 17. CHANGES RECORDED BY THE RE-OBSERVATIONS OF 1968 AND 1970

I *Station*	*Shift (N)*	*shift (E)*	*Resultant*
Karrabein	+3.0 cm	− 6.1 cm	6.8 cm, 296°
Berring	+39.6 cm	+21.3 cm	45.0 cm, 028°
Cunderdin	+18.3 cm	+24.4 cm	30.5 cm, 053°

II *Line*	*Length*	*Apparent change*
Bobakine-Crows Nest	22.4 km	+ 3.3 cm
Crows Nest-Karrabein	16.4 km	− 1.9 cm
Karrabein-Berring	27.7 km	+ 36.6 cm
Karrabein-Cunderdin	35.5 km	+ 9.5 cm

DIVISION OF NATIONAL MAPPING

In September 1969, the Division of National Mapping initiated distance measurements between Perth and Kalgoorlie, using Model 8 Geodimeters. The route included the section Bobakine-Crows Nest-Karrabein-Cunderdin, and stations at either end of the line, particularly Morangup Hill to the west and Nareling and Doodlakine to the east. The geodimeter results were compared with the distances obtained in mid 1968 by the same department for the Geodetic Network, using an MRA-4 Tellurometer. A plan of the line is given in Figure 66, and the results in Table 15. The adjusted difference in the last column of the table is to allow for an instrument factor of – 1 part per million in the geodimeter reading (K. Leppart, pers. comm.).



66. Division of National Mapping geodetic observations.

TABLE 18. PRIMARY DISTANCES MEASURED BY THE AUSTRALIAN DIVISION OF NATIONAL MAPPING

Line	*(MRA-4) mid 1968*	*Sept 1969 (Mod. 8 Geodim.)*	*Change*	*Corrected change* [1]
Morangup-Bobakine	21.8 km		unchanged	
Bobakine-Crows Nest	22 450.459 m	22 450.520 m	+ 6.1 cm	+ 8.3 cm
Crows Nest-Karrabein	16 437.104 m	16 437.084 m	– 2.0 cm	unchanged
Karrabein-Cunderdin	35 587.660 m	35 587.392 m	– 26.8 cm	– 23.2 cm
Cunderdin-Nareling	39 999.723 m	39 999.876 m	+ 15.3 cm	– 23.2 cm
Nareling-Doodlakine	18.8 km		unchanged	

(1) Includes Instrument correction of –1 part per million

RESULTS

Of the five sets of observations that have straddled the Meckering area it is unfortunate that no two sets were made by the same agency using the same instruments. Apart from the instrument variation many of the smaller changes recorded were close to the accuracy limits. A further source of variation might be the time interval between the measurements; if the areas is under continuous stress then the change noted between 1958 and November 1968 might well be different from measurements made shortly before and after the earthquake. This might be of particular significance with regard to the observations of November 1968 and May 1970 made by the Lands and Surveys Department. The small difference noted in Table 13 for the Karrabein-Berring line could be due either to instrument variation or to readjustments following the Calingiri Earthquake of March 1970. Nevertheless, some of the changes noted are too large to be completely disregarded.

The changes recorded by the Lands and Surveys Department (Tables 13 and 14) are impossible to reconcile with the simple dextral thrusting and crustal shortening observed at the fault trace, even when modified by tension faulting in the Backscarp Zone. The maximum crustal shortening at the scarp was 2.44 m, and although much of this was taken up by tension fractures it leaves unexplained the apparent crustal lengthening of 9.1 cm between Karrabein and Cunderdin. In addition, the apparent resultant movement of the Cunderdin station, to the northeast, would result in tension rather than compression and is at variance with the known surface displacements.

The greatest elongation, however, is in the Karrabein-Berring line, to the northwest of Meckering. No surface faulting was observed to account for the 40 cm increase, but there is evidence, which will be considered in Chapter 11, to show that deformation occurred in this area following the earthquake. The fact that the Karrabein-Cunderdin line lies largely outside the Meckering mobile block and passes through this area of deformation might also explain the lengthening observed.

The Division of National Mapping observations were made only a few months before and after the earthquake, and can therefore be expected to indicate better the adjustments that took place as a result of the seismic event. The extended line to the west, from Bobakine to Morangup Hill confirmed the assumption of the Lands and Surveys Department that Bobakine remained unchanged. To the east, the line between Nareling and Doodlakine also remained unchanged. The survey did, however, extend the known area of distortion east of Cunderdin and an extension of 19.3 cm was recorded between

Cunderdin and Nareling. Overall the Australian Division of National Mapping recorded an extension of 4.4 cm across the deformed zone, about half of the error that could be expected along a traverse of 110 km.

Between Bobakine and Cunderdin the two agencies used the same survey stations, yet their results are considerably at variance. The Lands and Survey Department report a net lengthening of 10.9 cm while the Australian Division of National Mapping report a shortening of 15.3 cm. Most of this difference is found in the Karrabein-Cunderdin line which was reported as being 9.5 cm longer by one agency and 23.2 cm shorter by the other. The difference could be due to poor instrumentation in the 1958 traverse, or to an error in surveying, but this seems unlikely for several reasons. The difference in length for the two post-earthquake traverses is only 1 cm in 74 km, and for the Crows Nest-Karrabein line, which both agree is unchanged, the difference between the 1958 and 1968/70 surveys is a maximum of 2.9 cm, which is within the limits of error of the instruments. For the Bobakine-Crows Nest line, both agencies agree that it has been lengthened, the 1958/70 value being 3.4 cm, and the 1968/69 value being 8.3 cm, a difference, which although beyond instrumental error could be explained by changed techniques combined with instrumental factors. No such explanation is possible for the Karrabein-Cunderdin measurements, as both results are beyond any instrumental or operator variation.

The discrepancy between the two measurements of the distance between Karrabein and Cunderdin can be rationalized in the following manner: between 1958 and November 1968 a net increase of 9.5 cm occurred. Between mid 1968 and May 1970 a net decrease of 23.2 cm was caused by the Meckering Earthquake. This implies that in the ten years between the mesurements made by the Lands and Surveys Department and the pre-earthquake measurements of the Division of National Mapping, an unnoticed increase of 32.7 cm took place. This has implications for the mechanism of the earthquake, and the underlying structure which produced the surface faulting, which will be discussed in Chapter 10, but at this stage it should be noted that an annual creep of over 3 cm seems excessive, and without a series of measurements over a considerable time-span cannot be accepted as proven.

Unfortunately, prior to the earthquake, the trig station on Mount Bakewell, 23 km south-southeast of Northam, had been destroyed, and a complete triangulation of the area was not possible. The measurements taken, however, have shown that there was noticeable distortion over a 74 km section across the gneissic rocks around Northam and the granites of the western Wheat Belt. The changes in certain parts of the section were considerable, but the paucity of data does not allow a complete interpretation.

LEVELLING CIRCUITS

Third order levelling profiles were measured on four routes to give a picture of vertical changes in height around Meckering. The profiles were compared with first order levelling completed in 1961, and it was assumed that the tide gauge at Fremantle had not been displaced. The routes taken are shown in Figure 67, and were:

(1) Fremantle-Canning Highway-Clackline-Northam.

(2) Northam-Goomalling-Wyalkatchem-Kununoppin-Merredin.

(3) Northam-Meckering-Merredin.

(4) Northam-Bruce Rock-Merredin.

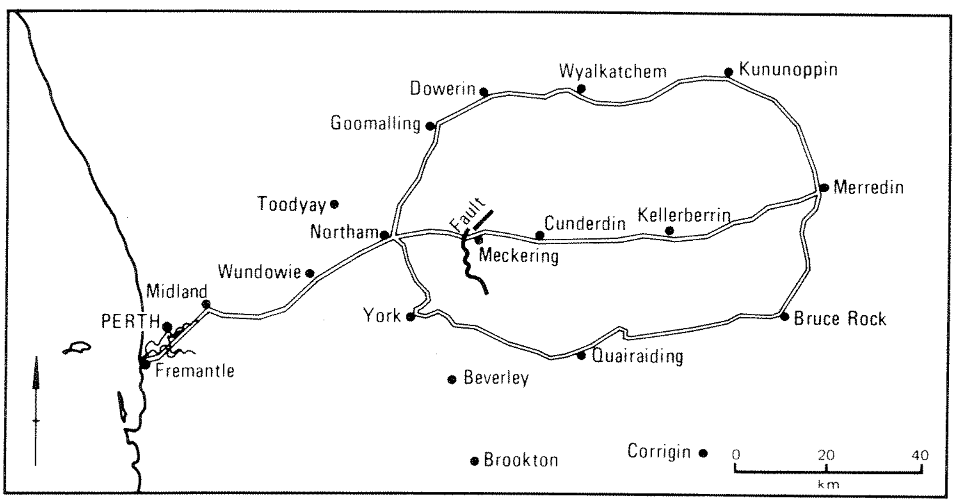
In addition, the Eastern Goldfields Water Supply pipeline through Meckering was also relevelled.

All levelling along roads was carried out on bench marks at 1.6 km (one mile) intervals. On the Goldfields Water Supply pipeline the concrete pipe supports at 201 m (ten chain) intervals were used. Elevations and distances quoted in S.I. units have been converted by the present authors.

No significant differences were recorded for the route from Fremantle to Northam, or for the southern loop from Northam to Merredin via Bruce Rock. The two routes through Meckering traversed the mobile block and recorded the disturbance at the Meckering Fault and in the Backscarp Zone to the east of the town. The northern route showed some significant variations from the earlier first order survey, particularly near Dowerin, to the northwest of Meckering.

LEVELLING PROFILE OF THE GREAT EASTERN HIGHWAY

The most immediately important levelling route, on the Great Eastern Highway through Meckering, showed a simple pattern of deformation which had already been apparent in general form from the geological investigations. The changes were regular and directly related to the movement of the Meckering Fault. At the fault the eastern side had been uplifted 1.5 m and there was a slight depression of the western block. The uplift gradually decreased to the east, and for 6.5 km through the Backscarp Zone was below the pre-earthquake level. The fault profile is shown in Figure 68, and the variation in pre- and post-earthquake levels in Fig. 69.



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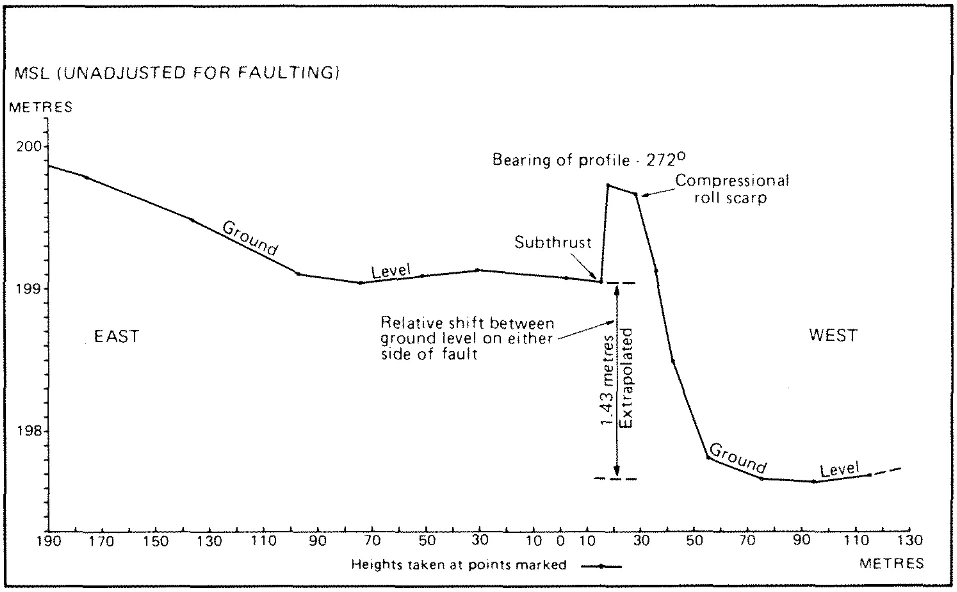
67. Traverses of third order levelling.



68. Profile of the Meckering Fault on the Great Eastern Highway.

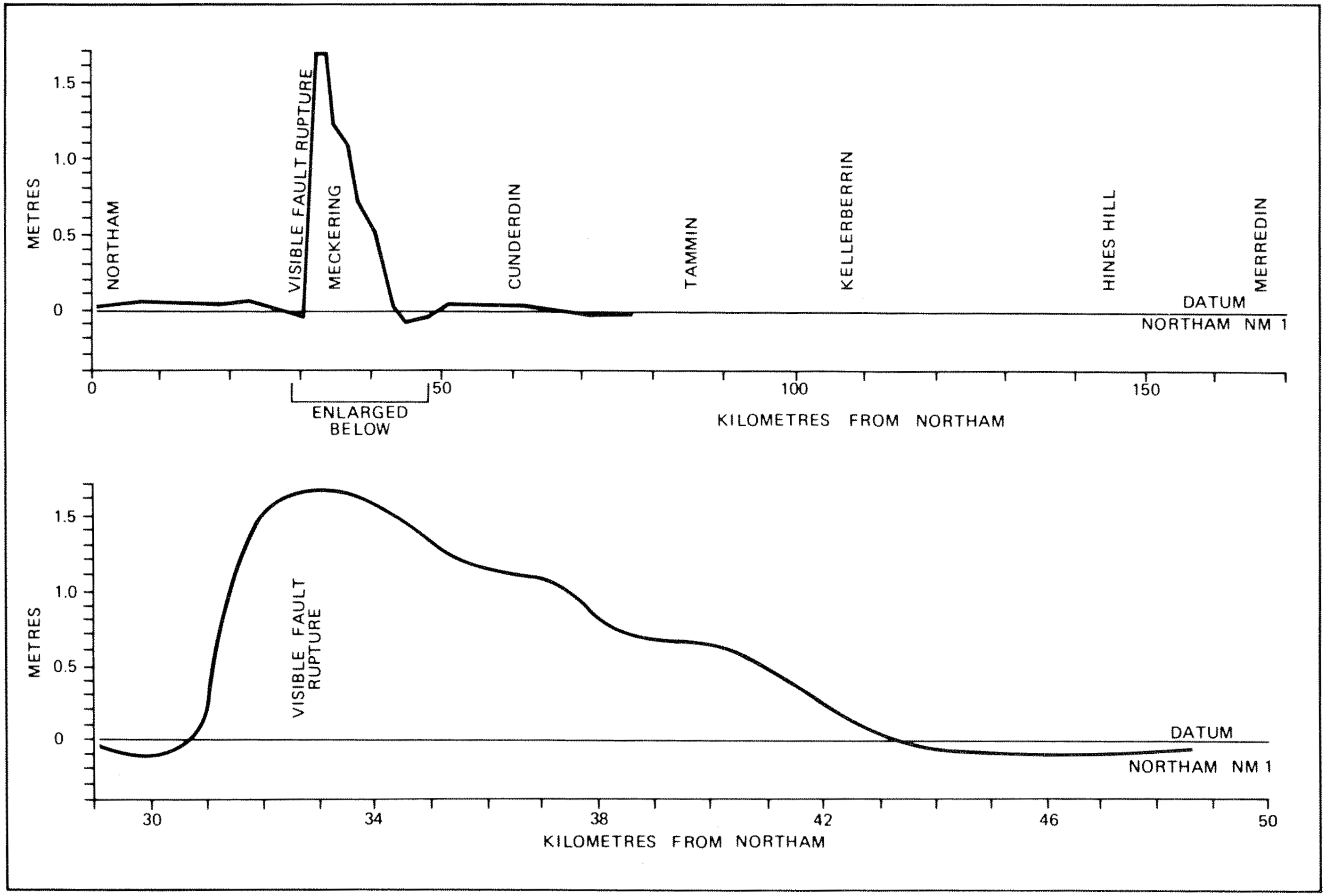
For the first 24 km eastward from Northam there was a small positive variation between the levels of August and September 1961 and the post-earthquake levels of October and November 1968. For the next 5 km, until the fault scarp was reached, the ground profile was slightly depressed. The maximum elevation of 4.6 cm was attained near the eastern end of the uplifted part of the profile, and the maximum depression was 7.6 cm, immediately in front of the fault scarp.

At the fault scarp, the rise in ground level due to the faulting was 1.25 m, but rose over the next 2 km to the east to a maximum of about 1.6 m. There was then a general fall to the east of about 9.5 cm per kilometre, or one second of arc, although the general slope was interrupted by two areas of accelerated depression 6 km and 9 km from the scarp. About 13 km east of the fault the former ground level was intersected and the slope flattened. For the next 6.5 km the ground was depressed by up to 8.9 cm below its former level and this marked the Backscarp Zone and the eastern limit of visible faulting. Finally, an elevation of ground levels by about 5.0 cm was recorded for the 15 km section from the Backscarp Zone to a point 4 km east of Cunderdin.

With the exception of the two depressions on the eastern slope, the picture derived from the levelling profile was consistent with the concept of uplift along a thrust fault.

LEVELLING PROFILE OF THE GOLDFIELDS WATER SUPPLY PIPELINE

The Goldfields Water Supply pipeline diverges considerably from the Great Eastern Highway in the vicinity of Meckering. The pipeline takes a more direct line, following the railway east from Meenaar to the wheat silos west of Meckering. From there the pipeline



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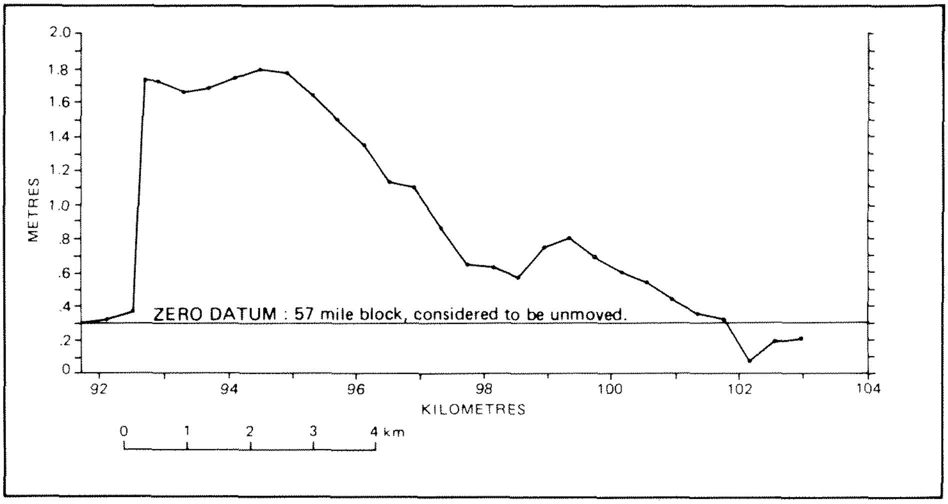
69. Variation between 1st order levelling, 1961, and 3rd order levelling, November, 1968, along the Great Eastern Highway.



70. Variation between pre-earthquake levels and levelling of November 1968 along the Goldfields Water Supply pipeline.

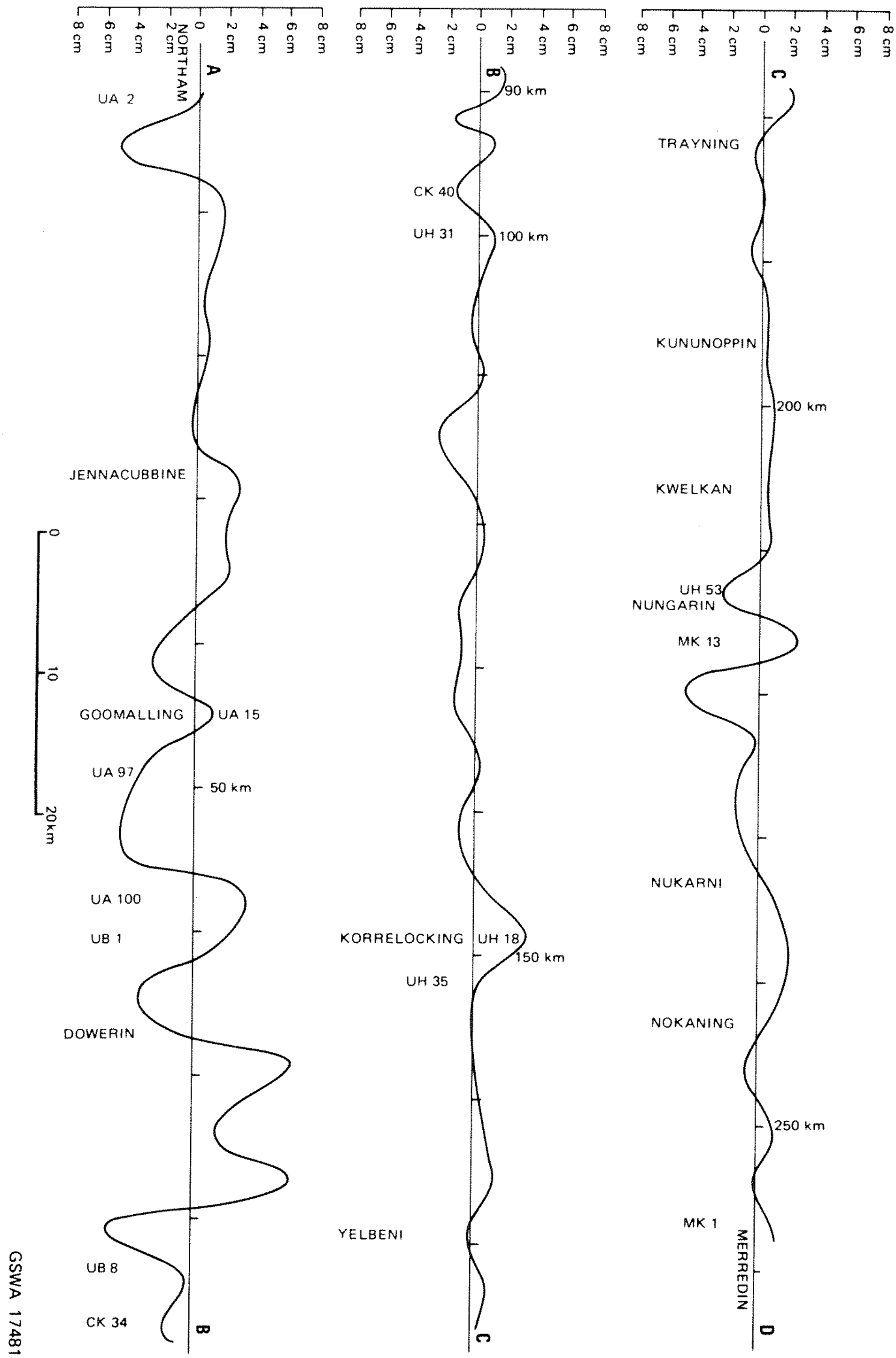
crosses the Mortlock River at right angles and follows Vanzetti Street, on the south side of the township. The direct line is maintained until the Great Eastern Highway is again encountered 7.5 km east of Meckering. The pipeline is supported on concrete blocks which were relevelled in November 1968. The differences between the new levels and the pre-earthquake levels are shown in Fig. 70.

Immediately in front of the Meckering Fault scarp there was a slight rise, rather than the depression which was recorded on the Great Eastern Highway. This rise is attributed to a small monoclinal fold that formed on the southward extension of the Splinter Fault.

The closer spaced observations on the pipeline survey enabled a better definition of the gross form of the uplifted area, but the same features were observed as in the highway levelling. The vertical uplift of 1.4 m at the scarp is followed by a slight depression to the east, and the greatest uplift of 1.5 m is reached about 1.7 km east of the fault. Within that distance are most of the tension faults that formed at the time of the earthquake. The largest tension fault was immediately east of the highest uplift point, and caused a break in the pipeline.

The uplift of the mobile block decreased in a regular manner towards the east, but with two breaks in slope. At 98.3 km the elevation remained constant over a distance of 400 m, and between 97.7 km and 99.4 km a small increase in elevation was recorded. The backslope then resumed its downward trend until it reached the Backscarp Zone at 102 km and ground levels were depressed with respect to earlier surveys.

The two areas where the uplift was interrupted cannot readily be identified with tectonic features. The first break was on the crest and western slopes of the large granite 'rock' to the east of the townsite, and the second occured on the flat sand plain immediately south of the Great Eastern Highway. The two areas could, however, be matched with similar features on the highway levelling profile.



71. Variation in levelling profiles between Northam, Dowerin and Merredin.

LEVELLING PROFILE: NORTHAM-GOOMALLING-MERREDIN

Unlike the southern route through Bruce Rock the levelling profile between Northam and Merredin on the northern circuit shows many differences from the first order levelling of 1961. The differences of level are shown in Fig. 71.

Between 2 km and 4 km from Northam, the ground level was depressed about 5.4 cm, and in the vicinity of Jennacubbine there was an elevation of 3.2 cm over a distance of 4 km. For the next 50 km of the circuit to the east there was a remarkable series of alternate troughs and ridges with a maximum uplift of 6.7 cm immediately east of Dowerin and a maximum depression of 5.6 cm, 1.6 km further east. The amplitude of the changes gradually died out at 110 km from Northam and there were only minor discrepancies at Korrelocking and Nungarin, 250 km from Northam.

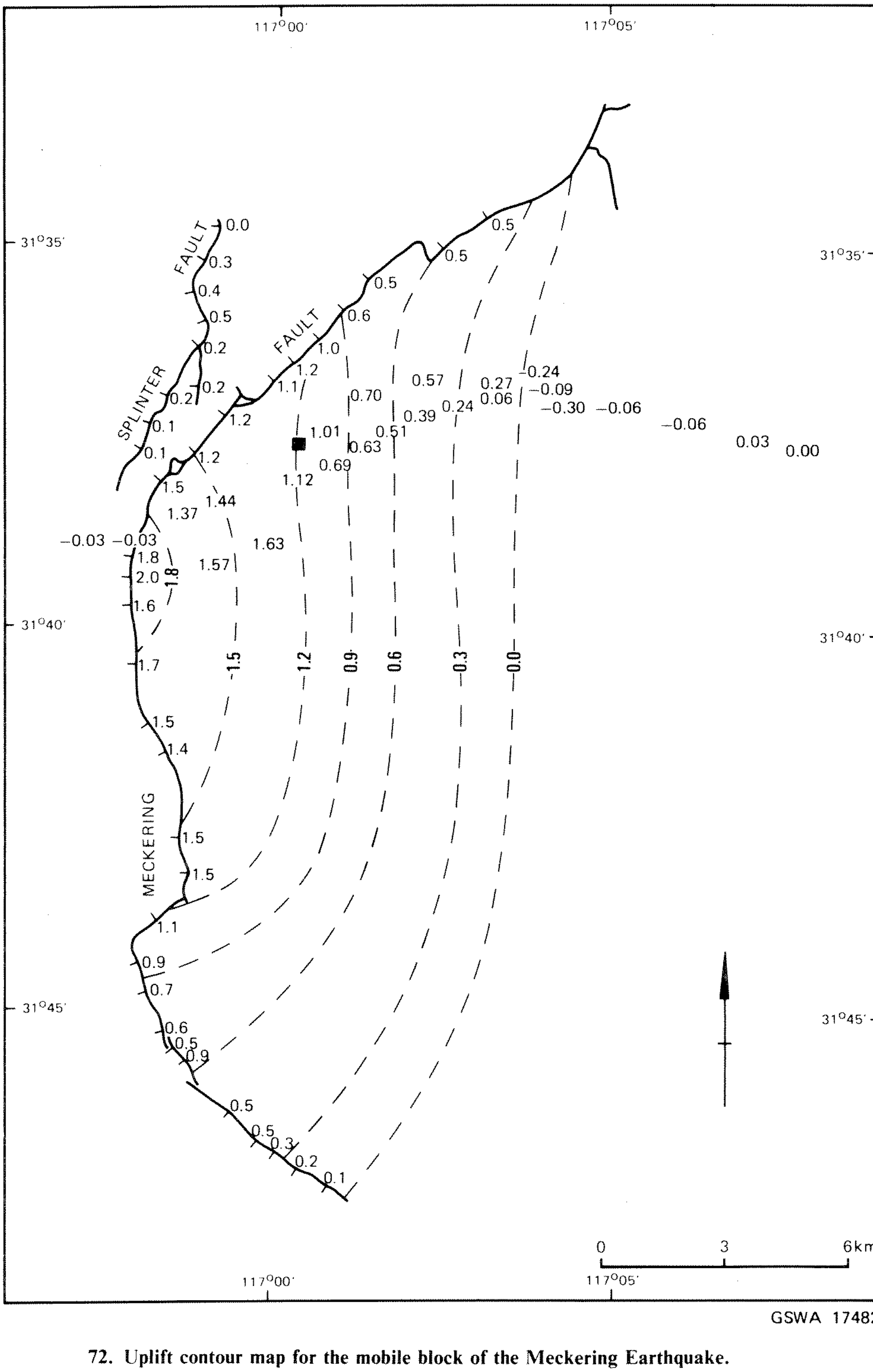
The levelling profile thus shows widespread ground distortion between Jennacubbine and Dowerin, to the north and west of Meckering. Unfortunately the results of the relevelling were not available until early 1970, when field work on the Meckering project had terminated. Investigations into the cause of the variations were hampered by the possible loss of minor surface cracking in the time that had elapsed. However, four sets of cracks across the road and in adjacent fields were found on either side of Dowerin in late 1970.

THE FORM OF THE UPLIFTED AREA

An attempt has been made in Figure 72 to contour the uplift of the mobile block associated with the Meckering Fault. Unfortunately the number of lines that were relevelled do not provide sufficient information on their own and must be supplemented with less accurately determined data. It was assumed that the uplift along the western margin of the block was given by the throw of the fault, and that minor faulting within the arc of the Meckering Fault caused insignificant changes. This was found to be true along the relevelled lines, where the western block was almost unchanged and such major features as the Chordal Fault caused no noticeable disturbance of the profile. It should be noted, however, that the considerable throw of the Splinter Fault has not been contoured or allowed for.

The shape of the contours have been drawn to be consistent with the course of the Blackscarp Zone which joins the northern and southern extremities of the Meckering Fault. On the levelling profiles, it was found that the western edge of the zone marked the intersection of the old and new surface levels and this has been extended to the whole mobile block.

The contours indicate that the block enclosed within the arc of the Meckering Fault was uplifted and tilted to the east. The easterly tilt continues into the Backscarp Zone as a slight depression and the movement is finally absorbed at the eastern edge of this 6 km wide zone. The total apparent downthrow of the small faults within this zone was 60 cm, compared with a maximum measured depression of only 20 cm on the water supply pipeline. The discrepancy was probably caused by the eastward tilt of many of the small fault-bounded blocks.



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72. Uplift contour map for the mobile block of the Meckering Earthquake.

CHAPTER 10

The Mechanism of Faulting at Meckering

At the time of the Meckering Earthquake, the area covered by the Southwest Seismic Zone had not been mapped geologically in any detail. A reconnaissance survey by Wilson (1958) had outlined a northwest trending belt of gneisses and high grade metamorphic rocks through Northam, flanked on either side by granites, but no major faults were found. The seismic zone itself had been delineated by many small earthquakes, but few had caused any significant damage, and none had caused surface faulting. The geomorphology of the region had been studied in more detail (Jutson, 1934), and it was known that the gneissic belt, and by inference the seismic zone, was an area of downwarp, bounded on the east by the Meckering Line. Wilson had proposed a major fault for the western margin, but detailed mapping southwest of Northam (Stephenson, 1970) failed to find any positive evidence for it.

The minor earthquakes which characterize the Southwest Seismic Zone had been studied only with respect to their distribution, thus there was no evidence from either geology or seismology to suggest a mechanism for the faulting at Meckering when it occurred in 1968. In addition to the lack of knowledge of the area, the Meckering event was not only unique in recent Australian geological history, but presented features which were difficult to interpret with the information available from other seismically active regions.

THE NATURE OF FAULTING AT MECKERING

THE SHAPE OF THE MOBILE BLOCK

As shown in Chapter 9, vertical movements connected with the faulting were confined largely to the block east of the Meckering Fault. Similarly, any horizontal ground movement west of the fault was probably minor in comparison with the eastward thrusting measured along the fault trace. The mobile block is thus bounded on the west by the Meckering Fault, except that to the northwest there were similar but much smaller movements along the Splinter Fault.

To the east, the boundary of the mobile block is not so well defined. The levelling profile between Meckering and Cunderdin shows a small positive anomaly for most of the distance, yet there is no evidence of faulting east of the Backscarp Zone, which joins the northern and southern extremities of the main fault. Also, the rise in ground level west of the Backscarp Zone is large, rising to maximum near the Meckering Fault scarp. The superficial shape of the mobile block is thus an arcuate segment bounded by the Meckering Fault and the Backscarp Zone.

The dip of the fault plane was approximately 45° throughout its length. If this dip continued at depth, the three-dimensional shape of the mobile block would be a section of a cone. However, the fault plane probably flattened at depth, and the overall shape of the mobile block was probably that of a segment of a saucer shaped body.

HORIZONTAL FAULT DISPLACEMENTS

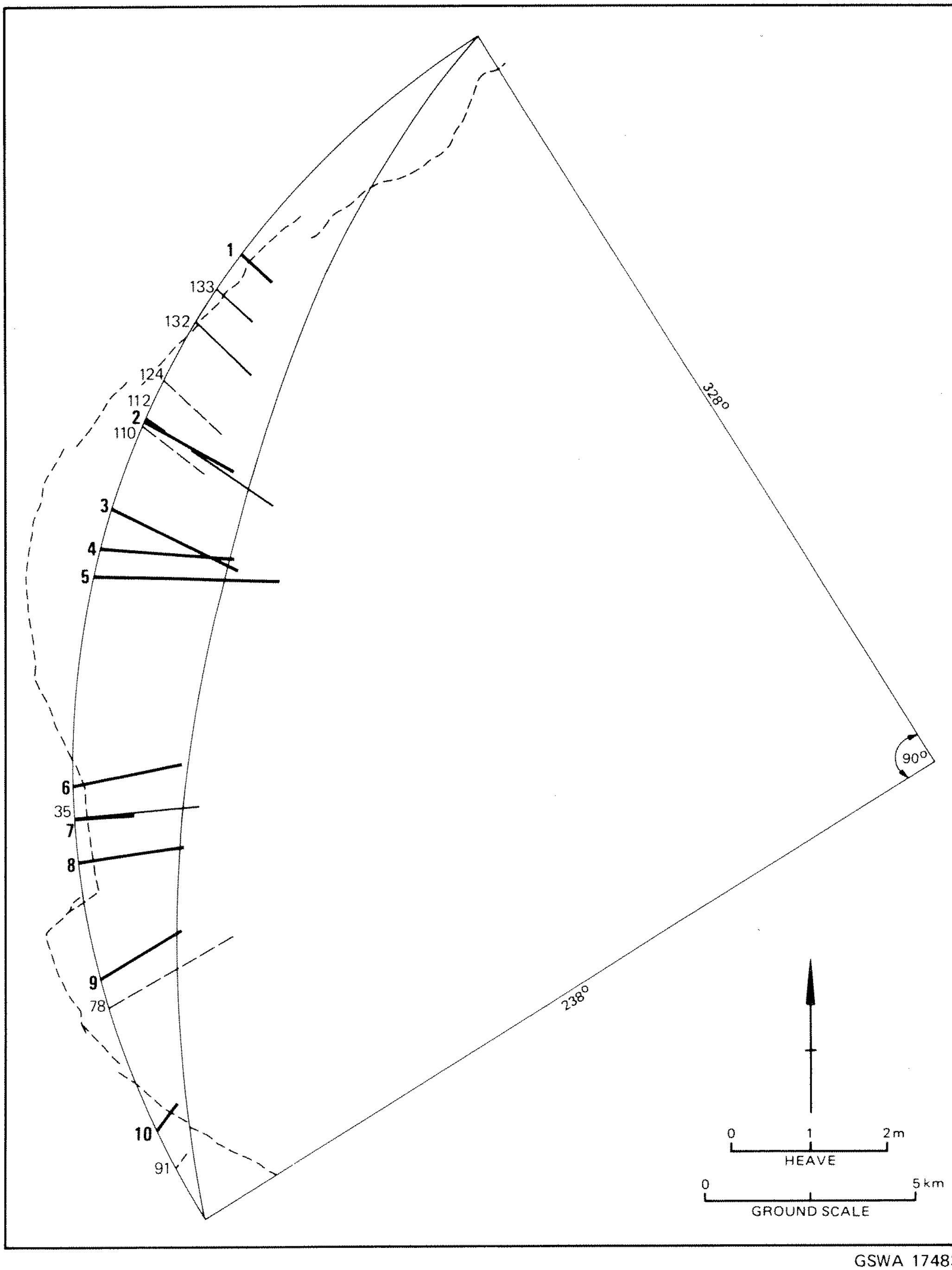
Total fault displacement along the Meckering Fault varied from zero at each end to a maximum at the most easterly point of the arc. Throughout the length of the fault there was a constant dextral strike-slip component which varied from 5.0 cm to 1.17 m (Table 9), but which, apart from these exceptional values, usually ranged between 30 and 70 cm.

If the fault trace is considered as a quadrant of a circle and the observed heave plotted along the arc then the resulting vectors are enclosed by a quadrant of an ellipse. This is shown in Figure 73, and the reasonably close approximation of displacements calculated from this figure to those observed in the field is shown in Table 19. The direction of the calculated and observed heave of the fault commonly agrees within 15°, and although the amount of heave diverges more noticeably, it follows the same pattern as that calculated. In the right hand columns of Table 17, a resultant displacement has been calculated assuming a constant dextral strike-slip of 50 cm, the average of the strike-slip observed, and this agrees even closer with the measurements taken in the field.

These observations, while not conclusive, provide a limitation to the type of model which must be constructed to explain the faulting at Meckering.

TABLE 19. CALCULATED AND OBSERVED DISPLACEMENTS OF THE MECKERING FAULT

Location	*Heave*				*Resultant displacement*			
	Calculated		*Observed*		*Calculated*		*Observed*	
	Direction (°)	*Distance (m)*	*Direction (°)*	*Distance (m)*	*Direction (°)*	*Distance (m)*	*Direction (°)*	*Distance (m)*
	I *Cadastrally surveyed displacements—see Table 9 and Plate 2*							
1	310	1.13	315	0.50	286	1.23	278	0.63
2	296	1.55	303	1.29	278	1.63	290	1.32
3	290	1.63	298	1.80	273	1.70	265	2.14
4	287	1.65	276	1.73	270	1.72	264	1.77
5	285	1.65	273	2.36	268	1.72	256	2.46
6	271	1.48	260	1.38	252	1.56	248	1.41
7	269	1.42	267	0.76	249	1.50	235	0.90
8	266	1.34	264	1.35	246	1.43	229	1.65
9	258	1.03	241	1.20	232	1.14	217	1.32
10	247	0.45	217	0.45	199	0.67	211	0.45
	II *Displaced Fence lines—see Table 10 and Figure 39*							
133	306	1.25	315	0.61	284	1.35	276	0.79
132	304	1.30	316	0.99	283	1.39	287	1.13
124	299	1.45	314	1.07	281	1.53	—	
112	296	1.55	306	1.98	278	1.63	285	2.12
110	296	1.55	306	0.99	278	1.63	—	
35	269	1.43	267	1.60	250	1.51	237	1.84
78	255	0.95	241	1.83	228	1.07	—	
91	244	0.25	224	0.20	182	0.56	—	



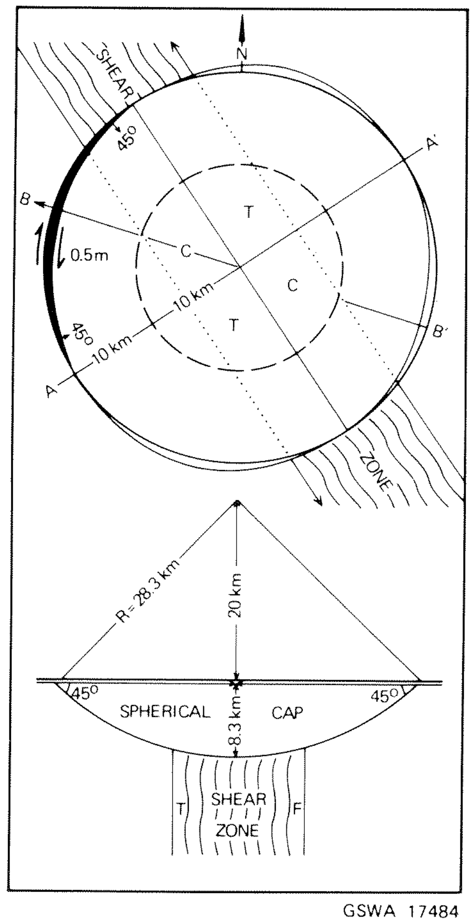
73. Measured heave of the Meckering Fault normalized to a quadrant of a circle. The inner arc is a quadrant of the ellipse which encloses the vectors.

A MODEL FOR COMPARISON

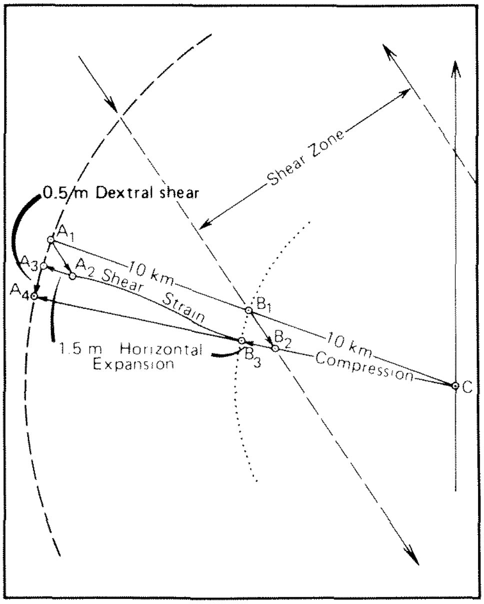
Assuming that the Meckering Fault represents a quadrant of a complete circle, the displacements given are those that could be expected if a fixed circular body was first subjected to shearing stresses, and then allowed to spring back to its original shape. A model based on this concept was proposed by Gordon and Wellman (1971) and is reproduced here with minor emendations.

Consider a circular cap, approximately 20 km in radius, resting on a vertical sinistral shear zone that is narrower than the cap (Fig. 74). The rock of the cap is assumed to be firmly attached to the underlying rocks. The centre of the cap is assumed to be fixed.

Sinistral shearing now takes place, the part of the cap above the shear zone is sinistrally strained, and the part outside is carried along bodily without being strained. The cap then snaps free from the underlying rock and resumes its unstrained shape, the snapping free causing the earthquake.



74. Plan and section of the postulated spherical cap and shear zone.



75. Diagram (not to scale) showing stages in the displacement of a line A-B-C at 45° to the inferred shear zone.

The shape of the margin of the cap immediately before (ellipse) and immediately after the earthquake (circle) is shown in Fig. 74. There are two quadrants of expansion and two of contraction, and counter-clockwise rotation of the whole cap that produces dextral faulting at its margin. The amount of dextral faulting is determined by the amount that the cap extends beyond the shear zone in cross section.

In order to estimate the extension of the cap, consider the stages of movement of line A-B-C in Figure 75. The line is in the compressional quadrant and at 45° to the strike of the shear zone. In the first stage (Fig. 75: A_1, B_1, C) the cap is unstrained. Gradual movement then takes place and in the second stage (A_2, B_2, C) the cap is strained to snapping point. It then suddenly snaps back into its unstrained shape as represented by stage three (A_4, B_3, C). During the gradual movement, the part of the line outside the shear zone moves parallel to itself, A_1 to A_2 and B_1 to B_2. There is no change in length. The part above the shear zone is rotated and shortened as B_1 moves to B_2. Because part of the line is rotated and part not, the initially straight line is bent at B_2. In the sudden movement the line B_2-C expands to its original length, B_2 moving to B_3.

The sudden movement outside the shear zone is considered as taking place in two steps. The first step is the result of the expansion causing A_2 to move to A_3, and the second is the result of the unbending at B, causing A_3 to move to A_4. The total resultant displacement is from A_2 to A_4.

The line A_2-A_3 is the maximum compressional heave, with a normalised value of about 1.5 m. The line A_3-A_4 is the dextral slip which has an average value of about 0.5 m. From the ratio 1.5:0.5 it is inferred that B-C is about four times the length of A-B, hence that the half-width of the shear zone is about 11 km.

The other lines through the centre of the cap must also be considered; the first is parallel to the shear zone, and the second is at right angles to it. For the first, there is no change in length and no rotation for either the gradual or the sudden movement. For the second, there is no change in length but a rotation greater than that of the 45° line for the sudden movement. It is assumed that the actual rotation of the entire cap is the average for all possible lines, and thus about that for the 45° line.

THE MODEL AND OBSERVED FAULTING

The match between the model and the pattern of faulting actually observed is inexact. The model postulates two quadrants of compression and two of extension, whereas in fact only a single compressional quadrant was observed. It is possible that the other quadrants exist, but that displacements were distributed and unobservable, or that movement on the other quadrants had taken place earlier or has yet to occur. The aftershock sequence at Mawson could be connected with the extensional quadrant south of Meckering, and an aftershock of magnitude 3.3 centred southwest of Cunderdin, in the compressional quadrant opposite Meckering, caused damage in the town on 25 May 1970.

Another assumption of the model is that the trace of the fault forms part of a circle. In fact the trace is more complex and consists of two exponential curves with their origins along the Burges Fault. As a result, when the heave was normalised to a circular fault in Figure 73 the direction was not radial but showed a pattern of divergence, the azimuth of heave being more northerly in the northern half of the fault trace and more southerly in the southern half.

THE MECHANISM DERIVED FROM SEISMOLOGICAL OBSERVATIONS.

The model proposed above was based purely on the observed faulting that resulted from the Meckering Earthquake. As shown earlier for the Alaskan and Kern County earthquakes, the pattern of surface faulting need not reflect accurately the underlying cause of an earthquake. An alternative approach is to study the directions of first motion as recorded on a number of seismographs throughout the world. For the Meckering Earthquake such a study has been completed by Fitch and others (1973), and confirms some of the features of the model proposed.

The seismograms of the Meckering Earthquake were unusually complex and suggested a multiple rupture, with the main shock following 3.5 secs after the initial rupture. Records of the main movement are consistent with a steeply dipping reversed fault trending 332° and dipping at 68° to the northeast. Although the amount of movement along this fault cannot be determined it is inferred that there was a sinistral strike-slip component equal to the reverse component.

The main event at Meckering proved difficult to read on Australian instruments, as many seismographs were over-driven. Records of the initial event from these stations are, however, in conflict with the solution for the main event, and suggest that the mechanism was different from that of the main event. It is possible that this initial event can be correlated with rupture along the arcuate, shallow dipping thrust fault observed at the surface.

The work of Fitch and others (1973), thus confirms that the underlying cause of the Meckering Earthquake was movement along an unobserved sinistral strike-slip fault, but with the addition that the fault had an equal reverse component along a steeply dipping fault plane.

DISCUSSION

Both the observational model and the seismological model agree in all essentials on the mechanism of faulting at Meckering. The observed faulting outlines a superficial cap of rock which was sheared off by movement along a deep-seated sinistral strike-slip fault. The underlying fault, being a sinistral thrust fault rather than a simple strike-slip fault, was more complex than that proposed in the simple model, but this probably explains better the actual shape of the mobile block. The idea of a vertical strike-slip fault led to the suggestion of a circular cap, but the presence of a sinistral thrust fault would not only tend to confine the faulted segment to the west of the underlying fault, it would introduce a more complex stress pattern which might account for the non-circularity of the actual fault trace. As noted earlier, the actual trace of the northern section of the Meckering Fault follows a logarithmic curve of the general formula $Y = ae^{bx}$ (Fig. 56). Durrance (1967) has shown that a family of such curves is produced as the maximum shear-strain trajectories from a point pressure acting vertically, and that the resulting fracture surfaces would be logarithmic spirals originating from the axis of compression. However, if the pressure is not vertical the shear-strain trajectories are distorted and Durrance has constructed the pattern for a compression inclined 65° to the horizontal. This inclination is close to the 68° dip calculated for the major fault underlying Meckering and it is noteworthy that the trace of the Meckering Fault fits well the shear-strain trajectory which lies along the long axis of the distorted pattern. Furthermore, the long axis is parallel and close to the position of the Chordal Fault and cuts the trace of the Meckering Fault at the point where the fault trace curves northward along a direction of 035°. It appears possible, therefore, that the actual shape of the Meckering Fault trace is that of a major shear fracture produced in an overlying cap of rock by reverse movements on an underlying fault.

The observational model is consistent with the reports of local observers and the sequence of movements of the Meckering Fault. The earthquake was felt in three distinct pulses, the first vertical and the other two dominantly east-west shaking. These observations were confirmed by examination of overthrown objects especially monuments in Meckering townsite and cemetery. The first pulse possibly represented rupture along the major underlying reverse fault, while the later periods of shaking were caused by thrusting on the Meckering Fault. At a number of points the Meckering Fault was shown to have moved in two separate phases, an initial thrust followed in time by dextral strike-slip motion, both of which would have produced horizontal shaking. The model allows for all three pulses and it appears that, in the case of the Meckering event, close geological observation has yielded explanations which would not normally be obtainable from instrumental records alone.

Unequivocal surface evidence for the existence of a deep-seated sinistral thrust fault beneath Meckering is lacking, but some evidence presented earlier can be interpreted to give support.

The epicentre of the main event and all the foreshocks of the Meckering Earthquake were located northwest of the township, in the area between the Splinter Fault and the Meckering Fault, by the Mundaring Geophysical Observatory. That these locations were correct was shown by local reports of felt intensity and by minor damage sustained in this area during the foreshocks of 3rd October. If the focus of these shocks is assumed to be on the plane of exposed faulting then it is possible that rupture was begun on the small Splinter Fault, but became effectively transferred to the larger Meckering Fault. The main event, however, has been postulated by Fitch and others (1973) to have occurred on a major underlying sinistral reverse fault, and it is possible that the foreshocks had the same origin. The epicentre of the main event should give one point on this major fault which had a trend of 332°. The only surface fault in the Meckering area which followed this trend was the small Sudholz Fault northeast of the town. This fault also showed a small sinistral movement, in contrast to the major surface faults, and terminated near a sinistral offset in the Meckering Fault. If extended, the line of the Sudholz Fault passes close to the epicentre of the main event, and it appears that this fault was the surface manifestation of the major underlying fault which was responsible for the Meckering Earthquake.

In describing the relationship of faulting to geomorphology (Chapter 8), it was noted that a conspicuous line of granite outcrops crossed the Meckering area with a southeasterly trend, parallel to the Meckering Line. This is the same 330° trend as measured seismologically for the underlying major fault that caused the earthquake. A line drawn at this azimuth through the epicentre of the main event passes along the line of breakaways that form the Meckering Line and immediately to the west of the granite outcrops. It appears possible that these outcrops occur because of repeated small uplifts along the line of the major fault, and some evidence for this may be the small uplift that was noted in levels along the Great Eastern Highway between Waeel and Cunderdin.

Geodetic measurements and levelling circuits made by the Lands and Surveys Department also provide evidence for the existence of an unobserved major fault. Considerable ground distortion was noted in the vicinity of Dowerin, north-northwest of Meckering, during relevelling of the northern circuit, but the disturbance was over a wide zone, and there was little evidence of movement along a single fault plane. Similarly, the geodetic measurements can only give indications of extension or contraction over a zone but the lines Karrabein-Berring and Karrabein-Cunderdin cross the supposed sinistral thrust fault at low angles so that strike-slip movement should be reasonably reflected in any changes in length. Karrabein Hill is to the west of the fault and the other two stations to the east, with Berring to the north and Cunderdin to the south of Karrabein. From Table 14 it will be seen that, between 1958 and 1968, the Karrabein-Berring line increased by 36.6 cm, which is consistent with a sinistral strike-slip movement along a fault between the two stations. However, for the same period the Karrabein-Cunderdin line also increased, by 9.5 cm and this suggests a dextral movement.

Measurements made by the Australian Division of National Mapping along the same line, shortly before and after the earthquake, suggest a sinistral movement, but, as shown in Chapter 9, the only way of reconciling the two measurements is to propose a large dextral movement between 1958 and early 1968, followed by a smaller sinistral movement in October 1968. Thus, while geodetic measurements support the notion of strike-slip movement along a fault through Meckering the results are not consistent with any simple picture of the motion.

THE ENERGY OF THE EARTHQUAKE

As the main outlines of the mechanism of the Meckering Earthquake have been established, it is possible to calculate the energy released in the main event. Neglecting the comparatively small amount of energy required to cause the dextral component of faulting the principal energy was that needed to strain the rock in that part of the mobile cap resting on the shear zone. This energy can be calculated from the formula

$$E = \tfrac{1}{2}\, V S^2 \mu$$

Where V is the volume of rock, S the strain, and μ the coefficient of rigidity.

If the strained rock is assumed to extend about 10 km deep and the area above the shear zone to be about 20 km × 11 km, then the volume of rock involved is about 2 200 km^3, or 2.2×10^{12} m^3. From Figure 75 the shear strain is 2 m in 11 km or 1.8×10^{-4}, and according to Gutenberg (1951) the rigidity of granite is 3×10^{10} Pa.

From these figures the total energy released is calculated as 1.1×10^9 MJ, which is of the same order as the energy calculated from empirical formulae and detailed in Chapter 4.

CHAPTER 11

The Calingiri Earthquake of 11 March 1970

Early in the morning of 11 March 1970, seventeen months after the Meckering Earthquake, a magnitude 6 earthquake having its epicentre 4 km southeast of Calingiri, produced the second fault scarp in the recorded seismic history of Western Australia. There were no reported injuries, and property damage was minor, but the earthquake was felt over a large part of southern Western Australia.

The Calingiri Earthquake was important not only because it produced surface faulting, but because it gave meaning to a mass of data which had been collected after the Meckering Earthquake. The two events appeared to be spatially connected and the Calingiri Fault gave confirmation of the proposed geological mechanism of the Meckering Earthquake. In most senses the Calingiri Earthquake can be seen as a distant aftershock of the Meckering Earthquake.

Field investigations were undertaken in March and April 1970 by F. R. Gordon and B.P. Paterson utilizing air-photos made for the purpose by the Lands and Surveys Department. The faulting occurred entirely on the property of Mr G. D. Lindsay, and his interest and co-operation, along with that of Mr F. Cooper, Shire Clerk of Victoria Plains, is acknowledged.

THE TOWN OF CALINGIRI

Calingiri is a small township 111 km northeast of Perth and 77 km northwest of Meckering. It is the administrative centre of the Victoria Plains Shire, and has a population of about 150 people. Like Meckering the town is a local centre for the wheat and sheep farming of the area.

The landscape is generally flat, with wide plains of residual and alluvial sand, and few rock outcrops. The underlying rocks are vertically foliated Archaean migmatites and metasediments to the west of the town, and equigranular granite to the northeast. A few dolerite dykes and quartz veins are also exposed.

EARTHQUAKE EFFECTS

SEISMIC SHAKING

Because the earthquake occurred at 1.15 a.m., most people were asleep, and there were few reports other than of a general shaking. The earthquake was felt over a wide area, and in Calingiri the shaking lasted about 30 secs, although cars were noticed to be still rocking several minutes later. In Perth, many people were awakened by the shock, especially those living in high-rise buildings. According to newspaper reports, windows rattled and light bulbs swung for up to five minutes, although the seismic shaking was felt for only a few seconds.

DIRECTION OF SHAKING

Although the Calingiri Earthquake was much less severe than the Meckering Earthquake, there were numerous reports of objects being overturned and water being slopped over the side of storage tanks.

A 91 kl concrete tank was situated at the top of a hill slope 66 m east of the Calingiri Fault scarp. Prior to the earthquake the tank was full to within 30 cm of the top. Examination during the morning following showed that about 2 kl of water had splashed out on the western side of the tank towards the fault. A 4.5 kl tank beside a farm building 1.9 km east of the fault scarp also lost a quantity of water, which splashed out westward towards the fault. The tank itself was moved 21 cm on a bearing of 275°, breaking two asbestos cement sheets, and coming to rest against the back verandah of the house.

A massive concrete pillar 1 m high, with a 35 cm square base was bolted at the top to a wooden block and was close to the wall of a house 500 m east of the south end of the fault scarp. There had originally been a gap of about 0.3 cm between the wall and the block but movement in the direction of 165° during the shaking had been sufficient to close this gap and break off the top of the pillar.

Throughout the Calingiri district there were several reports of small objects being overthrown to the west. At Wyening telegraph station, 10km south of the fault scarp, the shaking was particularly strong, and the motion was clearly described as coming from about 070°, overturning crockery and household items to the west.

DAMAGE TO BUILDINGS

Although the Calingiri Earthquake was felt over a wide area, significant damage was confined to the epicentral region. A complicating factor, however, was that the earlier Meckering Earthquake had also damaged or weakened structures in the Calingiri district, and it was usually not possible to separate the two effects.

In general, more damage was caused east of the fault than to the west of it, a pattern similar to that at Meckering; and the felt intensity of the earthquake was also greater to the east. Amongst the most seriously damaged structures were three dwellings on the property of Mr. G. D. Lindsay, all situated east of the fault scarp. Substantial damage occurred to a rather old but solid brick house 2.5 km north-northwest of the northern end of the fault. A brick wall cracked through from the window frame to the top of the wall and shifted slightly, leaving a 2.5 cm gap. An asbestos cement dwelling, 2 km east of the southern end of the fault showed signs of damage at the corners, and the ceilings were displaced, but only one concrete foundation block was moved slightly.

To the west, the fault damage was usually minor, and in Calingiri, about 4 km northwest of the fault, there was little damage done.

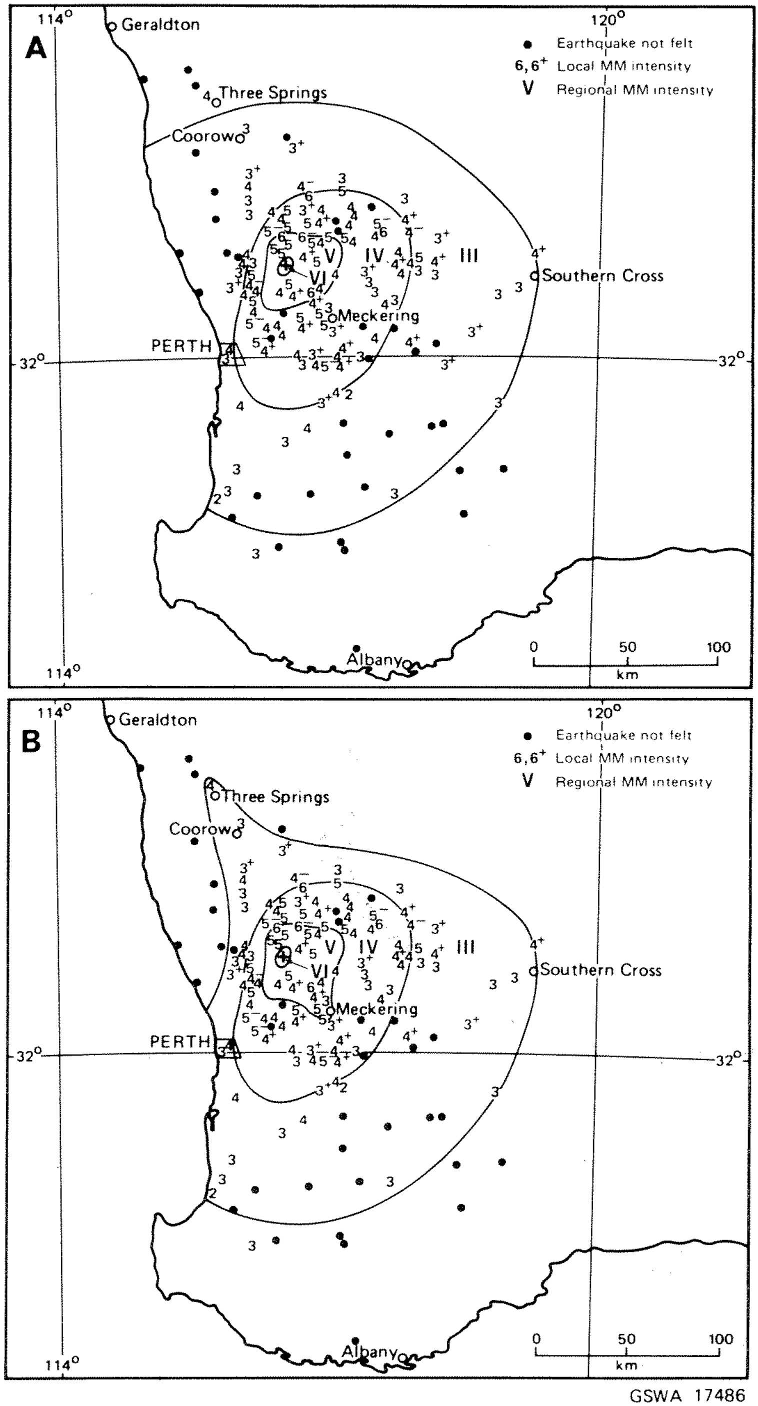
Elsewhere in the Calingiri district, damage from the Meckering Earthquake was often more substantial than from the local event, and in several instances damage repaired after the Meckering Earthquake was cracked open again. An example of this was a house 9 km northwest of the Calingiri Fault and 84 km northwest of Meckering. The earlier shaking had cracked all the concrete columns supporting the verandah around the house and displaced or cracked several interior walls. This damage had been repaired at a cost of $1 600, and the Calingiri Earthquake reopened cracks in the newly repaired walls, although not to the full extent of the original damage.

Serious damage was also done to a farm house 16 km southeast of Calingiri, in the vicinity of Wyening. However, in view of the surprising history of seismic activity at this locality, it was difficult to estimate the structural condition of the house before the Calingiri Earthquake. The house had been repaired following seismic shakings in 1948, 1952, 1958 and 1964, although there may have been a lag of several years between damage and repairs. In each case the noise of the earthquake had appeared to approach from the southwest. Prior to the Meckering Earthquake, the most severe damage was done in 1952 when Bolgart, 10 km southwest, was heavily shaken. The latest repair bill had been for $3 000, but, although the Meckering Earthquake caused extensive ground movement, only small cracks appeared in the cement brick house. During the shaking from the Calingiri Earthquake, ground movement was not as great as during the Meckering event, but more damage was caused. Cement bricks were broken through at the corners of the house, and walls moved outward. The estimated cost of bracing and tying the walls was about $2 000.

ISOSEISMAL MAP OF THE CALINGIRI EARTHQUAKE

The Calingiri Earthquake was felt in an area bounded by Three Springs, Southern Cross, Bridgetown and the coast, an area of approximately 130 000 km^2. Accurate assesment of the felt intensity, however, was difficult because the earthquake occurred at night when most people were asleep, and damage was slight. Nevertheless, Everingham and Parkes (1971) have constructed an isoseismal map (Fig. 76) from replies to 360 questionnaires. At Calingiri, the intensity reached MM VI, some three grades lower than the epicentral region of the Meckering Earthquake and the MM V isoseismal covered an area of only 25 x 15 km. In Perth, however, the intensity reached MM IV in places, the same as the lowest intensity produced by the earlier event. The Calingiri Earthquake was thus felt relatively more strongly than the Meckering Earthquake, possibly because of the lack of any geological barriers between the epicentre and Perth.

The general shape of the isoseismals as drawn in Figure 76 is oval, with the major axis slightly east of north, but as with the Meckering isoseismal map (Fig. 19) a detailed examination of the intensity readings would allow some modifications. Between Calingiri and Three Springs, in the MM III zone there is a line of intensity values of MM III-IV flanked by numerous localities where the shaking was not felt. If the record near Jurien is discounted then this would allow the MM III isoseismal to be redrawn to show a spur towards Three Springs, on line with the Southwest Seismic Zone. Similarly, it is possible to extend the MMV isoseismal in a southeast direction, to encompass a series of anomalous MM V intensity records in the vicinity of Meckering.



76. Isoseismal maps of the Calingiri Earthquake.
(a) after Everingham and Parkes (1971)
(b) as modified by J. D. Lewis.

SEISMIC DATA OF THE CALINGIRI EARTHQUAKE

SEISMIC HISTORY

Perth Observatory files covering the period from 1904 do not record any seismic activity in the Calingiri area until 1952. On 11 March of that year a substantial earth tremor was recorded on the long period instrument at Perth, and tall buildings in the city swayed. The Post Office at Bolgart rocked, and ceilings were cracked in the new school. The seismic shaking was felt over a wide area, and the epicentre was located at 31°S, 116½°E, about 13 km northeast of Calingiri. Aftershocks were felt between the 12th March and 28th April, causing walls and ceilings to crack in Bolgart (Everingham, 1968).

On 30 April 1955, Perth Observatory recorded an earthquake near Calingiri, and the seismic shaking was felt over a radius of 130 km, indicating a magnitude of about 4.7. Later in the year, between 29 and 31 August, three shocks were recorded in Perth, which from felt intensities were located at Yerecoin, about 19 km north of Calingiri. During 1956, Konnongorring, 32 km east of Calingiri, suffered two minor earthquakes, and a third was recorded in 1957.

In 1963, the three component seismograph at the Mundaring Observatory recorded an earthquake near Carani, 13 km north of Calingiri. This was felt 40 km to the north-northeast and 105 km to the east and was assigned an instrumental magnitude of 4.9 (Everingham, 1968).

Between the Meckering Earthquake of 14 October, 1968 and the 11 March 1970, the Calingiri district experienced thirteen shocks of magnitude 3.0 or more, and numerous smaller shocks. These will be considered later, but in the week preceeding the Calingiri Earthquake several minor foreshocks were recorded at the Mundaring Observatory.

THE PRINCIPAL EVENT—THE CALINGIRI EARTHQUAKE

The seismic data for the Calingiri Earthquake have been determined by the Mundaring Geophysical Observatory and are reproduced below from the reports of Everingham and Parkes (1971), and Gregson (1971).

The origin time for the earthquake was 10th March 1970, at 17h 15m 11.2s U.T., or 11th March at 01h 15m 11.2s Western Standard Time. The epicentre was located at 31.11°S, 116.47°E, about 4 km southeast of Calingiri, and the computed depth of focus was 1 km. The magnitude determined locally was $M_S/M_L = 5.7$, and the magnitude determined from the body waves varied from $m = 5.7$, reported by the U.S. Coast and Geodetic Survey, to $m = 6.5$ determined by Mundaring. The magnitude finally adopted by Mundaring was $m = 6.2$.

THE ENERGY OF THE EARTHQUAKE

As noted in Chapter 4, the ideal method of comparing earthquakes is to compare the energy released, and, to this end, a number of empirical formulae have been developed which allow an approximation to be made. The formulae have been derived, however, from moderate earthquakes of magnitude $\geqslant 6$ and for focal depths of 10-20 km, and some are not applicable to such shallow events as the Calingiri Earthquake.

The formula most commonly accepted which relates energy to magnitude is:

$$10^{13}\text{Log } E = 11.8 + 1.5 \text{ Ms}$$

if the magnitude is taken to be Ms = 6, then the energy released would be 6.3×10^7 MJ.

Tocher (1958) has developed relationships between the length of faulting and magnitude, and between the product of the fault length and maximum displacement and magnitude, which when combined with the above formula allow a calculation of the energy involved. Recalculating the formulae to account for the particular formula used to relate magnitude and energy, they are:

$$10^{13} \text{ Log } E = 20.3 + 1.47 \text{ Log } L$$

and $$10^{13} \text{ Log } E = 19.63 + 0.8 \text{ Log } LD$$

where L is the fault length in kilometres and D the displacement in centimetres. Substituting the fault length of 3.24 km and the maximum net slip of 39.6 cm these formulae give an energy release of 1.1×10^8 MJ and 2.0×10^8 MJ respectively.

Comparing these figures with those obtained from the Meckering Earthquake of magnitude 6.8 suggests that the earlier event released between thirty and one hundred times more energy than the Calingiri Earthquake.

SURFACE FAULTING AND MAGNITUDE

In Chapter 4 the equations developed by Bonilla (1970) for the relationships between magnitude, displacement and the length of surface faulting were applied to the Meckering earthquake. These empirical formulae may also be applied to the Calingiri event. The formulae are:

$$\text{Log } D = 0.57 \text{ M}_L - 3.91$$

$$\text{Log } D = 0.86 \text{ Log } L - 1.15$$

where D is the maximum displacement (in metres) and L is the fault length (in kilometres).

Substituting $M_L = 6.0$ in the first formula gives a calculated displacement of 32.6 cm which is in close agreement with the measured maximum displacement of 33 cm. The measured fault length was 3.24 km, and substituting this in the second formula gives a calculated displacement of 19.5 cm, a little over half the measured displacement.

As was found with the Meckering event, Bonilla's formulae could be applied in Western Australia to give realistic estimates of surface faulting.

FORESHOCKS AND AFTERSHOCKS

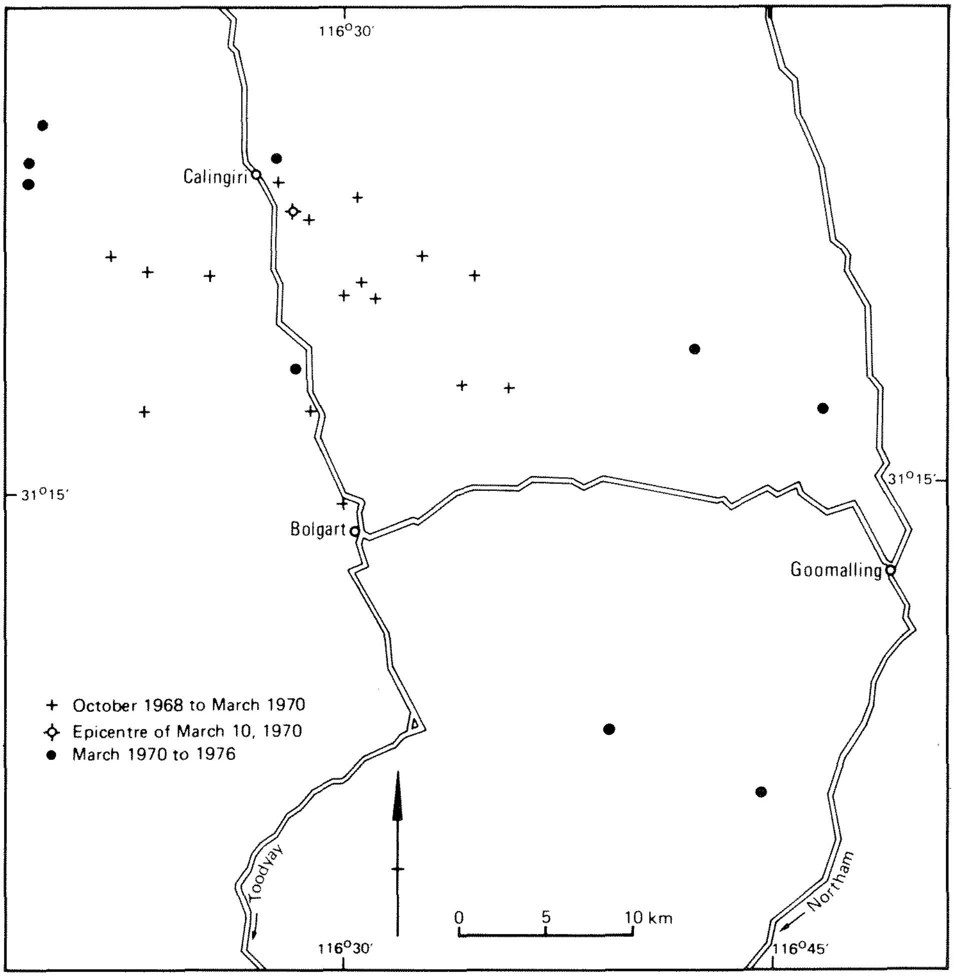
Unlike the Meckering event, there was no pattern of foreshocks or aftershocks which could be related exclusively to the Calingiri Earthquake. Following the Meckering Earthquake there were frequent minor tremors and several larger events in the Calingiri area, but this activity diminished during the later months of 1968 and throughout 1969, in line with the diminishing activity around Meckering. There was a slight increase in activity during 1970, including the main Calingiri Earthquake, but since 1971 there have been few tremors of magnitude greater than 3.0.

Table 20 lists the larger earthquakes in the Calingiri area between October 1968 and 1976, and the computed epicentres are plotted on Figure 77. Smaller tremors, more numerous but with a similar distribution, are listed in the Annual Reports of the Mundaring Geophysical Observatory. Of the twenty-seven earthquakes listed in Table 20, it will be seen that seventeen occurred between October 1968 and March 1970, and twelve of these in 1968. Only nine major tremors followed the main Calingiri event, and since 1973 activity has ceased. This pattern of events parallels the decline of activity at Meckering (Table 8), and provides evidence that the Calingiri Earthquake can best be seen as a major, but distant, aftershock of the earlier event.

The epicentres plotted on Figure 77 occur in a broad band trending southeasterly towards Meckering. Prior to the Calingiri event, the epicentres were centred on Calingiri itself, and there appeared to be no major activity along the zone of ground distortion northwest from Meckering. Since March 1970, however, the minor activity has been centred on an area 12 km north-northwest of Calingiri and in the broad zone between Meckering and Calingiri.

TABLE 20. EARTHQUAKES OF MAGNITUDE (M_L) GREATER THAN 2.8 IN THE CALINGIRI AREA, OCTOBER 1968—OCTOBER 1976

Date	*Origin time (U.T.)*	*Latitude °S*	*Longitude °E*	M_L	*m*
1968					
Oct 26	22 36 20.1	30.91	116.40	3.4	4.4
26	15 32 04.0	31.15	116.52	3.4	4.3
29	06 37 15.0	31.14	116.51	3.5	4.4
30	03 21 04.7	31.14	116.42	3.4	4.3
Nov 04	07 37 28.4	31.15	116.50	3.2	4.1
10	00 37 10.0	31.13	116.55	3.0	3.9
23	00 09 48.5	31.10	116.51	3.6	4.5
23	00 59 44.0	31.11	116.48	2.8	3.9
Dec 04	01 16 58.3	31.14	116.58	3.3	4.3
07	07 27 27.7	31.09	116.46	3.4	4.4
11	05 00 04.0	31.21	116.38	3.0	4.1
18	21 54 57.2	31.21	116.48	3.4	4.3
1969					
Mar 25	13 56 17.7	31.14	116.38	4.4	3.5
	15 19 16.9	31.13	116.38	3.5	4.4
Aug 01	08 48 32.0	31.2	116.6	2.8	4.0
14	06 13 52.0	31.20	116.57	2.6	3.9
Nov 05	07 06 39.8	31.26	116.50	2.8	4.0
1970					
Mar 10	17 15 11.2	31.1	116.47	5.7	6.2
Jul 19	16 38 02.0	31.18	116.71	3.8	4.5
Oct 05	13 30 36.4	31.08	116.46	3.1	4.1
Dec 26	18 25 51.0	31.08	116.31	4.0	4.6
26	18 32 40.3	31.06	116.32	3.2	4.1
26	21 57 55.2	31.09	116.31	3.0	3.9
1971					
Aug 04	00 27 47.4	31.19	116.47	3.1	4.1
1972					
Jul 03	07 28 57.2	31.41	116.75	3.4	4.2
1973					
Apr 02	14 23 14.5	31.21	116.79	3.0	3.8
Oct 31	10 33 02.1	31.38	116.66	3.3	3.9



77. Epicentres of earthquakes (M_L>2.9) in the Calingiri area between October 1968 and December 1976.

TECTONIC GROUND BREAKAGE

Faulting was much less prominent at Calingiri than Meckering, but many features similar to the fault pattern of the earlier earthquake were reported. The main Calingiri Fault was a slightly arcuate, sinistral thrust fault a little over 3 km long, which had several small sinistral and dextral offsets in the trace. About 0.7 km east of the northern end of the Calingiri Fault there was a small, dextral normal fault which resembled the Chordal Fault at Meckering. Tension fractures to the rear of the main scarp were common, and there was one area of secondary slumping. Two areas of older ground fractures, intimately associated with fresh fractures of the Calingiri event, were possibly caused by the Meckering Earthquake.

The thrust scarp of the Calingiri Fault traversed a variety of soil types, but no fresh or weathered rock was cut. The shallow angle of thrusting and the comparatively small size of the scarp meant that the feature was particularly vulnerable to destruction by animals and the elements. Winter rains eradicated many small features and the scarp is now only a bump in the fields and a kink in some fence lines.

THE CALINGIRI FAULT

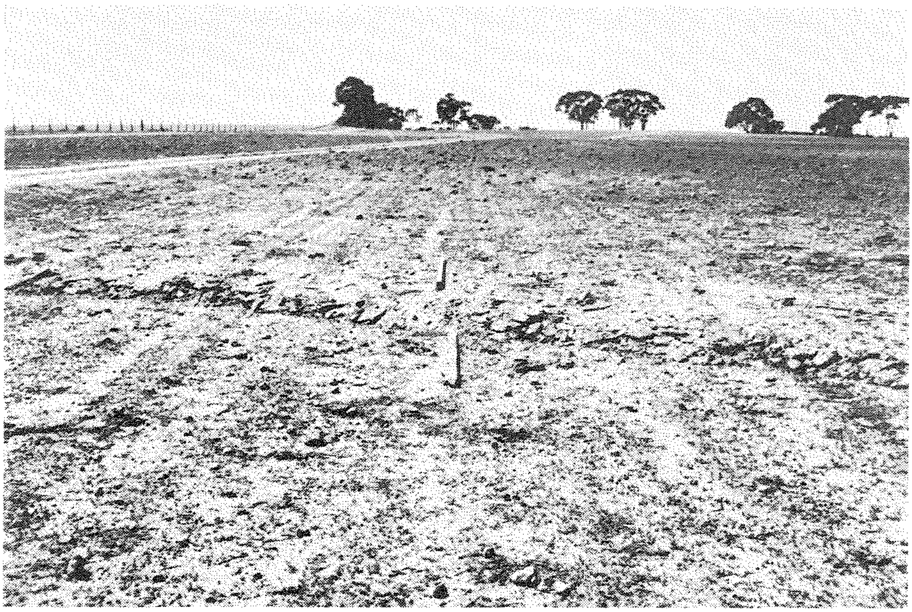
The Calingiri Fault, 3.24 km long, had a trend of 008°, and was centred on latitude 31°06.7′S, longitude 116°28.2′E. The fault trace was slightly arcuate, concave to the east, and was in two sections separated by an outcrop gap of about 100 m that occurred 350 m southwest of the intersection of the fault with the Calingiri-Goomalling road.

DIP OF THE FAULT PLANE

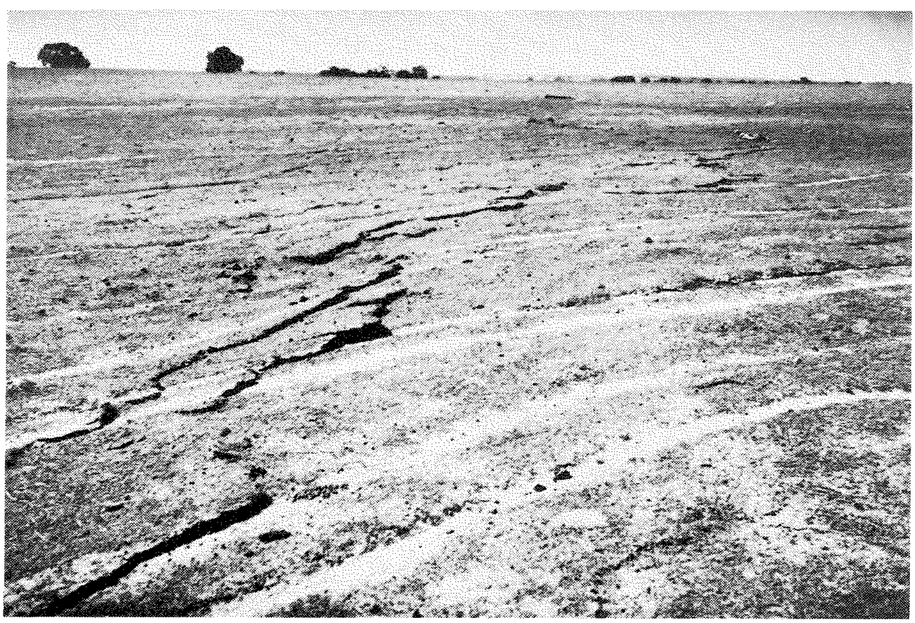
The most westerly portion of the fault traversed firm, heavy soil, and displayed a clear-cut thrust plane. A series of seven dip readings, ranging from 12° to 25°, was made, (Plate 5) giving a modal value of 18° eastward. In a deeply entrenched stream channel near the southern end of the fault, and in the drain alongside the Calingiri-Goomalling road, dips of only 10° were measured on the fault plane. In more compact soil a few hundred metres north of the road, the steepest dip, 31° eastward, was measured. The dip calculated from fault displacement was about 40° to the east; this indicates that the fault plane flattens when it enters the soil horizon. The extremely shallow dips recorded in the drain and stream sections were probably caused by the poorly consolidated soils at these locations. The near surface flattening of the fault plane was the probable cause of open tension cracks immediately to the east of the fault scarp.

78. Central portion of the southern section of the Calingiri Fault, looking north along the 28 cm-high thrust scarp.

A



B



79. Calingiri Fault, southern section:
(a) Sinistral displacement of 12 cm measured on plough furrows.
(b) Dermal subthrusting at the northern end of the southern section.

THE SOUTHERN SECTION OF THE CALINGIRI FAULT

The southern part of the Calingiri Fault was 2.0 km long and could be divided into several sections. Fault displacements were at a maximum near the centre of the fault trace (Fig. 78), and decreased both to the north and south (Plate 6).

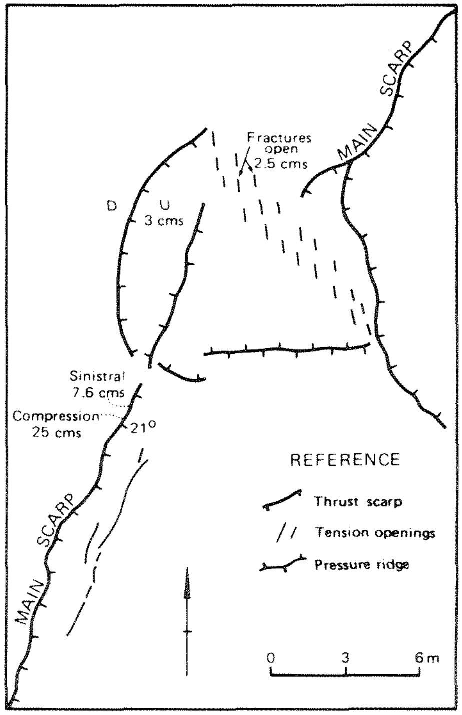
The fault began as low north-northeast-trending compression roll in Loc. 4604, but on crossing a small stream turned abruptly to a northerly course and followed a slightly arcuate path into Loc. 1223. Following a dextral offset in the fault trace there was a short section trending just east of north, in which displacements were at a maximum, and which ended in a further large dextral offset. The final 300 m of the fault trace trended 030° and displacements rapidly died out (Fig. 79b).

At the southern end of the fault, the vertical uplift of the eastern mobile block rapidly rose to about 13 cm, and then remained at between 13 cm and 20 cm until the fault passed into Loc. 1223. At the fence line, the elevation was 28 cm, but this rapidly died out northward as the scarp was replaced by a parallel scarp to the west. The compressional heave along this section of the fault was between 10 cm and 15 cm. Two small sinistral offsets were present in this part of the fault, and in each case, the fault was replaced by a parallel scarp to the west. No open wrench faults joined the scarps, and this suggests that sinistral movement on each portion of the fault was small or similar in amount. On the southern side of Loc. 1223 the sinistral step in the fault trace was accompanied by several small parallel subsidiary thrust scarps to the east of the main fault. These had no visible surface connection to the main scarp, and had a maximum length of about 100 m.

In Loc. 1223, the character of the fault changed; displacements rose to a maximum, and steps in the fault trace were dextral rather than sinistral. The maximum throw of the fault rose to 38 cm, and a sinistral strike-slip movement of 14 cm was measured on a fence line. The maximum heave of 25 cm westward was also found in this section of the fault. The dextral offsets in the fault were large compared with the sinistral offsets noted further south, and only in the northern and largest step was there a small outcrop gap. In both instances, the main fault scarp turned to a more easterly trend and changed to a strike-slip fault of small dextral movement. As movement on the main fault was sinistral, however, the easterly trending portions become pressure ridges rather than open fissures as found on the Burges Fault at Meckering.

In general, the form of the thrust scarp was quite simple, a compressional roll or suprathrust scarp, backed by occasional small tension cracks formed by the flattening of the fault plane in the unconsolidated soil. In parts, however, the scarp was complex, and an example is shown in Figure 80. This is a detail of the fault at the point of maximum heave. The main fault, showing a compression of 25 cm and a sinistral strike-slip of 7.6 cm died out northward in a small suprathrust and subthrust scarp before a small dextral offset of 4.5 m. Between the two portions of the main fault there was an east trending pressure ridge and a northwest trending set of small, open, *en echelon* shears.

After the last dextral offset in the trace, the fault continued a north-northeasterly course in Loc. 2245 as a series of *en echelon* dextrally offset shears of steadily diminishing displacements. This section of the fault began in Loc. 1223 as a northerly trending thrust scarp parallel to, and 140 m east of, the main fault trace. At the fence line a dextral



80. Complex portion of the southern section of the Calingiri Fault.

strike-slip displacement of 7.6 cm was measured, compared with a 14 cm sinistral strike-slip on the main fault, which indicates that sinistral movement on this last section of the fault was smaller than that of the block enclosed between the two parallel scarps.

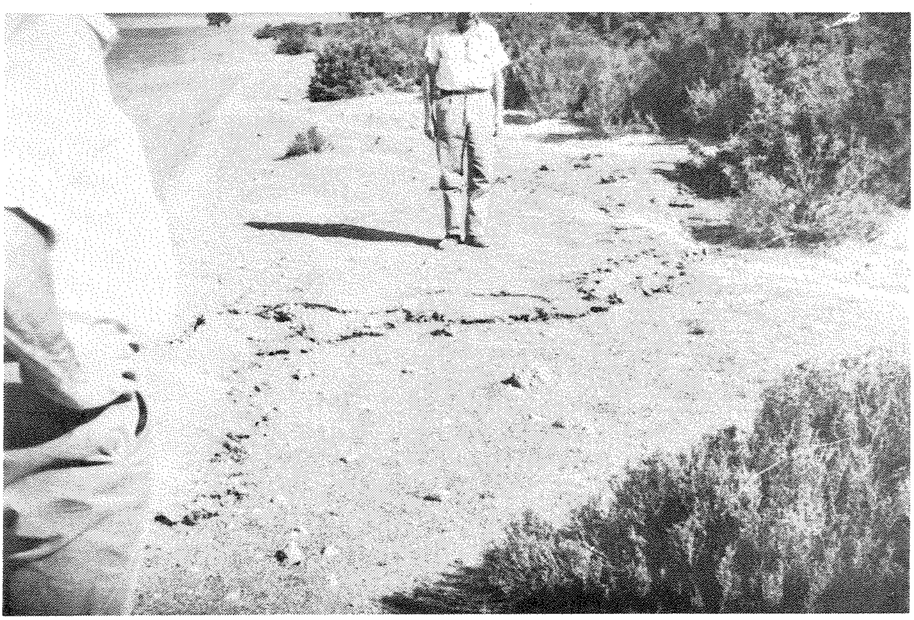
THE NORTHERN SECTION OF THE CALINGIRI FAULT

After an outcrop gap of about 100 m, the northern section of the Calingiri Fault followed a course trending 011° for a further 1.2 km. A small gap near the centre divided this portion of the fault into a southern complex section and a northern, relatively simple section. No fault-plane measurements were possible in the sandy soil at the northern end of the fault, but a dip of 31° east was obtained in the complex section of the fault where both horizontal and vertical displacements were at a maximum. Throughout the whole of the northern section of the Calingiri Fault, the displacements were only about one quarter of those recorded in the southern section.

In Loc. 2245, south of the Callingiri-Goomalling road, the thrust scarp was a series of small *en echelon* thrusts with a sinistral offset. At the road, the uplift of the eastern block was only 7.6 cm. North of the road, the fault became complex, and branch and parallel scarps formed a zone 100 m wide. Strong thrust features were visible in a scrub-covered

A

B



81. Calingiri Fault, northern section:
  (a) Central portion of the northern section. Note the abundance of quartz fragments in the vicinity of the fault.
  (b) Thrust scarp with vertical uplift of 15 cm, central portion of the northern section.

lateritic soil, and these will possibly remain visible for some years. For almost 400 m the scarp trended northerly on the edge of the scrub, swinging alternately from east to west in the form of a compression ridge bounded on either side by alternate subthrusts and suprathrusts. Where both types of thrusting were parallel, a strong wedge-like ridge resulted. This pattern was further complicated by the presence, 100 m east, of a parallel subthrust scarp. A dip reading of 16° west was obtained on this secondary fault plane at a point where the vertical uplift was about 7 cm. On the main fault, the uplift was about 8 cm and the westward heave about 9.5 cm. Thus, in addition to the small wedges uplifted at the main fault, there was a larger wedge uplifted between the two parallel scarps. After a small outcrop gap in Loc. 1620, the fault continued as a simple thrust scarp which showed a 3.8 cm sinistral strike-slip displacement where it crossed a fence line into Loc. 1724. At its northern extremity, the fault traversed firm salt impregnated alluvium and showed as a scarp about 8 cm high, which consisted of three or four parallel dermal suprathrusts, whose fault plane dipped apparently 10° or less to the east.

PREVIOUS HISTORY OF THE CALINGIRI FAULT

In Chapter 8, evidence was adduced to show that the Meckering Fault had a history of previous movements. At Calingiri, the fault movements of 1970 were small, and there were no rock outcrops in the vicinity so that consideration of fault breccia and geomorphologic evidence was not possible. Nevertheless, one of the strongest pieces of evidence that the Meckering Fault was a reactivated older fault was the coincidence of quartz strewn areas with the fault and with the line of its continuation. It was suggested that a fault plane would be a natural locus for silica solutions and that the scattered quartz fragments resulted from the weathering of quartz infilling an old fault zone. At Calingiri, a similar feature was noted, particularly in the southern section of the fault. The ground uphill from the fault scarp was covered with numerous pieces of quartzose rock in a band about 20 m wide. In addition, several test pits dug on either side of the fault suggested that several soil horizons were missing on the elevated block and that the total soil thickness to the east of the fault was less than that to the west. It would appear that, as at Meckering, the Calingiri Fault has a history of previous movement, although none is known from historic times.

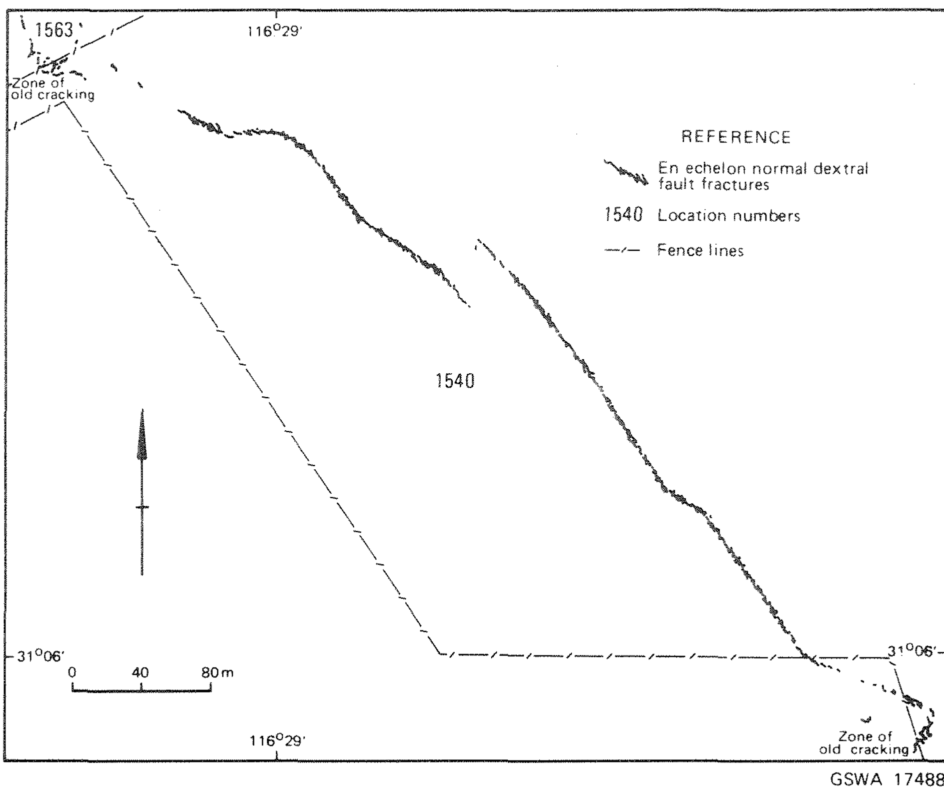
THE CALINGIRI CHORDAL FAULT

After the Calingiri Earthquake and the mapping of the main fault, a search was made on roads and farm tracks to the east for traces of further faulting. None was found, but six weeks later a landholder reported surface fractures from a field about 0.7 km east of the northern end of the main scarp. Despite frequent visits to the field throughout the period, the fractures had not previously been noted. Exactly similar circumstances surrounded the discovery of the Chordal Fault at Meckering, which was so named because it formed an almost complete chord across the northern end of the arcuate Meckering Fault. No such simple geometric relationship existed between the Calingiri Fault and the newly discovered fractures, but because of their overall similarity of form and occurrence, the new fracture was named the Calingiri Chordal Fault.

The fault trended about 125°, and its northern extremity was 680 m east of the northern end of the Calingiri Fault, which trended about 190° (Plate 5). The fractures consisted of two separate and parallel features with a sinistral offset of 26 m and an overlap of about 30 m. The total length of the fault was about 600 m (Fig. 82). The Calingiri Chordal Fault consisted almost entirely of small *en echelon* fault openings, offset left and trending about 20° east of the fault trend. At either end, the fault began as small discontinuous tension fractures, and the maximum displacements were found near the centre of each trace. The fault was principally normal in character, having its west side elevated up to 4 cm, and individual fractures open by the same amount (Fig. 83). Small dextral strike-slip movement was also noted, and reached a maximum of about 2.5 cm near the northern end.

SLUMPING

After the Meckering Earthquake there were numerous circular depressions formed which were attributed to slumping and consolidation in areas of high water table (Chapter 7). Only one similar area of circular cracking and slumping was noted after the Calingiri Earthquake, and the same explanation is invoked.



82. The Calingiri Chordal Fault.

83. Part of the Calingiri Chordal Fault, showing open fractures downthrown 4 cm to the east.

The area was about 180 m east of the Calingiri Fault at the Goomalling road intersection. The ground was cracked around an isolated banksia tree growing in a small drainage basin open to the northwest. The field was cultivated, and the water table was probably at a depth of about 3 m.

The cracking had an oval trace, with a north-south axis of about 50 m and an east-west axis of about 46 m. The cracking occurred in a zone about 2 m wide and consisted of tension fractures which were open up to 5 to 6 cm and which were displaced downwards in the centre by a similar amount.

THE MECHANISM OF THE CALINGIRI EARTHQUAKE

In the previous chapter the evidence was given for believing that the mobile block activated by the Meckering Earthquake was a superficial slice, and that the deep-seated mechanism was a sinistral strike-slip fault or shear zone. This mechanism was confirmed by the seismological work of Fitch and others (1973). At Calingiri the thrust plane was shallow dipping, and, although the fault was not as arcuate as the Meckering Fault, the pattern of faulting suggested a similar mechanism. Unlike the Meckering Fault, however, the Calingiri Fault was a sinistral rather than dextral thrust fault.

Fitch and others (1973) included the Calingiri Earthquake in their seismological study, and assumed a similar mechanism to the Meckering event. The resulting solution was that the earthquake was caused by a sinistral reverse fault trending 337° and dipping 76° to the northeast.

Like the Meckering Fault, the Calingiri Fault trace bears no simple relationship to the underlying mechanism, and the visible mobile block is but a superficial slice resulting from the release of deep-seated strain. Unlike Meckering, however, the Calingiri mobile block moved in the same sense as the underlying movement, and it would appear that the resulting fault could represent an *en echelon* shear directly connected to the deep seated fault.

MECKERING AND CALINGIRI

After the Meckering Earthquake, there were several reports of damage northwest of the town which could not be fitted to the regional picture. The levelling circuit through Goomalling and Dowerin, to the north of Meckering, also showed that there had been ground distortion to the northwest. It was this evidence which was used to construct the initial model for the mechanism of the Meckering event (Gordon and Wellman, 1971), a mechanism which was confirmed by the seismological studies of Fitch and others (1973). Following the Calingiri event, the previously anomalous records achieved a new significance as evidence for the continuance of the shear zone underlying Meckering to Calingiri and beyond.

New evidence collected after the Calingiri Earthquake reinforces this idea, and suggests that both events are ultimately connected, not only in the similarity of their surface expression but in their underlying causes.

ANOMALOUS DAMAGE REPORTS

Damage to Bolgart Golf Course, 87 km northwest of Meckering, has already been recorded, but in addition, 11 km to the east, along the Bolgart-Goomalling road, the Meckering Earthquake also damaged the telephone lines. Eight large telegraph poles on the north side of the road, and four smaller poles on the south side were overthrown towards the southeast. The poles were constrained by the telephone wires so that the direction of overthrow was not diagnostic, but the localized damage does suggest a zone of intensified seismic shaking at least 600 m wide.

Near the pumping station 9 km northwest of Meckering along the Goomalling road, five tension cracks were observed in late October 1968. The fractures crossed the bitumen seal at right angles and trended 063° whereas tension openings in the banks on either side of the road had a strike of 305°. The fractures showed small vertical displacements up to 2 cm, the south block down, and a right lateral displacement of about 1 cm. In April 1970, the number of fractures had increased to ten; the largest had rebroken the seal and opened a further 0.6 cm. The fracture surfaces did not look fresh.

At Quelquelling, 16 km south of Goomalling and 29 km northwest of Meckering, tension cracking was reported across the sealed road surface on 10 March 1970, the day before the Calingiri Earthquake. Numerous cracks had developed rather haphazardly on the road verges as well as the tar seal, but there was a strong set of fractures with a strike of 320°, and smaller but persistent sets at 300° and 230°. The greatest opening was about 0.6 cm, and the eastern or downhill side of the fracture was often slightly depressed. The condition of the road prior to 10 March was not known.

VERTICAL AND HORIZONTAL GROUND DISTORTION

The levelling profile from Northam to Merredin through Goomalling has been reported in Chapter 9, but it will be noted that a change in level from earlier surveys started near Jennacubbine, 29 km northeast of Northam, and continued for the next 60 km to beyond Dowerin. This zone traverses any possible shear zone between Meckering and Calingiri, and by comparison with earlier surveys a series of troughs and ridges had developed with a maximum amplitude of 13 cm.

Geodetic observations, also reported in Chapter 9, showed the the line, Karrabein to Berring, had increased in length by 36.6 cm. Karrabein Hill is 17 km northwest of Meckering, and Berring is a further 27 km north; the line cuts obliquely across the zone of ground distortion and suggests significant differential movement within it.

MINOR FRACTURES AT CALINGIRI

New evidence of a connection between the earthquakes at Meckering and Calingiri came from a number of small fractures discovered at Calingiri. They were associated both with the Calinigiri Fault and the Calingiri Chordal Fault, but were older than the main faulting.

The scarp of the Calingiri Fault was divided in two by an outcrop gap of about 100 m. In this gap, and adjacent to the end of the northern section of the fault, several discontinuous fractures between 3 m and 10 m long and having a northerly trend, were found. These fractures were partially filled with straw and sand, and had lost all sharp edges. Where the northern section of the Calingiri Fault commenced as a small thrust scarplet, some of the old cracking was intermingled with new fractures, and in places the old openings had been reactivated.

Similar old fractures were also noted at the northern corner of Loc. 1223, about 190 m south of the outcrop gap. The cracking consisted of five slightly curved tension openings with a northerly trend.

At either end of the Calingiri Chordal Fault, areas of old circular cracking were recorded (Figs. 82 & 84) which were unlike anything previously seen either at Meckering or Calingiri. As in the previous examples, the fractures were largely filled with leaves and rubbish and had lost all sharp outlines. At the southern end of the fault, the fractures had been partly eroded by running water.

The fractures at the southern end of the fault occurred in thin soil which covered a firm lateritic horizon. They extended over a roughly circular area 25 m in diameter, and consisted of interconnected, almost circular, cracks 2 to 3 cm deep, and in places up to 12 cm deep. The central areas were raised and the feature did not resemble slumping.

At the northern end of the Calingiri Chordal Fault, the fractures occurred near the crest of a ridge in firm lateritic clay. Again, their form was of interconnected almost circular cracks about 15 m in diameter. The curved cracks showed a small vertical displacement, but the blocks bounded by the circular fracture were elevated with respect to their surrounds. Both here and at the southern end of the fault, the old cracking had been intersected by fresh fractures, and at the northern end there was some reactivation of a group of old fractures that trended 110°, towards the northern end of the Chordal Fault.

84. Eroded fissures, infilled with leaves and debris, at the southern end of the Calingiri Chordal Fault.

The fractures in the outcrop gap of the main fault and at either end of the minor fault were similar in general appearance, and were demonstrably older than the fault scarp formed by the Calingiri Earthquake. An examination of old fractures in the vicinity of Meckering, after completion of mapping at Calingiri, showed similar features; the cracks had been partly eroded and were filled with leaves and straw. Although the fractures at Calingiri could have been formed after one of the minor earthquakes in the area between October 1968 and March 1970, it is possible that they were formed at the same time as the Meckering Earthquake.

DISCUSSION

The fault traces at Meckering and Calingiri greatly resembled each other, not only in their overall arcuate shape and shallow-dipping fault plane, but in many small features as well. The mechanism of faulting emphasized this similarity, and both faults have been shown to result from movement along otherwise undetected, steeply dipping sinistral reverse faults which strike north-northwest. Considering the geographical disposition of the two seismic events the obvious inference is that the two earthquakes represent movements along different parts of the same fault.

Evidence to support this suggestion includes the anomalous reports of damage northwest of Meckering, at distances which would not be expected from a moderate earthquake of magnitude 6.8, and which was not reported in other directions. The older fracturing associated with the Calingiri Fault may have formed at the time of the Meckering event, but certainly indicates that the ground distortion measured by geodetic and levelling circuits continued in the time between the two major earthquakes.

Assuming that each earthquake represents movement along a single fault trace, then the strike of these faults, as determined seismically, delineates a zone at least 20 km wide between Meckering and Calingiri which encompasses all the anomalous reports. This zone may be the wide shear zone that was postulated for the model mechanism of Chapter 10 or it may contain an *en echelon* series of smaller faults, each steeply dipping and sinistral reverse. There is little evidence that the fault zone could be extended to the south-east of Meckering, although this might explain the aftershocks that occurred at Mawson and as far distant as Quairading, 55 km southeast.

Beyond Calingiri, there were examples of houses that felt the seismic shaking from the Meckering Earthquake more strongly than from the nearer Calingiri event, and Yerecoin, 25 km north-northwest of Calingiri has been the centre of considerable seismic activity in the past.

The picture presented is that of a narrow, north-northwest trending zone within the Southwest Seismic Zone, which is considerably more active than neighbouring areas. With this in mind, the isoseismal maps can be redrawn (Figs. 19b and 76b) to show a possible extension of the zone towards the margin of the Archaean shield in the vicinity of Three Springs, 150 km north-northwest of Calingiri. Within this framework, the period October 1968 to 1975 can be seen as a period of intense activity in the 90 km section between Meckering and Calingiri, and the pattern of aftershocks from both events suggests that the Calingiri Earthquake was but a major aftershock and reactivation of the earlier Meckering Earthquake.

CHAPTER 12

The regional setting of the Meckering and Calingiri Earthquakes

Australia does not contain any active tectonic zones, and compared with such countries as Japan and Indonesia, or the western seaboard of North and South America, has very few major earthquakes. Compared with a global average of about 140 per year, Australia has about one earthquake of magnitude 6 or more every five years. No one has yet been killed by an earthquake in Australia, and the total damage caused, while of local importance, is minimal by world standards (Denham, 1976).

Nevertheless, there are several well known zones of minor seismic activity in Australia (Doyle and others, 1968b). In the east, from northern Queensland to Victoria, the Tasman geosynclinal zone is associated with many minor shocks scattered over a wide area, and has a local concentration about 50 km north of Canberra. Few of the shocks have exceeded magnitude 5, but only the Gladstone earthquake of 1918 was larger than magnitude 6 (Drake, 1976). In South Australia there is a well-defined zone of seismicity covering the Adelaide Geosyncline from Adelaide itself northward to Lake Eyre. Again, few of the shocks have exceeded magnitude 6, although the Adelaide earthquake of 1954, $M_L = 5.8$, was Australia's most damaging earthquake, with insurance claims totalling about $9 million (Denham, 1976). An isolated area of quite intense seismic activity has been located in the Simpson Desert, on the South Australia-Northern Territory border, and there have been a few small tremors throughout the remainder of the Territory.

In Western Australia, earthquake epicentres are scattered along the continental shelf from Broome in the north to Cape Leeuwin, and several of the largest earthquakes in the Australian region have occurred in this part of the Indian Ocean, including one of magnitude 7.8, 450 km west of Exmouth Gulf in 1906 (Gutenberg and Richter, 1954). On land there are zones of seismicity in the Fitzroy Trough and East Canning Basin, the Gascoyne region east of Carnarvon, and the Southwest Seismic Zone through the southwest corner of the Archaean Yilgarn Block. Each of these areas has experienced several major shocks of magnitude 6 or more, including the largest land based earthquake in Australia, the Meeberrie earthquake of 1941, with a magnitude of 6.8-7.0, which occurred at the southern end of the Gascoyne Province. Both the Meckering and Calingiri earthquakes occurred in the South West Seismic Zone, which is probably the most continuously active of all Australian seismic areas.

MAJOR WESTERN AUSTRALIAN EARTHQUAKES

Prior to 1941, all the larger earthquakes in the Western Australian region that had been recorded worldwide occurred in the shelf or deep ocean areas off the northwest of the State. The largest was that of 18 February 1906, of magnitude $M_S = 7.8$. Although the epicentre was in the Indian Ocean, over 400 km from Exmouth Gulf, it was sidely felt throughout the state, causing minor damage at Cue, over 1 000 km from the epicentre. On land, the East Canning Basin Earthquake of 1970 ($M_L = 6.7$, Denham and others, 1974) occurred in a remote and uninhabited region so that only the seismological details are known. However, in addition to Meckering and Calingiri, there have been three large and damaging earthquakes in relatively well-populated areas, at Meeberrie (1941), Nourning Spring (1963) and Landor (1969).

MEEBERRIE, 1941

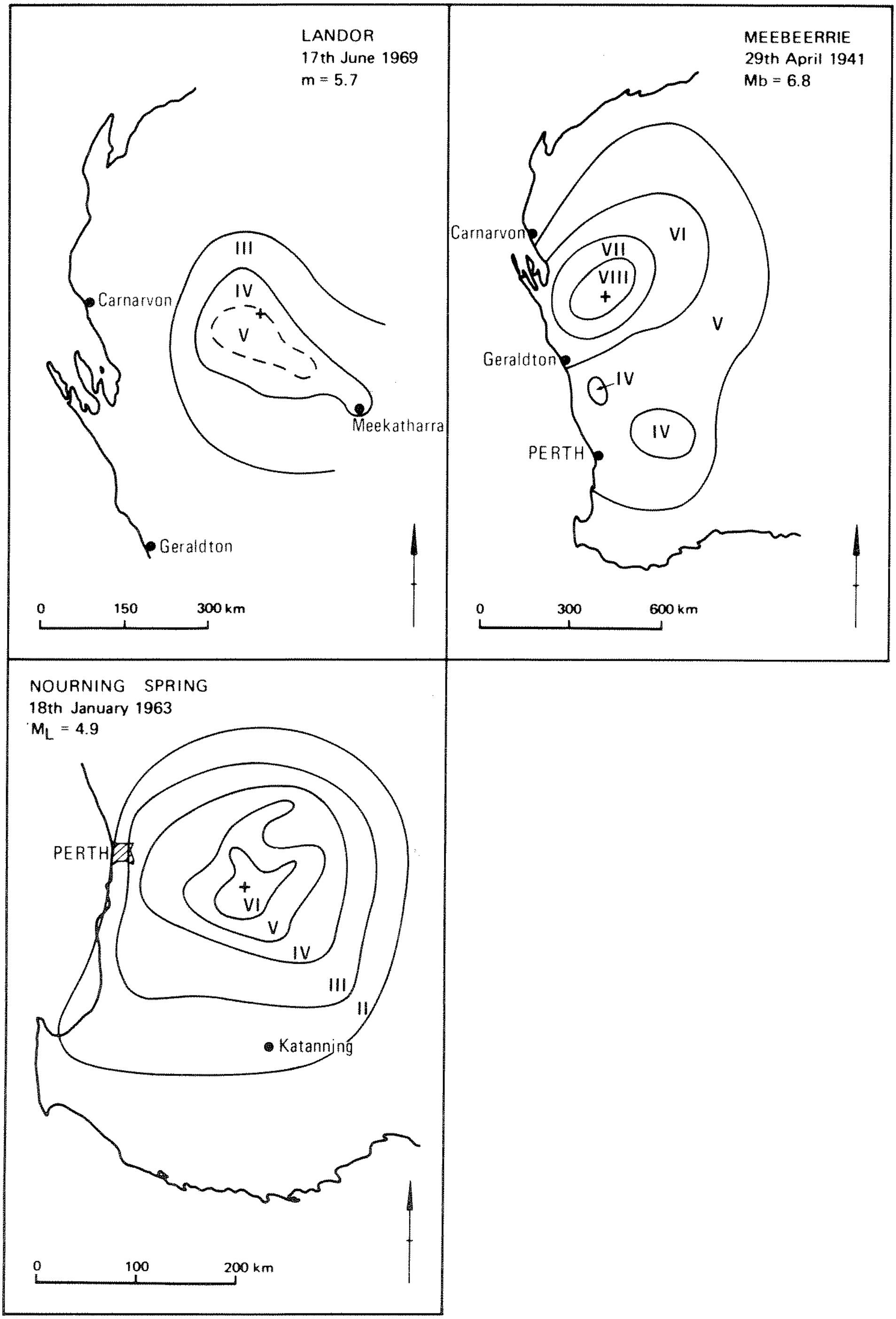
The seismological data for this earthquake are:

Origin time: 29 April 1941, at 01 35 41 hrs U.T.
Magnitude: Ms 6.8
Epicentre: 26.8°S, 116.1°E, close to Meeberrie Homestead.
Depth: 33 km.

The Meeberrie Earthquake was as large as, and possibly larger than, the Meckering event, but being deeper was felt over a wider area. Conversely, the felt intensity close to the epicentre was MM VIII, lower than the intensity at Meckering. The earthquake occurred at the southern end of the Gascoyne region, a sparsely populated area, and little damage was done except to Meeberrie Homestead. The homestead was constructed of granite, and although the building did not collapse every wall was cracked through. More serious damage, in this semi-arid region, was caused to water tanks, and several corrugated iron tanks were destroyed. Similar damage occurred on neighbouring stations but with lesser severity (Everingham, 1968a).

The earthquake was felt from Port Hedland in the north to Albany in the south of the State, and an isoseismal map is presented in Figure 85. This map, by Denham (1976), differs significantly from that presented by Bolt (1959), but is based on more information. Apart from the northeast-southwest elongation of the higher isoseismals parallel to the geological and structural trend of the area, the MM V isoseismal shows a large bulge covering most of the wheat belt. Two parts of the wheat belt, however, centred on Coorow and Merredin registered only MM IV, but the reason for these anomalies is not known.

The Meeberrie Earthquake provided the first example in Australia of ground cracking due to a seismic event. Several open fractures ranging from 9 m to 20 m long, up to 40 cm deep, and from 1 to 7 cm wide were found in the vicinity (Everingham, 1968a). The fractures were probably not representative of subsurface faulting, and may have been slump features, as they were found in the banks of the Murchison River. The epicentral region was not geologically well known in 1941, but recent mapping has shown that a major fault exists 10 km west of Meeberrie homestead. This has been named the Meeberrie Fault (van de Graaff and others, 1977), and may have been the source of the earthquake. An earlier suggestion by Gordon (1972) that slightly arcuate features visible on air photos near Mount Narryer, and only 21 km north of the Meeberrie epicentre, may have resulted from this earthquake, has been investigated by Williams (1979). The features, which are almost certainly recent fault scarps have been shown to be at least 90 years old.



85. Isoseismal maps of the Meeberrie, Nourning Spring, and Landor earthquakes.

NOURNING SPRING, 1963

Origin time: 18 January 1963, at 05 49 18 hrs U.T.
Magnitude: M_L 4.9, m_b 5.8
Epicentre: 32.2°S, 117.2°E, 25 km northwest of Brookton.
Depth: 18 km.

Prior to the Meckering event of 1968, this was the strongest shock recorded from the South West Seismic Zone. An isoseismal map was prepared by Everingham (1968), and is reproduced in Figure 85. At lower intensities the isoseismals are roughly circular, with some irregularities towards the southwest, but the MM V and MM VI isoseismals are lobate, with pronounced extensions towards the northeast, in the direction of a line of seismic activity within the South West Seismic Zone. There is some suggestion that, in the area close to the epicentre, seismic energy was best propagated towards the northeast while regionally it was propagated to the southwest.

LANDOR, 1969

Origin time: 17 June 1969, at 19 54 34 hrs U.T.
Magnitude: M_L 5.6 m 5.9
Epicentre: 25.0°S, 116.8°E, 20 km north of Landor Homestead.
Depth: 15 km.

Landor homestead is situated 240 km northwest of Meeberrie homestead, and the earthquake that occurred there in 1969 was the second largest in the Gascoyne region. The district is sparsely populated and only minor damage to old or poorly constructed buildings was reported from the epicentral region, where the intensity was MM V. The isoseismal map of Everingham and Parkes (1971) is reproduced in Figure 85. The isoseismals show a marked elongation towards the southeast, cutting across the geological structure of the region, but perhaps reflecting the thick gravels and sands filling the valley of the Murchison River and its tributaries.

SOUTHWESTERN AUSTRALIA

GEOLOGY

Most of southwestern Australia is underlain by granitoid rocks of the Yilgarn Block, an ancient and stable Archaean shield. Worldwide, such shield areas are nearly aseismic. To the west, the Yilgarn Block is terminated by the Darling Fault, and the adjacent coastal areas are occupied by the Perth Basin. Southwards the shield abuts the Albany-Fraser Province, a northeast trending Proterozoic mobile belt.

The Perth Basin is a deep, linear trough of sedimentary rocks extending north-south for about 1 000 km. The sediments range in age from Proterozoic to Cretaceous, and have a thin cover of Quaternary sands, clays, and laterite; the total thickness of the sediments may be as much as 15 km. The basin is essentially half a graben, bounded to the east by the Darling Fault and extending westward to the edge of the continental shelf. Only near the southern extremity does the Leeuwin-Naturaliste Block, of Proterozoic granites and gneisses bounded by the Dunsborough Fault, form a western margin to the basin. The tectonic style of the sedimentary sequence is characterized by intense normal faulting, and although there is evidence of epeirogenic movements during the Tertiary, the basin appears to have been tectonically inactive since the Cretaceous. The sediments and structure of the Perth Basin have been fully described by Playford and others (1976). In historic times the Perth Basin appears to have been seismically inactive, except for a small number of epicentres offshore.

Little is known of the geology of the southwestern part of the Albany-Fraser Province except the presence of a late Proterozoic adamellite in the Albany area, large areas of poorly exposed migmatites, and the slightly metamorphosed quartzites and phyllites of the Stirling Ranges. By analogy with better known areas to the northeast (Doepel, 1975), it is possible that the migmatites are reworked Archaean material, but include the metamorphosed equivalents of the Stirling Range Beds, which are preserved only where they were deposited on the stable Archaean shield. The adamellite is a younger intrusive body, about 1 100 my old (Turek and Stephenson, 1966).

That part of the Yilgarn Block under consideration is known as the Southwestern Province (Williams, 1975), it is a triangular area extending from Geraldton in the north to Bridgetown and Ravensthorpe in the south. Unlike the adjacent Eastern Goldfields, it contains no large arcuate or linear 'greenstone belts', but does contain smaller patches of high-grade metamorphic rocks, along the western margin, there are extensive areas of schistose, pelitic and psammitic rocks. The principal rock types however, are granites and migmatites, which occupy about 95% of the area. The description given in Chapter 1 of the geology of the Meckering district is typical of the granitic terrain.

The general structural trend of the Southwestern Province is north-northwest, and of particular interest is the broad belt of gneissic and schistose rocks which stretches from Wongan Hills, through Northam, to Katanning in the southwest. This is the zone in which much of the seismic activity of Western Australia is centred. The western margin of the belt is formed by a line of granite plutons; to the east the gneisses grade into migmatitic and granitic rocks with enclaves of mafic to ultramafic granulites. Regional geological studies in this area have been made by Wilde (1974, 1976) and Carter and others (1978).

The Wongan Hills consist of metamorphosed basic igneous and pelitic rocks, now represented by amphibolites and garnet-cordierite gneisses and schists, with prominent bands of resistant banded iron-formation. Similar rocks, but with a thick sequence of flaggy quartzites, have been described from the Toodyay district by Prider (1934, 1944), and from York by Stephenson (1970). Small lenses of intrusive ultramafic rocks are known from several localities. These are either peridotites and bronzite peridotites, or their metamorphosed equivalents. The rocks of the layered series are poorly exposed, but the banded iron formation often forms prominent hills such as Mount Bakewell, near York and the Wongan Hills.

The dominant quartzo-feldspathic gneisses of the belt are of diverse origin, and ortho- and paragneisses are often interlayered. The paragneisses may contain, in additon to the normal quartzo-feldspathic assemblage, sillimanite, cordierite, staurolite and almandine, whereas the orthogneisses have a simple granitic mineral assemblage.

Granulite facies rocks are sparsely distributed throughout the metamorphic belt and in enclaves in the granitic terrain to the east. Pyroxenites, hornblende granulites and charnockitic rocks, some with sapphirine, have been described by Wilson (1958, 1971).

This belt of gneisses forms part of what is possibly a continuous zone of high-grade metamorphic rocks encircling the cratonic nucleus of the Yilgarn Block which is metamorphosed only to the greenschist facies. The belt is linear, and the seismic activity suggests instability. For these reasons Anhaeusser (1969) has suggested that the zone may represent an embryonic mobile belt.

THE DARLING FAULT

As a fracture extending for about 1 000 km, with a throw of up to 15 km, the Darling Fault is one of the major tectonic features of the earth's crust. The fault extends from the south coast of Western Australia, northwards to the Badgerada Range area, and separates the Archaean Yilgarn Block from the sediments of the Perth Basin. The fault is normal, with downthrow to the west, and follows an almost straight, northerly course from its southern extremity to the vicinity of Coorow, 260 km north of Perth. At this point the fault changes direction westward to about 330° and follows a gently curving course to its northern extremity. A complete description of the fault, from geological and geophysical evidence, is given by Playford and others (1976).

Throughout its length, geophysical evidence shows the Darling Fault to be normal, with a westerly dip on the fault plane of between 50° and 80°. There is, however, a large negative gravity anomaly over the Perth Basin (Fig. 86; and Everingham, 1965, 1968), and because of this isostatic imbalance without accompanying seismicity, Vening Meinesz (1948) suggested that the Darling Fault was reverse. The compression associated with the nearby Meckering Earthquake also led Prider (1972) to suggest an east dipping reverse fault. The early history of the fault may have included both transcurrent and compressive movements, and Playford and others (1976) suggest that the Woodrarrung Fault, a high-angle reverse fault, dipping west, and located 10 km east of and parallel to the northern end of the Darling Fault (Perry and Dickins, 1966), is probably genetically related. Movement on the Woodrarrung Fault took place in late Proterozoic or early Palaeozoic times, however, and since at least the Silurian, the Darling Fault has been a normal tensional fault.

The main movements along the Darling Fault occurred prior to the Early Cretaceous, as Neocomian sediments extend undisturbed across the fault into valleys incised into the Archaean at Bullsbrook and Donnybrook. In the Perth region, however, there appears to have been a further subsidence of up to 1 000 m to accommodate the Lower Eocene King's Park Formation. In the same area, the fault has developed its most prominent topographic expression, the Darling Scarp, which suggests more recent movement. This is supported by some elements of stream morphology. In the vicinity of Perth several streams show small northward 'kinks' in their course about 2 km west of the foot of the present scarp. The incision of a number of rivers into the Archaean granites also indicates recent movement, and Cope (1975) has measured an epeirogenic uplift of about 300 m on the Darling Plateau since the Eocene. Such uplift entails either an uplift of the Perth Basin sediments or compensatory movements along the Darling Fault.

In historic times the Darling Fault has been seismically inactive, although epeirogenic uplift of the Darling Plateau is probably continuing. Between 1959 and 1970 only one small shock has been recorded from the line of the fault, and this, in the Gosnells area, was probably caused by a large explosive charge in the granite quarries on the scarp. There is no evidence that the fault bears any direct relationship to the South West Seismic Zone.

THE URELLA FAULT

The Urella Fault is over 240 km long, and extends in a north-northwest direction from a point about 25 km east of Coorow to the Greenough River. The fault lies entirely within the northern Perth Basin, and is parallel to and about 25 km west of the Darling Fault. The fault is normal, dips steeply to the west, and in its southern part, replaces the Darling Fault as the main down-to-the-west fault (Playford and others, 1976). The maximum throw of the fault is about 11 000 m, but north of Mingenew, this diminishes rapidly until the fault dies out, whereas the throw of the nearby Darling Fault increases.

The Darling and Urella Faults are probably genetically related, and the location of the latter appears to be significant with respect to the structure of the Archaean basement. The Urella Fault begins near the point where the Darling Fault diverges westward from its northerly course, and for much of its length is parallel to the north-northwest trend of the Darling Fault. The Urella Fault, however, maintains this trend to its northern termination, whereas the Darling Fault resumes its northerly trend. A further feature of the Urella Fault is that it is on-line with the continuation of the South West Seismic Zone. The fault is not known to be active at present, and is a normal rather than reverse transcurrent fault, but its position with respect to the seismic zone is suggestive of deep-seated control. The Urella Fault is thought to have been active mainly between Middle Triassic and early Neocomian times.

THE DUNSBOROUGH FAULT

The Dunsborough Fault marks the eastern boundary of the Leeuwin Block, and the western margin of the Perth Basin near its southern extremity. It is complementary to the Darling Fault, being a normal, east-dipping fault with a maximum throw of between 3 000 and 4 000 m (Playford and others, 1976). The fault was last active in earliest Cretaceous times, and is overlapped by Neocomian sediments.

There has been no known activity along the Dunsborough Fault in historic times, but an examination of the seismic record shows a surprising number of moderate earthquakes offshore and about 70 km east of the fault. Three of the larger shocks are noted in Appendix I, and there have been numerous smaller ones from the area. The Leeuwin Block is a narrow belt of Proterozoic granulites and gneisses, dated by Compston and Arriens (1968) at 670 m.y. The Dunsborough Fault marks its eastern boundary, but its western boundary is obscure. On the off-shore Naturaliste Plateau there is a sedimentary sequence up to 2 km thick, and Playford and others (1976) believe this may onlap the Leeuwin gneisses. The seismic activity, however, suggests the possibility of an active fault. Alternatively the seismicity of the area could be connected with epeirogenic uplift along the Jarrahwood Axis of Cope (1975), although the trend of the seismicity is perpendicular to the axis.

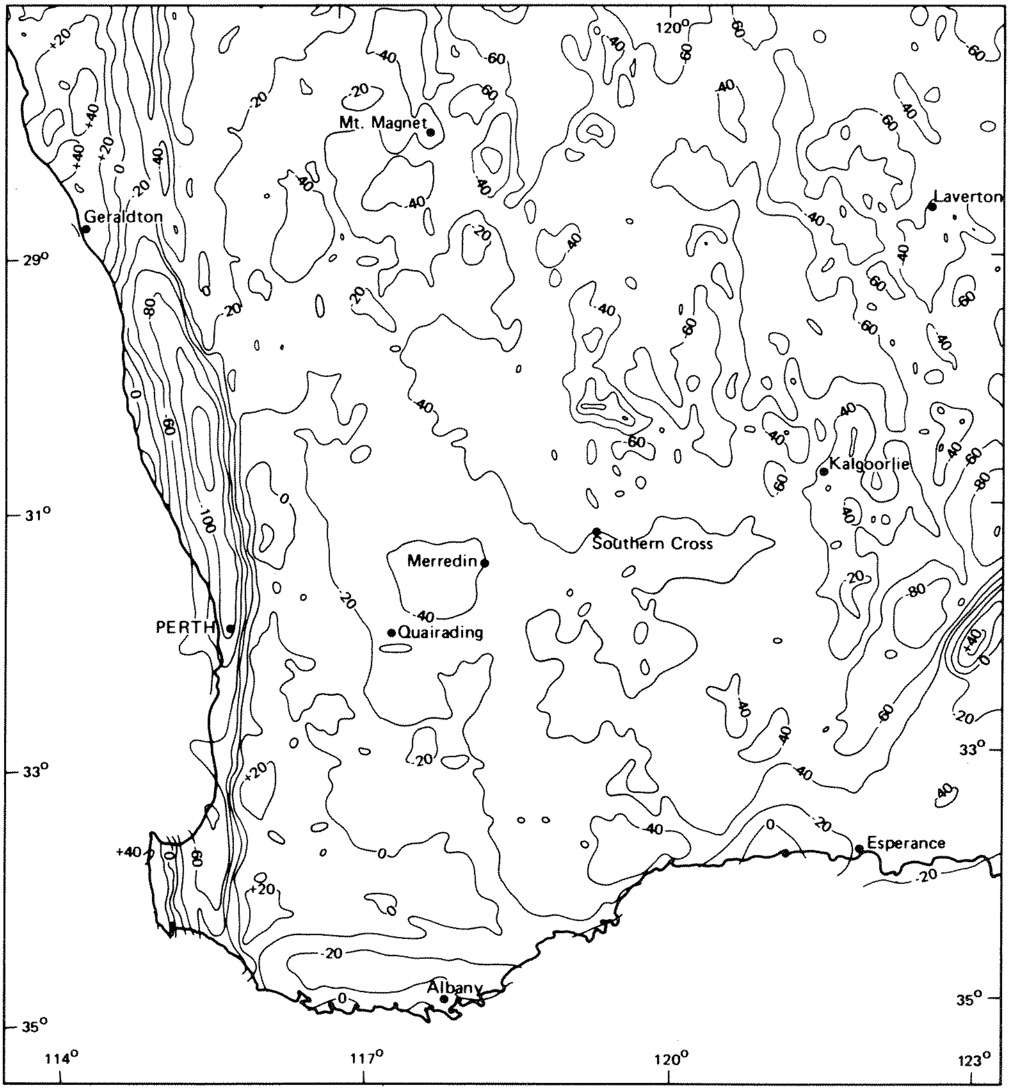
THE SOUTH WEST SEISMIC ZONE

Even before the installation of a comprehensive seismograph network in Western Australia, reports of earth tremors from the line of small towns along the Great Southern railway had been noted. It was possible that this 'line', through Northam, and York to Beverley and Katanning was due solely to the concentration of population along the Avon Valley and the wheat growing regions east of the Darling Plateau. With the installation in 1959 of a three-component seismograph at Mundaring which gave the ability to record and locate small tremors, it soon became evident that the 'line' was real and stretched beyond the limits within which tremors had been previously felt. Everingham (1965, 1968) named this the Yandanooka-Cape Riche Lineament, from Yandanooka, a small town close to the Urella Fault, and Cape Riche, the point on the southern coast, east of Albany, where the extension of the lineament passed into the ocean. Further recording showed that the seismic activity took place along a zone about 30 km wide and 275 km long, with scattered epicentres eastward from the zone, and the region is now formally known as the South West Seismic Zone (Doyle, 1971).

Geologically, the South West Seismic Zone is coincident with the belt of schists and gneisses which trends south-southeast from Wongan Hills to Katanning. Northwards from Wongan Hills the gneiss zone has branches towards Moora and Dalwallinu, both of which have recorded small earthquakes. At its southern end, both the seismic zone and the gneiss belt are terminated by the northeast trending Albany-Fraser metamorphic province. The western boundary of the seismic zone is coincident with the margin of the granites which form the Darling Plateau, and although Wilson (1958) has suggested that this is a fault line, the geological evidence is inconclusive, and the pattern of earthquake epicentres does not support the presence of an active fault. The eastern boundary can be drawn with less confidence; most epicentres are situated west of the Meckering Line and within the gneissic belt, particularly in the most active section between Wongan Hills and Beverley, but there have been scattered tremors throughout the wheat belt. Overall the epicentres in the South West Seismic Zone are included in the region which Wilson mapped as containing high grade metamorphism and charnockitic rocks, but the majority occur in a 30 km wide zone along the western margin of this area.

The South West Seismic Zone is also marked by certain features of the crustal structure of Western Australia, including gravity anomalies and changes in crustal thickness. The average crustal thickness throughout the Archaean shield is about 36 km, but in the vicinity of the seismic zone this increases to 42 km, and beneath the Perth Basin to 46 km (Everingham, 1965). In addition, a high velocity layer within the crust, normally 20-30 km deep, rises to within 14 km of the surface beneath the Darling Plateau. Within the Perth Basin 20 km of the crustal thickness is made up of Proterozoic to Cretaceous sediments.

The gravity map of southwestern Australia shows a strong correlation between geological and physiographical features and Bouguer anomaly contours (Fig. 86). The Perth Basin shows a strong negative anomaly of up to –120 milligals, with closely spaced contours paralleling the outline of the basin. The Darling Fault is marked by a steep slope in the gravity contours from about –40 milligals up to zero. East of the seismic zone, the gravity contours are widely spaced and the anomaly does not vary much outside the limits of –40 to –50 milligals. Across the seismic zone, the gravity anomaly rises steadily from



86. Bouguer gravity anomalies over Southwest Australia.

–40 milligals in the east, to zero in the west, and the contours trend south-southeast, following the geological structure of the country. The –20 milligal contour passes down the centre of the South West Seismic Zone, and the Darling Plateau forms a large triangular area with zero gravity anomaly.

Physiographically, the South West Seismic Zone is distinctive in that it falls largely within a downwarped zone which separates the low relief, gently warped interior of the Yilgarn Block from the uplifted, marginal, Darling Plateau. The interior, Salinaland of Jutson (1934), is an undulating plateau of low relief, with broad, widely spaced drainage channels which are probably tertiary in age. The drainage channels contain strings of salt lakes, and there is flow only after exceptional rains. The Darling Plateau has been epeirogenically uplifted (Jutson, 1934; Cope, 1975), and the main drainage system, the Swan-Avon River, is now deeply incised. Between these two regions is a narrow zone of younger laterites and rejuvenated drainage (Mulcahy, 1967) which covers most of the seismic zone. In this zone, which is about 80 m below the general level of the Darling Plateau, the main drainage is in narrow, flat-floored valleys, and it is fed by a network of small, sharply incised tributaries. Figure 87 shows the close correlation of seismic activity with this physiographic unit, although it should be noted that in the south the position of the Meckering Line, the change from salt lake country to rejuvenated drainage, is probably governed by uplift along the east-west Jarrahwood Axis.

The close coincidence of a physiographic unit with geological structure, gravity anomalies, changes in crustal thickness, and a narrow seismically active zone suggest that they are linked. If this is so, as seems probable, then the seismic zone is a reflection of deep-seated crustal structure. Possibly the most significant feature is the change in crustal thickness. Although the Darling Plateau is in isostatic equilibrium the increased potential energy 'stored' in this region of the crust will produce lateral forces as the crustal material flows horizontally to compensate for the crustal inhomogeneity (Artyushkov, 1973). Such forces could be sufficient to give rise to the present activity of the South West Seismic Zone.

SEISMICITY

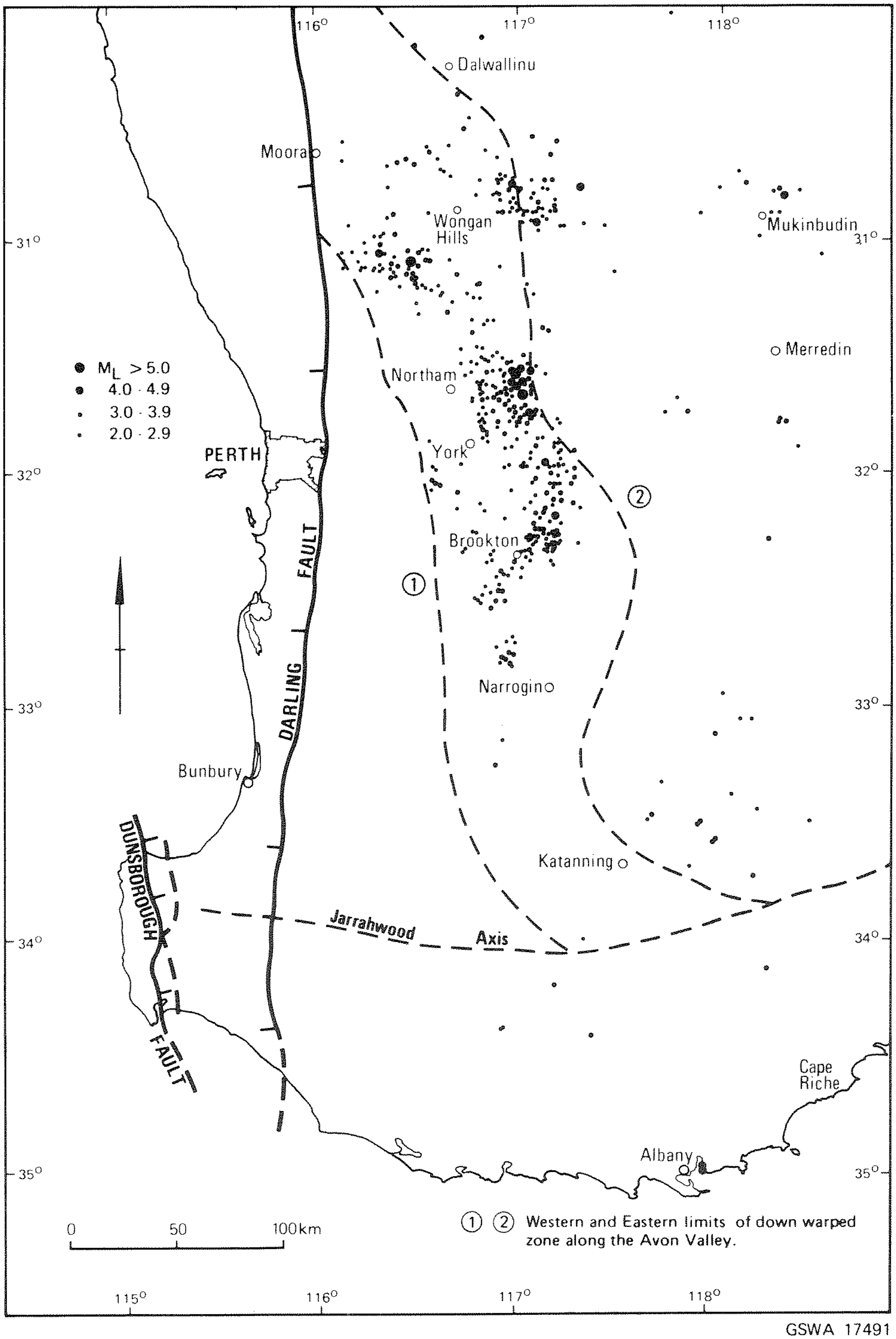
Since 1959 the Mundaring Observatory has recorded several hundred earthquakes from within the South West Seismic Zone. The majority of these have had a magnitude (M_L) of 2.9 or less, and only the Meckering and Calingiri events, and one aftershock of the Meckering Earthquake, have exceeded $M_L = 5.0$. Everingham (1968a) has given a list of the larger shocks between 1959 and 1965, and since 1966 the total number of shocks recorded have been published in the Annual Reports of the observatory.

TABLE 21. ANNUAL NUMBERS OF EARTHQUAKES RECORDED IN THE SOUTHWEST SEISMIC ZONE

Magnitude (M_L)	*2.0-2.9*	*3.0-3.4*	*3.5-3.9*	*4-4.9*	*≥5.0*
1966	30	8	7	—	—
1967	24	4	1	—	—
[1]1968	81	22	5	3	—
[2]1968	117	50	26	11	2
1969	118	25	13	2	—
1970	57	9	2	1	1
1971	42	5	—	1	1
1972	70	9	1	—	—
1973	36	5	—	—	—
1974	72	7	3	3	—
1975	24	6	2	—	—
1976	19	1	—	1	—
1977	27	4	3	2	—
1978	20	3	3	—	—

[1] Excluding the Meckering area, 1 Oct to 31 Dec 1968

[2] Meckering area only, between 1 Oct and 31 Dec 1968



87. Location of epicentres in the Southwest Seismic Zone (1959-1977).

Table 21 is a compilation of the number of earthquakes in the seismic zone for the period 1966-1978, and shows that, apart from the Meckering event of 1968 and its aftershocks in early 1969, there was constant and continuing minor activity throughout the period. Only with respect to the larger shocks, of magnitude 4 or more, were there periods of no activity. The general level of activity consists of minor tremors of magnitude 2 to 3, and only a quarter of the tremors exceed this figure. Nevertheless, a few earthquakes exceed $M_L = 5.0$, and these may cause damage and be felt over a wide area.

But if the overall activity of the South West Seismic Zone has been continuous it is not evenly distributed, and in each locality it is sporadic. Figure 87 shows several zones of intense activity, including the Meckering and Calingiri areas. At Meckering itself, the principal activity was in 1968 and 1969; but to the west there is a north-south group of minor tremors between Quellington and Southern Brook, which was active prior to 1966. The Calingiri district has shown a lower level of activity than Meckering, but the tremors have been more evenly distributed through time although there was a peak between 1968 and 1970. The most continuously active zone has been the northeast trending belt from Pingelly through Brookton, and to the east of Beverley. This has been characterized by innumerable small tremors of M_L 2.0-2.9, with only a few larger shocks such as the M_L 4.9 earthquake at Nourning Spring in 1963. But even here, activity in any one section has been sporadic, near Pingelly one year, perhaps followed by the Beverley sector the next year.

In addition to the main zones of activity which are obvious in Figure 87, there are several other weakly active areas. Northwest of Narrogin there is a small group of epicentres, isolated from the main active areas, and northeast of Katanning there is a widely spaced group of epicentres from tremors which occurred in the early 1960's. Around Muckinbudin, well to the east of the main seismic zone, there have been a number of small tremors at widely spaced intervals.

In trying to interpret the seismicity of the southwestern Australia it is tempting to see patterns in the location of epicentres which could be related to faulting. A northwest trending structure could join Meckering and Calingiri, a northeast trending fault could pass near Brookton, and an east-west structure could exist between Muckinbudin and Wongan Hills. But there are no known geological structures which could account for the epicentre patterns, and the studies of Fitch and others (1973) show that the Meckering and Calingiri Earthquakes were caused by at least two parallel faults, not a single fault joining the two centres. In addition, activity northwest of Narrogin and the widely spaced epicentres near Katanning would still require an explanation. Nevertheless, the South West Seismic Zone is characterized by a large number of small, shallow earthquakes, with occasional larger events followed by a swarm of aftershocks, and without periods of quiescence. Richter (1971) described this as continuous seismic activity and suggests that it is produced by the readjustment of relatively small crustal blocks to the regional stress.

STREAM MORPHOLOGY

Regional geological mapping had provided no examples of faulting or geological structure that could explain seismicity within the South West Seismic Zone, and detailed geological mapping of the Meckering district had not explained the location of the

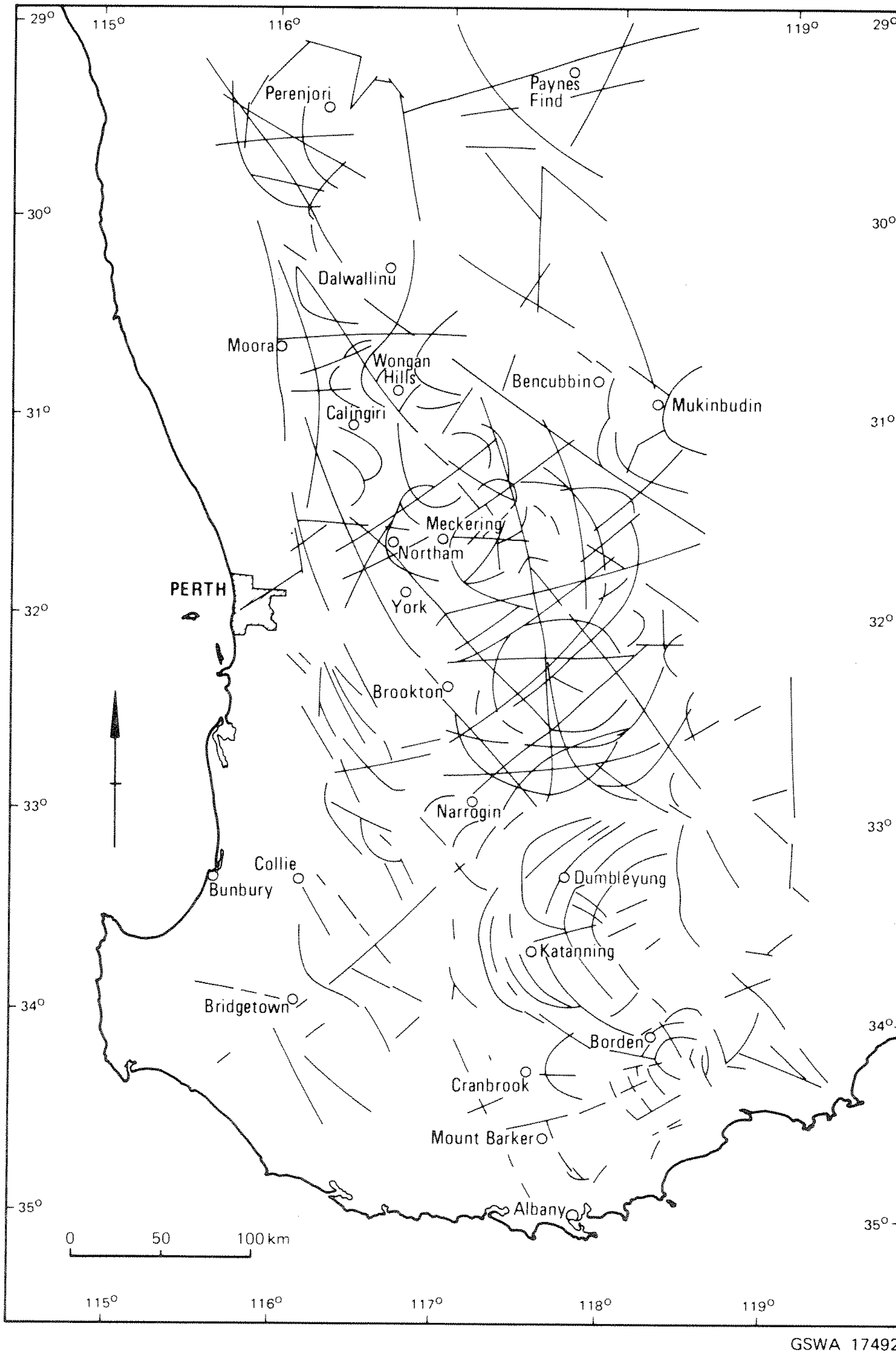
Meckering Fault. Investigations have shown, however, that the Meckering and Calingiri faults are reactivated features, and at Meckering there is a suggestion that the course of the Mortlock River was in part related to the faulting. In addition, movement along the Meckering Fault dammed all easterly flowing streams and flooding was only averted by channel deepening on the uplifted block. Under normal conditions of erosions stream courses would have conformed to the arcuate pattern imposed by the fault scarp and an arcuate pattern of streams and elongated lakes would be present. On the assumption that past activity might have produced such features, an investigation of stream morphology was undertaken at a scale of 1:250 000.

In order to aviod bias due to known natural or cultural features, the stream patterns of fifteen 1:250 000 scale topographic maps covering the southwest of the State were traced and reduced to 1:500 000. Lineaments due to straight sections of river courses or the alignment of tributaries in neighbouring streams were then drawn in, giving the pattern shown in Figure 88. This work was carried out by Dr. J. L. Daniels, but its interpretation is that of the present authors.

Two main types of lineament were found: firstly, linear features up to 250 km long and commonly trending between 300° and 330°; and secondly, arcuate and circular lineaments with a radius up to about 50 km. The linear features were found throughout the area, but the arcuate lineaments were largely confined to a zone which included the South West Seismic Zone and western wheat belt areas. In the southwest of the area, the Darling Plateau contains predominantly straight lineaments trending at about 330°, parallel to the strike of the western margin of the seismic zone. The separation of the Darling Plateau lineaments from the circular lineaments of the seismic zone is artificially emphasized by the presence of the wide alluviated valley of the Avon River, in which no lineaments could be plotted. The arcuate and circular lineaments are confined to a south-southeast trending zone from Perenjori in the north to Cheyne Bay in the south. The zone is up to 150 km wide, and the lineaments occur in a series of overlapping groups, often with five of more concentric arcs. Not only is the main seismic zone covered by this lineament pattern, but it extends into the wheat belt and includes the area of sporadic seismicity from Muckinbudin to east of Katanning. To the north and east of the arcuate patterns, lineaments are again straight, but are sparsely distributed and irregular in orientation.

The relationship of the arcuate and circular patterns to geology and seismicity is problematic. The lack of detailed geological mapping throughout the region does not allow a direct comparison of stream lineaments and geological structure, but the persistence of the pattern throughout the wheat belt does suggest a similar structure in both the main seismic area and the western portions of the salt lake country.

An overlay of Figure 88 on Figure 87 is suggestive of a relationship between seismicity and arcuate stream lineaments, but the evidence is not conclusive. The Meckering event shows a strong correlation, with a pre-existing arcuate stream lineament which follows the fault line. Between Dalwallinu and Ballidu, a gently curving lineament can be correlated with a series of earthquake epicentres, and to the northeast of Wongan Hills the Manmanning and Cadoux group of epicentres is enclosed by another arcuate structure. Southwest of York, the Talbot Brook earthquakes lie along a straight lineament which trends at about 330° from Brookton towards Moora. In the south, the scattered group of epicentres northeast of Katanning are enclosed by part of a series of seven



88. Stream lineaments in Southwest Australia.

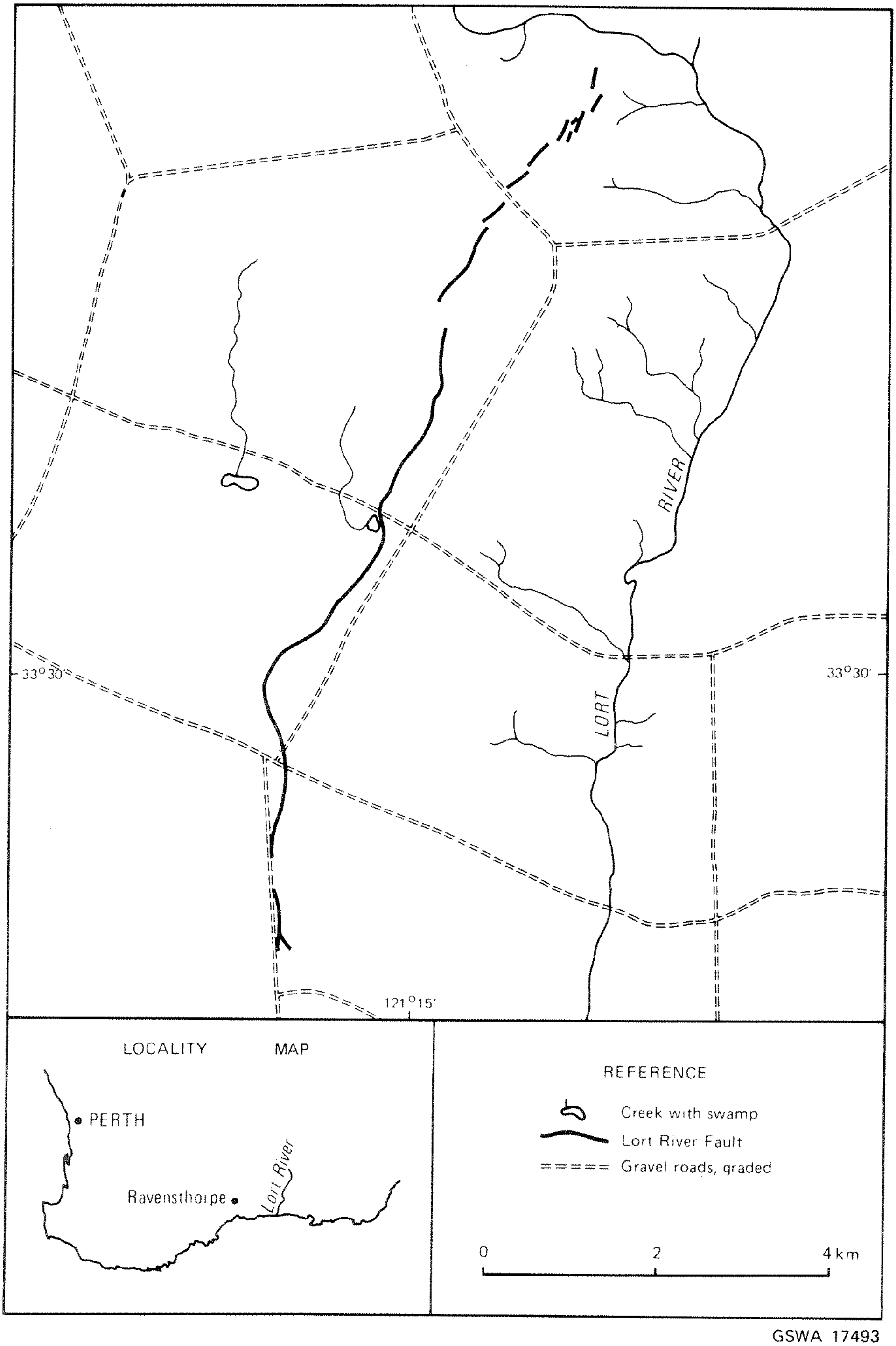
concentric arcs of large radius, and the single epicentre near Borden, recorded in February 1963, was located near the centre of a small circular lineament southeast of the town. Earthquakes in the Muckinbudin area can also be correlated with an arcuate lineament east of the town, and it seems remarkable that a group of epicentres separated from the main seismic areas should also coincide with an extension of arcuate lineaments into the same area.

In contrast, most of the epicentres located in the South West Seismic Zone cannot be readily correlated with stream lineaments, and many prominent lineaments are not associated with seismicity. No lineament corresponds to the Calingiri Fault, and the Dalwallinu-Ballidu lineament, which may be seismic, continues into a prominent arcuate lineament near Wongan Hills where there is no recorded seismicity. At Northam an arc, parallel to the arc through Meckering, is also aseismic. East of Brookton and Narrogin, a large circular lineament, 90 km in diameter and criss-crossed by numerous straight lineaments correlates well with an area of the western wheat belt in which no earthquake epicentres have been recorded. Finally, the most prominent seismic zone, from Pingelly northeastwards through Brookton, does not follow but cuts across the stream lineaments of the area.

From the study made it is obvious that stream lineament and present day seismicity cannot be correlated with any confidence. Some of the lineaments may reflect the effect of faulting on the topography, but most are probably controlled by geology. Arcuate lineaments could be a reflection of gneissic foliation, whereas straight lineaments could be due to major joints and dykes. Without greater ground control than is available, it is not possible to come to a conclusion. What the study has shown, however, is that lineaments in the aseismic areas of the Darling Plateau and the inland areas of the Yilgarn Block are different from those in the seismically active areas. The pattern of arcuate lineaments begins at the eastern edge of the Darling Plateau and extends beyond the main seismic zone to include the scattered epicentres in the wheat belt areas. It would appear, then, that the arcuate lineaments outline the seismic area, but that the seismicity is related to the deeper crustal structure which has produced the downwarping along the South West Seismic Zone. The arcuate lineaments may, however, indicate areas that may become seismically active in the future, or have been active in the past.

RECENT FAULT SCARPS IN WESTERN AUSTRALIA

Up to the present, the only surface fractures known to have been caused by earthquakes, except the minor fractures at Meeberrie, are the major faults at Meckering and Calingiri. A search was made of aerial photographs of the South West Seismic Zone for evidence of earlier fault scarps, but without success. The only other reports of recent fault scarps in Western Australia are from R. Thom (1972) in the Lort River area, between Ravensthorpe and Esperance and about 200 km east of the southern end of the South West Seismic Zone, and from I. Williams (1979) in the Mount Narryer area, 60 km north of Meeberrie Homestead in the Gascoyne Region.



89. The Lort River Fault.

THE LORT RIVER FAULT

The Lort River Fault forms a low north trending scarp, 40 km long and up to 2 m high, with the east block relatively uplifted (Fig. 89). The longer southern section has an irregular trace, and at one point has dammed a stream, forming a small pond in front of the fault. The northern section consists of a series of short *en echelon* scarps, offset left. The fault trace has a general appearance similar to the Meckering and Calingiri Scarps, and may be a low angle sinistral thrust fault.

The fault scarp has been preserved because the area was not cleared for agriculture until the 1960's; it is present on air-photos taken in 1957 but its age is otherwise unknown. The only earthquake recorded in the area is a verbal report of two shocks in the Ravensthorpe-Hopetoun district on 3rd May 1916 (Everingham, 1968). A fault similar in extent to the Meckering Fault would require an earthquake of similar magnitude, yet there have been no reports from Esperance, 50 km east, or from further afield, in the 70 years that have elapsed since settlement of the area.

THE MOUNT NARRYER FAULTS

At Mount Narryer two slightly curved, northeast trending, lineaments are well marked on air-photographs of the region. On inspection the lineaments were found to be caused by a small break in slope accompanied by a dense growth of large mulgas *(Acacia aneura)* in a narrow belt 10 m to 500 m wide. The surrounding vegetation, except in stream courses, was low stunted mulga scrub growing on thin alluvium and colluvium overlying hardpan in broad valleys west of the Murchison River. The dense growth along the lineaments indicated a narrow zone of deeper colluvium. The lineaments cut across the local drainage and from their general disposition Williams (1979) concluded that they represented relatively recent fault scarps. Erosion of the scarps had brought about a local thickening of the colluvium sufficient to support a tall stand of mulga. The two faults were 33 km and 11 km long, and downthrown to the east about 1.5 m. A number of small branch faults near the northern end of the smaller eastern fault were downthrown to the west. All displacements appeared to be normal faulting.

The mulga trees along the eroded fault scarps showed a remarkable uniformity of size, and a lack of old dead trees, when compared with those growing in stream courses. On the assumption that this represented coeval germination shortly after the formation of the fault a number of the largest trees were cut down to determine their age. Despite the irregular rainfall of the Murchison area, which could produce false growth rings, dendrochronology indicated that the trees were between 80 and 90 years old and therefore germinated in the period 1888 to 1898. The seismological records report a strong earthquake felt in the Geraldton area in 1885 (Everingham 1968a), and from the description of that event and the age of mulga trees at Mount Narryer it appears probable that the earthquake originated from Mount Narryer.

The Mount Narryer faults are only 21 km north of the epicentre of the Meeberrie earthquake of 1941. An inspection of air photographs in the vicinity of other known epicentres in the Gascoyne region, including Landor (1969), revealed other tree-lined lineaments similar in size and trend to the Mount Narryer faults. It would seem that although the seismicity of the Gascoyne region is sporadic and less than that of the South West Seismic Zone it nevertheless has a long history and has produced several examples of surface faulting.

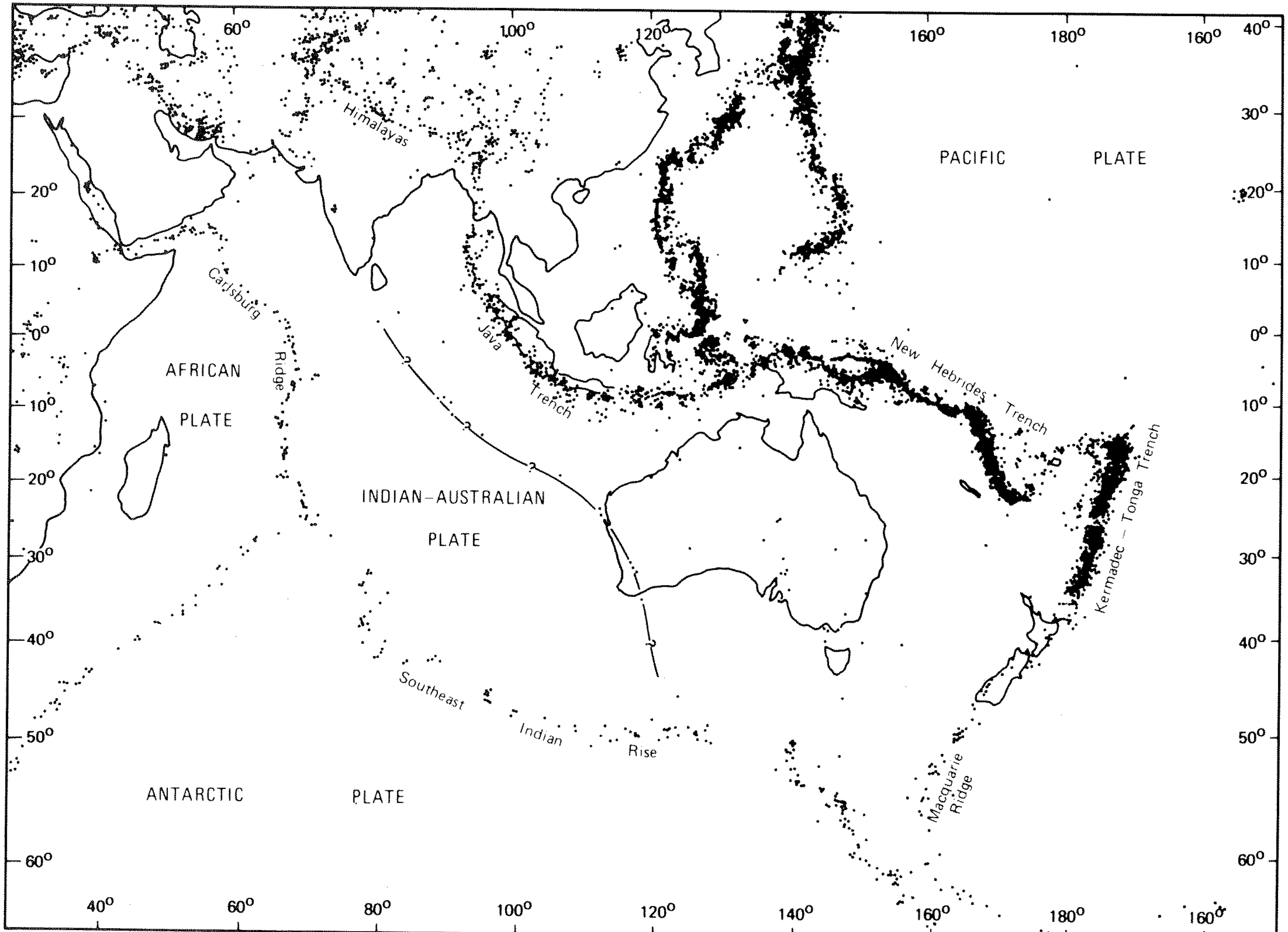
PLATE TECTONICS AND AUSTRALIAN SEISMICITY

Australia forms part of the Indian Plate, a fundamental unit of the earth's crust which includes the Indian sub-continent, two-thirds of the Indian Ocean, and the seas surrounding Australia. It was orginally defined by le Pichon (1968) from magnetic data on sea-floor spreading, combined with data from orogenic zones. Isacks and others (1968) showed that the margins of the plates were also major seismic zones which accounted for about 90% of the world's earthquakes and almost all of the major shocks. It was also shown that the directions of movement of the plate, as calculated by le Pichon, were consistent with the focal mechanism of the earthquakes. The Indian Plate is outlined (Fig. 90) partly by ocean ridges which stretch from the Gulf of Arabia southward and eastward through the Indian Ocean to an east-west ridge between Australia and Antarctica. To the north and east, the plate margin is marked by the Himalaya mountain chain, and a series of island arcs from Sumatra through Java to New Guinea and Tonga, where it turns abruptly southward through the Tonga and Kermadec ridges, through New Zealand, to join the mid-ocean ridge near Macquarie Island.

The evolution of the Indian Plate has been described by McKenzie and Sclater (1971). Briefly, if the Antarctic is assumed fixed, India broke from Gondwanaland, the ancient super-continent, in the Mesozoic and moved northward, with the Ninetyeast Ridge as a centre of spreading. Later the Australian continent broke away from Antarctica, and with the Ninetyeast Ridge now inactive, the present system of mid-ocean ridges and island arcs developed. This has resulted in a plate containing two major land masses and the Indian Ocean basin in addition to the remains of earlier ocean ridges and fragments of continental material which now form sea mounts.

THE AUSTRALIAN CONTINENT

As a stable land mass within the plate boundaries, Australia, like peninsular India, has a very low seismicity. However, as the Meckering and Calingiri events have shown, quite significant earthquakes can occur, even within an Archaean shield area. Stress in the Australian land mass could be the result of residual strain from an earlier orogeny, particularly in the Tasman geosynclinal zone, but much of it is probably caused by the mechanics of plate movement. Australia is moving northward with respect to Antarctica, the ocean ridge south of the continent spreading at the rate of about 6.4 cm/yr in the direction of 333° (le Pichon, 1968). The northern boundary of the plate, however, is being subducted beneath the Indonesian island arc at only 4.9 cm/yr in the direction of 019°. It is possible that the large sialic mass of Australia is the cause of this retardation (Isacks and others, 1968), but the result of such differential movement is that the continent is under compressive forces. This need not be a uniform compression, and indeed, the presence of Pleistocene and Holocene volcanism in South Australia and Western Victoria indicates that dilation has also been present in recent times. From the pattern of



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90. Seismicity associated with the Indian Australian Plate, 1961-1967 (after Barazangi and Dorman, 1969).

earthquake epicentres in Australia, Cleary and Simpson (1971) suggested that the diffuse seismic zone across eastern Australia and the South West Seismic Zone were compressive features while a sinuous zone from South Australia to the Canning Basin of Western Australia was a dilational region. Doyle (1971), however, suggested that thrust and reverse faulting is typical of Australian seismicity, and that stresses are normally compressional, a suggestion confirmed by the studies of Stewart and Mount (1972) in South Australia, and Denham and others (1974) for the East Canning Basin. On a world-wide examination of intraplate earthquakes, Sykes and Sbar (1973) have shown that horizontal compressive stresses are characteristic of continental areas, and are probably related to the driving mechanism of plate tectonics. A further suggestion of Doyle was that the lack of active transcurrent faulting, which would be usual under horizontal compression, could be the result of semi-radial compression. The compilation of data from earthquakes and *in-situ* rock stresses by Denham and others (1976) shows that although the predominant stress direction is east-west there is also a tendency for it to dip towards the continental margins.

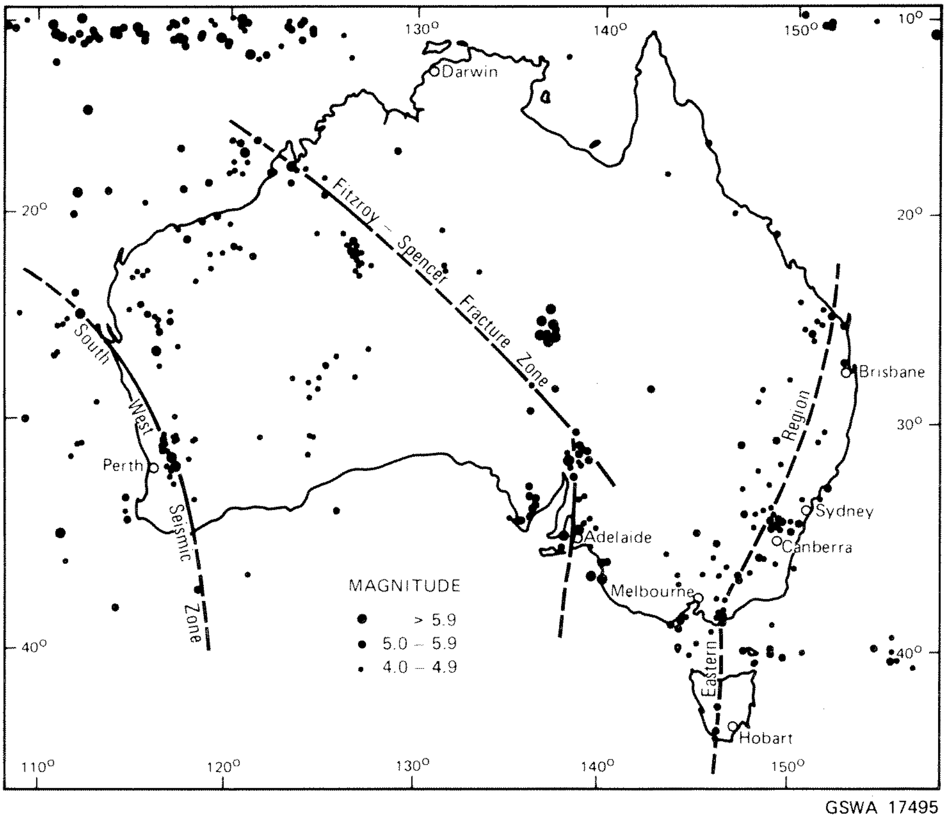
SEISMICITY AND THE STRUCTURE OF AUSTRALIA

Although Australia has relatively few earthquakes, their concentration in particular zones (Fig. 91) suggests that they may be related in an important way to the structure of the continent. The theory of plate tectonics assumes that the interior of the plate is perfectly rigid, but as Doyle (1971) has noted, the postulation of second order effects—smaller plates within the larger plates—may be necessary to explain Australian seismicity. Cleary and Simpson (1971) first made a division of the continent based on seismic zones, and suggested that, relative to a fixed sub-plate centred on South Australia, both eastern and southwestern Australia were moving northward. However, known sinistral movement in the South West Seismic Zone, and possible dextral movement along the Fitzroy-Spencer Fracture Zone could indicate that the South Australian sub-plate is moving northwest with respect to the remainder of the continent.

Some of the seismic zones can be traced beyond the continental margin and linked to transform faults in the mid-ocean ridges. Although there is no direct connection between faulting in solid rock and transform faults produced by sea-floor spreading, Wilson (1965) has pointed out that a line of structural weakness in the continent at the initiation of continental drift might well provide the locus for a future transform fault. The seismic zones may therefore provide clues to the structure of the Australian continent over a considerable period of geological time.

EASTERN AUSTRALIA

Earthquakes occurring along the eastern margin of Australia appear to be associated with the Tasman Geosynclinal zone, but there is no pattern which would suggest a major seismic lineament. Studies have been confined to individual shocks or to localised clusters, such as those of the Gunning zone, north of Canberra (Cleary, 1967), and the Sydney Basin (Doyle and others, 1968a). In both locations, focal plane studies indicate reverse faulting on easterly dipping fault planes. At Gunning, the earthquake of 8th February 1961 involved movement along an old high-angle reverse fault, and included a large sinistral



91. Seismic zones of Australia.

component (Cleary, 1967), while the Picton event of 9th March 1973, on the southern margin of the Sydney basin was dominantly a thrust movement (Fitch, 1976). In both cases no surface faulting was visible. Little information is available on earthquakes outside New South Wales, but Beavis (1960) showed that the Tawonga Fault in northeast Victoria thrust gneisses over Quaternary gravels along a fault plane which dipped at only 16° to the southeast.

Although the whole of the eastern continental margin is now under compressive forces, this must be a relatively recent event towards the southern end of the zone. Wellman and McDougall (1974) have shown that, during the formation of the Tasman Basin and since Australia separated from Antarctica about 55 m.y. ago, a tensional regime existed with widespread volcanic activity. Central type volcanism migrated steadily from Queensland to Victoria, beginning about 35 m.y. ago and ending as late as 4.5 m.y. ago in the Macedon area. Present day seismicity does not appear to be related to any single deep-seated crustal feature, and although a tentative seismic zone may be drawn to encompass most epicentres, it is lost beyond the continental shelf. A ridgelike structure extends south of Tasmania and is possibly related to a transform fault in the mid-ocean ridge mapped by Heirtzler and others (1968), but there is very little seismicity in this area.

There is a possibility that several separate seismic zones are involved, each related to a more local crustal structure. Doyle and others (1968a) have suggested that the earthquakes in the Sydney Basin might reflect the basin margins and its extension on the continental shelf.

THE FITROY-SPENCER FRACTURE ZONE

The Fitzroy-Spencer Fracture Zone is the name given by Cook (1966) to a postulated zone of fracturing extending from the Fitzroy Trough in Western Australia to Spencer Gulf and the Adelaide Geosyncline in South Australia. The name has also been adopted by Stewart and Mount (1972) to explain the seismicity of the two areas.

Seismicity in South Australia is centred largely on the western side of the north-south Adelaide Geosyncline, but minor seismicity extends northwestward towards Lake Eyre, and a further minor seismic zone is on the Eyre Peninsula. Earthquakes in the area of the Adelaide Geosyncline are of both compressional and dilational type, and their distribution has been related by Stewart and Mount (1972) to the movement of several major structural blocks in the region. To the west, the epicentres on the Eyre Peninsula appear to be related to the Port Lincoln Fault, which trends northeast and has a major dextral strike-slip component of movement. The seismic zone is terminated at its northern end by a northwest-striking zone, having a dominant dextral strike-slip movement, which can be traced seismically to Lake Eyre, and forms the southern end of the Fitzroy-Spencer Fracture Zone. Block movements in the Adelaide region can be related to the 'kink' in the zone, which is thought to be of ancient origin, possibly controlling the location and development of the Proterozoic Adelaide Geosyncline. To the south, several writers (Doyle and others, 1968; Cleary and Simpson, 1971; Stewart and Mount, 1972) have noted that the South Australian Seismic Zone is almost continuous with a prominent fracture zone which extends from the mid-ocean ridge almost to the continental shelf (Heirtzler and others, 1968).

At the northwest end of the proposed Fitzroy-Spencer Fracture Zone, in the Fitzroy Trough, a graben structure is bounded on the southwest by the Dampier and Fenton Faults and on the northwest by the Pinnacle Fault. The trough developed during the Paleozoic and Mesozoic, and contains up to 9 000 m of sediments (Playford and others, 1975). The overall configuration of the Fitzroy Trough, together with parts of the Carnarvon Basin and Perth Basin, has been compared by Veevers and Cotterill (1976) to a rift-valley system similar to that found in East Africa. Movement on the major faults of the trough have been predominantly normal, but in the mid-Jurassic, at about the time that Australia separated from India, there was a period of reverse movement on the Fenton Fault. This period of tectonism was accompanied by dextral wrench movement between the two sides of the graben, resulting in east-west anticlinal folds and an *en echelon* pattern of minor normal faults which extends across the platform area of the Northeast Canning Basin (Smith, 1968). Rixon (1978) has shown experimentally that the complete fault pattern of the Fitzroy Graben can be produced by a dextral shear in the basement. More recent compressive forces are indicated by the Fraser River structure on the Dampier Peninsula. This broad upwarp, parallel to the axis of the Fitzroy Trough, has diverted the course of the Fitzroy River and was initiated in the Tertiary (Brunnschweiler, 1957).

Present day seismic activity in the Fitzroy Trough is minor, but since accurate recording began in 1959 a number of epicentres have been located in the western half of the area. Two small earthquakes (M_L 4-5) have been located in the area of the Dampier Fault, and one further east on the Fenton Fault, but most activity has been offshore and in the region of the Dampier Peninsula. On the axis of the Fraser River anticline, several small tremors have been recorded, and on 23 March 1964, a shallow earthquake of $M_L = 6.8$ was recorded from the same area, about 90 km east of Broome. In the offshore extension of the Fitzroy Trough, several moderate earthquakes have been recorded, but these have been correlated with the tectonic downwarping of the continental margin in this area (Doyle and others, 1968).

The most recent seismic activity in the north of Western Australia has been in the East Canning Basin, southeast of the Fitzroy Trough (Denham and others, 1974). An earthquake of $M_L = 6.7$ on the 24th March 1970 was followed by many smaller aftershocks over a period of two years. The aftershock swarm occupied an area of 140 km by 20 km, elongated in a northwest direction. The swarm was located in the Broome Platform area, between the Fitzroy Trough and the Kidson Sub-basin, and southwest of the wrench fault system which Smith (1968) noted extending from the trough into the northeast Canning Basin. The focal mechanism of the main shock indicates a pure thrust movement on a fault plane dipping steeply to the southwest. This supports the idea of regional compression but is at variance with the dextral strike-slip faulting postulated by Stewart and Mount (1972).

The central portion of the Fitzroy-Spencer Fracture Zone has recorded very few earthquakes and there are no obvious structures which could mark it out across the Arunta Block. The main structural trend in Central Australia is east-west, as shown by the Amadeus and Ngalia Basins. Cook (1966) originally postulated the fracture zone on a succession of east-west thrust structures occupying a northwest-trending belt within the Amadeus Basin, and the lack of seismicity in the region could be the result of the fracture 'locking' on these east-west structures.

THE SOUTH WEST SEISMIC ZONE

The main features of this seismic zone have been described in detail earlier in this chapter, including the linear nature of seismic activity which gave rise to the earlier name of Yandanooka-Cape Riche Lineament (Everingham, 1965). This 'lineament' can be extended both north and south if several tremors to the south of Albany, and faults and coastal features north of Yandanooka are included.

Only a small number of epicentres have been located in the ocean south of Albany since recording began in 1959, and to include these in the South West Seismic Zone involves traversing the east-west Albany-Fraser Province, of Proterozoic age, and the Blackwood Axis, the hinge line of Tertiary epeirogeny. The cause of seismicity in the region, however, is probably a deepseated crustal structure related only indirectly to surface geology. Nevertheless, only four epicentres have been recorded on land and south of the Blackwood Axis (Fig. 87), and a similar number offshore. This low degree of activity, when compared with the main active zone is insufficient to draw firm conclusions, but activity in the ocean areas is continuing, and on 15th May 1977 a shock of M_L 4.5 and at least eight minor tremors were recorded from an area a few kilometres east of Albany. A further shock of M_L 4.0 was recorded from the same area on 2nd June 1977. The mid-ocean ridge south of Western Australia is complex, with many small transform faults, and unlike the South Australian seismic zone it is not possible to suggest any particular relationship with the South West Seismic Zone.

At the northern end of the South West Seismic Zone, the 'lineament' is continued by the strike of the Urella Fault, and the gently curved, faulted coastline from Kalbarri to False Entrance near Shark Bay. Beyond this point there have been a number of epicentres which could be considered as a continuation of the seismic zone into the eastern Indian Ocean Basin. The Urella Fault and the shore-line fault at the base of the Zuytdorp Cliffs (Megallaa, in prep.), however, are normal faults, and there is no geological evidence for lateral movement, whereas studies of the Meckering and Calingiri events indicate sinistral thrust faulting. But neither of these faults has a direct surface expression, and although the Meckering Fault has been shown to be reactivated (Chapter 8), it is probably a geologically recent feature. Under these circumstances, when total movement along the seismic zone has been small and is controlled by a crustal structure which would be blanketed by several kilometres of sediment in the Perth and Carnarvon Basins, it is possible that the fracture zone might have no surface expression in the area. The area is very nearly aseismic although a shock of M_L 3.9 was reported from 30 km south-southeast of Dongarra on 10 January 1977. The epicentre was probably located on the Beagle Fault, and was only a few kilometres north of Jurien Bay, where the Meckering Earthquake caused damage in 1968.

Assuming a connection between the South West Seismic Zone and epicentres north-west of the Shark Bay region, the lineament can only be extended with certainty to the edge of the continental shelf. Cleary and Simpson (1971) suggested a possible extension towards the Indonesian island arc, whereas Sykes (1970) has proposed an extension towards a seismically active region near the Cocos Islands. Ocean basins are usually very nearly aseismic, but a wide zone of persistent seismicity is present from about Sri Lanka to the Cocos Island. Several large earthquakes have occurred, and focal mechanisms indicate strike-slip faulting, possibly with thrusting. The zone is parallel to the Andaman-Indonesian island arc but corresponds to no known topographic feature of the ocean floor, and leads to the suggestion that it represents a nascent island arc. There is a rather large gap, however, between the end of this seismic zone and the Western Australian epicentres, and any correlation must be tentative. Some confirmation of the possibility of an extension of South West Seismic Zone lineament in the direction of Shark Bay is provided by recent studies of the physiography of the West Australian continental shelf. Falvey and Veevers (1974) describes a series of plateaux and abyssal plains trending northwest from the coast and suggest that the plains were formed by the subsidence of faulted blocks. A tectonic reconstruction by Veevers and Heirtzler (1974) suggests that the separation of India from Australia during the Lower Cretaceous gave rise to a series of transform faults, one of which, separating the Wallaby-Perth Platform from the Cuvier Abyssal Plain, is a continuation of the Shark Bay-Kalbarri-South West Seismic Zone lineament. The present seismicity of the zone may represent the release of residual strain or a reactivation of this old fracture zone.

APPENDIX I

CATALOGUE OF LARGER EARTHQUAKES RECORDED IN SOUTHWESTERN AUSTRALIA

A complete listing of all earthquakes recorded in Western Australia can be found in the publications of the Mundaring Geophysical Observatory. Prior to 1923, and the installation of a Milne-Shaw seismograph at the Perth Observatory, no measurements could be made of the magnitude of earthquakes unless they were sufficiently strong to be recorded on distant seismographs. Only one such earthquake, that of 1920 in the Indian Ocean, occurred in the area under consideration. Everingham and Tilbury (1971) have collected newspaper reports of earthquakes between 1849 and 1900, and it appears from their account that only one event, that of 8th May 1885, at Geraldton, would have a magnitude of 4 or more. Between 1904 and 1923 there were numerous reports of earthquakes in the southwest of the State (Everingham, 1968a) but none appear to have been large. It must be remembered however that population density was very low throughout the region, and that some of the reports could have referred to moderate earthquakes of about M_L 4 located in uninhabited areas.

The Perth Observatory instruments were in operation between 1923 and 1959 when they were replaced by the modern seismographs at the Mundaring Geophysical Observatory, operated by the Bureau of Mineral Resources. The records of the Perth Observatory have been summarized by Everingham and Tilbury (1971), and for the Mundaring Observatory between 1959 and 1965 by Everingham (1968a). Since 1966, the Annual Reports of the Mundaring Geophysical Observatory have given a complete list of earthquakes recorded throughout the state.

Table 22 provides a list of the larger earthquakes recorded in southwestern Australia, an area south of Latitude 30°S and west of Longitude 121°E. A local magnitude (M_L) of 4.0 or greater was chosen both to exclude the many hundreds of small tremors that have been recorded, and to restrict the list to those earthquakes likely to be felt over a reasonable area.

TABLE 22. EARTHQUAKES OF MAGNITUDE 4 OR MORE IN SOUTHWESTERN AUSTRALIA

Date	*Origin time (U.T.)*	*Epicentre* *Latitude °S*	*Longitude °E*	M_L	*Location*
1920					
Feb 08	05 24 30.0	35.00	111.00	6.2	260 km SW Cape Leeuwin
1940					
Dec 18	21 45 —	32.20	117.20	4.2	Beverley/Brookton
1946					
Apr 19	21 13 —	(38.5)	(114.5)	5.7	W of Yallingup
Sep 17	15 12 —	(32.5)	(116.9)	4.5	Pingelly
1949					
May 02	10 00 —	30.90	116.40	5.1	Yerecoin
07	17 09 —	30.90	116.40	4.1	Yerecoin
1952					
Mar 11	06 09 —	31.30	116.50	5.1	Bolgart
1954					
Nov 27	08 36 —	(32.0)	(116.7)	3.9	Talbot Brook
1955					
Apr 29	09 14 —	30.90	116.40	4.7	Yerecoin
29	19 49 —	30.90	116.40	4.4	Yerecoin
Aug 29	06 09 —	30.70	116.40	5.3	Gabalong
30	13 52 —	30.70	116.40	5.8	Gabalong
30	14 07 —	10.70	116.40	4.7	Gabalong
30	16 56 —	30.70	116.40	4.6	Gabalong

Table 22—continued

Date	Origin time (U.T.)	Epicentre Latitude °S	Epicentre Longitude °E	M_L	Location
1956					
Feb 24	06 27 —	(30.9)	(116.4)	4.5	Yerecoin
Apr 05	23 13 —	(30.9)	(116.4)	4.5	Yerecoin
1958					
Mar 20	03 03 —	32.20	117.20	4.8	Beverley/Brookton
1959					
Oct 03	12 07 22.0	34.50	114.50	4.2	55 km SW Cape Leeuwin
1961					
Jun 12	18 00 51.0	34.20	114.50	4.1	50 km SW Cape Leeuwin
25	17 59 18.0	32.20	117.20	4.4	Beverley/Brookton
Jul 30	07 28 34.0	36.90	121.00	4.2	Southern Ocean
Nov 10	14 59 14.0	37.50	118.40	4.4	Southern Ocean
1963					
Jan 18	05 49 18.0	32.20	117.20	4.9	Nourning Spring
Nov 19	17 52 05.0	31.00	116.30	4.2	New Norcia
1964					
Jun 12	14 08 54.0	33.60	118.10	4.3	Lake Grace
1968					
Feb 22	04 40 10.5	30.80	117.30	4.0	Cadoux
Apr 08	01 44 55.4	30.80	117.30	4.4	Cadoux
June 21	07 54 56.3	30.80	118.30	4.0	Mukinbudin
Oct 03	03 55 33.4	31.59	116.98	4.2	Meckering
14	02 58 50.3	31.60	117.00	6.9	Meckering
14	03 15 21.4	(31.6)	(117.0)	4.0	Meckering
14	03 57 47.7	31.66	116.99	4.0	Meckering
14	04 09 07.5	31.60	117.01	4.6	Meckering
14	06 47 50.4	31.69	116.98	4.2	Meckering
Oct 15	03 30 07.0	31.68	117.03	5.7	Meckering
16	00 55 10.2	31.66	117.02	4.2	Meckering
18	10 31 47.9	31.76	117.07	4.1	Meckering
21	15 32 59.2	31.61	117.09	4.6	Meckering
22	01 04 04.9	31.58	117.01	4.1	Meckering
Oct 26	04 22 30.2	31.67	117.03	4.9	Meckering
31	00 58 48.9	31.78	116.98	4.1	Meckering
Nov 28	14 17 31.5	31.64	117.00	4.0	Meckering
1969					
Feb 01	03 29 57.7	31.96	117.15	4.0	Mawson
Jul 01	09 20 47.8	30.95	117.10	4.2	Moonijin
1970					
Mar 10	17 15 11.2	31.11	116.47	5.1	Calingiri
Dec 26	18 25 51.0	31.08	116.31	4.0	Calingiri
1971					
Jul 16	12 32 26.9	31.62	117.09	4.0	Meckering
1974					
Jul 09	10 46 47.4	31.65	117.00	4.3	Meckering
Sep 04	23 17 42.4	30.79	116.97	4.5	Manmanning
Nov 19	09 30 22.6	31.63	117.03	4.0	Meckering
1976					
Mar 31	21 26 48.4	38.22	113.50	4.7	450 km SW Cape Leeuwin
Oct 29	06 04 48.2	31.64	117.00	4.7	Meckering
1977					
May 15	19 16 07.6	35.00	117.95	4.5	Albany
June 02	13 37 33.0	35.00	117.95	4.0	Albany

APPENDIX II

PHENOMENA REPORTEDLY ASSOCIATED WITH THE MECKERING EARTHQUAKE

Before 1968 the population of Meckering would have considered that earthquakes occurred only in distant countries, the local tremors being explained as the collapse of underground caverns in wet seasons. The events of 14 October 1968 changed this, and introduced a range of new phenomena not normally experienced by most people. In order to assimilate these experiences, the populace became keen observers of any minor change in the local environment which might be connected with the earthquake, and today such terms as epicentre, thrust fault, magnitude and intensity are part of the local vocabulary. As a result of the traumatic events, however, occurrences which might previously have been ignored assumed importance as possible results of the earthquake. Most could quickly be dismissed, but nevertheless two phenomena could not be easily explained and may have been caused, albeit indirectly, by the earthquake.

EFFECT OF VEGETATION

Two weeks after the earthquake the trees in Lundy Road, a section of the Meckering-York road about 5 km south of Meckering, were showing dead leaves on one side. The road trends northwest for 3 km, then northeast for 1 km, and is about 4 km northeast of the Meckering Fault scarp where it crossed the salt flats of the Mortlock River. The leaves of many of the trees in both sections of the road were found to be dead and brown on the southwest side but still green on the northeast side. The effect was more clearly seen in fine-leaved shrubs such as sheoaks than in the broad-leaved eucalypts, but leaves on York Gums were visibly damaged.

No other areas were found showing a consistent pattern of burning, although on the Dowerin road, 5 km north of Meckering, several small areas of affected vegetation were noted. Generally the southwest side of the shrubs were dead, but this was not consistent.

Movement along the plane of the Meckering Fault, and some of the larger minor faults, would generate a considerable amount of heat which could possibly have affected the vegetation. Byerly (1942) notes that after the Sonora (Mexico) earthquake of 1897 trees overhanging the fault were scorched, and following the Owens Valley (California) earthquake of 1872 landslides developed sufficient frictional heat to start bushfires. At Meckering, however, no burning effects were recorded near the fault trace, and the area has insufficient relief to give rise to landslides. It seems unlikely, therefore, that the vegetation on Lundy and Dowerin roads was affected directly by earthquake generated heat.

A botanist from the West Australian Department of Agriculture examined the trees, and submitted samples of dead and green leaves from the affected trees to the Government Chemical Laboratories. Analysis showed that there was no significant difference in sulphur content between the affected and unaffected foliage, and the cause of the burning was not due to stray weedkiller from spraying operations. Partial death of the plants probably resulted from the action of hot winds (R. Royce, Dept. of Agriculture, pers. comm.).

EFFECTS ON SKIN

Several Meckering residents developed skin complaints within a few days after the earthquake. One woman, who had felt a burning sensation whilst running over cracking ground at the time of the event, next day developed a sore skin and her lips were chapped. Another couple living near the salt flats, also noticed an effect like sunburn, while a woman on the northern side of the Mortlock salt flats developed a sore skin and described her condition as similar to severe windburn. With normal treatment these conditions all cleared up within a few days. One factor common to this group of people was that they all lived close to the salt flats.

In the weeks following many people in the town suffered temporary loss of voice and slight inflammation of sensitive skin under the chin and nose. These symptoms were attributed by a local general practitioner to an abnormal exposure to the sun and the rigours of living outside in tents and temporary shelters.

APPENDIX III

GLOSSARY

This glossary contains a brief explanation of some of the terms used in this bulletin, particularly with respect to seismology, and is intended for the non-technical reader.

Aftershock: A secondary, small magnitude earthquake which follows the main earthquake and originates at or near the focus of the main shock. Commonly a large number of aftershocks follow a large earthquake, decreasing in frequency over a period of days or months. (cf. foreshock).

Dextral: Right handed, see Fault. (Ant: sinistral).

Earthquake: A sudden motion or trembling in the earth caused by the abrupt release of slowly accumulated strain, either by faulting or volcanic activity.

En echelon: "in steplike arrangement". Said of a series of short separate faults or fractures that are in an overlapping or staggered arrangement but together form a linear zone.

Epicentre: That point on the Earth's surface which is directly above the focus of an earthquake.

Fault: A zone of rock fracture along which there has been relative movement between the two sides. A fault may vary from a few metres to many kilometres long. Faults may be divided into several types, although an individual fault commonly combines two types of movement. (Fig. 92).

Normal fault: A fault in which the block above the fault plane appears to have moved downward relative to the lower block. The dip of the fault plane is usually 45° to 90°.

Reverse fault: A fault in which the block above the fault plane appears to have moved upward relative to the lower block. The dip of the fault plane is usually 45° to 90°.

Thrust fault: A reverse fault in which the fault plane dips at less than 45°. Horizontal compression is more important than vertical movement.

Strike-slip fault: A fault without vertical movement in which the two blocks move horizontally and parallel to the strike of the fault. The fault plane may dip at any angle but is commonly near vertical. If on crossing the fault, the other block has moved relatively to the right it is a dextral strike-slip fault, if to the left then it is a sinistral strike-slip fault.

Fault plane: The more or less planar surface on which fault movement takes place.

Fault scarp: The steep slope or small cliff formed directly by movement along one side of a fault.

Fault trace: The line along which a fault plane intersects the ground surface, i.e. the surface exposure of a fault.

Focus: That point within the Earth which is the centre of an earthquake. However, as earthquakes originate from faults, which are planar features, it is perhaps best seen as the point at which rock fracturing begins during an earthquake.

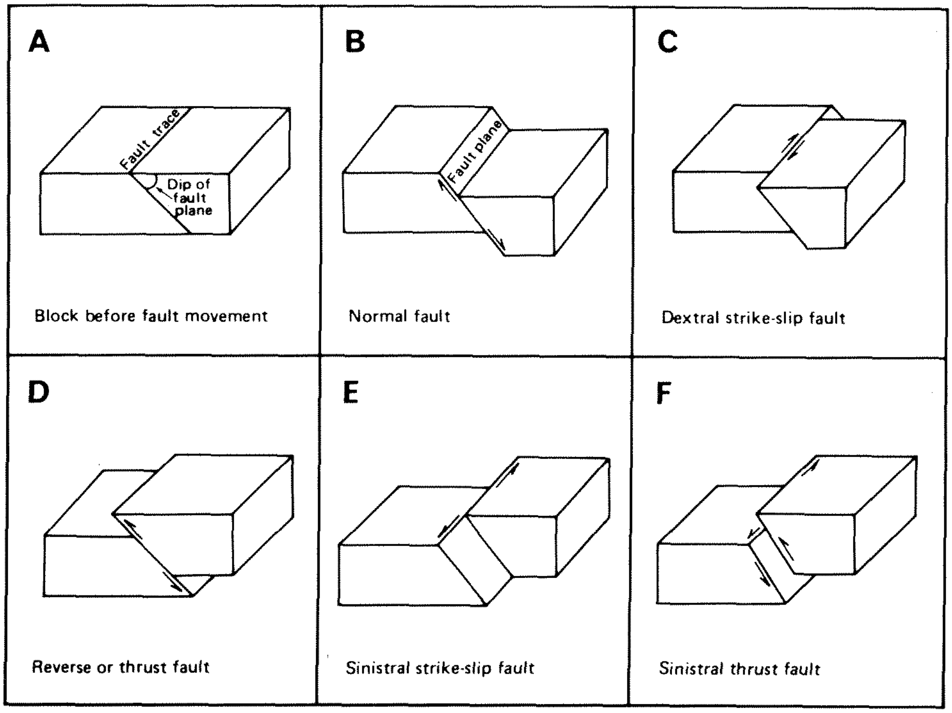
Foreshock: A small tremor that preceeds a large earthquake and originates at or near the same focus. Foreshocks may occur seconds or weeks before the main event. (cf. Aftershock).

Hypocentre: See focus.

Intensity: A measure of the effects of an earthquake at a particular place on humans and/or structures. The intensity depends not only on the *magnitude* of an earthquake but also on the *distance* from the focus and the local geology. Various scales have been devised, e.g.: Rossi-Forel scale, Mercalli scale, and the Modified Mercalli scale (Appendix IV).

Isoseismal: A line connecting points on the Earth's surface at which earthquake intensity is the same. Usually a closed curve round the epicentre. A series of such lines can be constructed to form an *isoseismal map.*

Magnitude: (M_L, M_S, m_b) The Magnitude of an earthquake is related to the energy released and is determined by the amplitude of the seismic waves as recorded by a seismograph. The best known scale is that devised by C. F. Richter and known commonly as the *Richter Scale.* This scale is logarithmic, each whole number step on



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92. Types of Faulting.

the scale representing an increase of 10 times in the energy of an earthquake. Thus a magnitude 6 earthquake is 10 times as large as one of magnitude 5. Although the scale is open ended the largest magnitude recorded is about 9. M_L, or local magnitude, is the abbreviation used for magnitudes measured on the Richter scale; M_S is the magnitude measured from surface waves; m_b is the magnitude measured on body waves. Magnitude is not to be confused with intensity.

Modified Mercalli scale: (M.M.) An arbitrary scale of earthquake intensity ranging from I (barely perceptible) to XII (almost total destruction). It is named after G. Mercalli, who originally devised it, and has been modified for use in various countries. The New Zealand version is given in Appendix IV.

Normal fault: See Fault

Reverse fault: See Fault.

Sag Pond: A pond formed when a fault scarp dams a stream.

Seiche: The oscillation of the surface of the water in a lake or bay caused by an earthquake. Not to be confused with the "tidal wave" (properly: tsunami) which is caused by a submarine earthquake or volcanic eruption.

Seismogram: A record of the ground motion caused by an earthquake.

Seismometer: A device for detecting the ground motion caused by an earthquake.

Sinistral: Left handed, see fault. (Ant: dextral).

Strike-slip fault: see fault.

Thrust fault: see fault.

Tremor: A minor earthquake, particularly foreshocks and aftershocks.

Universal Time (U.T.): Time as measured at 0° longitude, i.e. Greenwich Mean Time.

Western Standard Time (W.S.T.): Local time in Western Australia, normally eight hours in advance of Universal Time.

APPENDIX IV

MODIFIED MERCALLI SCALE, N.Z. VERSION, 1965
(EIBY, 1966)

The Mercalli Scale is used to assess the felt intensity of an earthquake. A measure of the intensity will, therefore, be available throughout the whole area that the shock was felt, and will decrease as the distances of the observer from the source of the earthquake increases. This is not to be confused with the magnitude of the earthquake which is a single figure, calculated from seismogram recordings of the shock, related to the energy of the earthquake at its source.

MM I: Not felt by humans, except in especially favourable circumstances, but birds and animals may be disturbed. Reported mainly from the upper floors of buildings more than 10 storeys high. Dizziness or nausea may be experienced.

Branches of trees, chandeliers, doors and other suspended systems of long natural period may be seen to move slowly. Water in ponds, lakes, reservoirs etc., may be set into seiche oscillation.

MM II: Felt by a few persons at rest indoors, especially by those on upper floors or otherwise favourably placed. The long-period effects listed under MM I may be more noticeable.

MM III: Felt indoors, but not identified as an earthquake by everyone. Vibration may be likened to the passing of light traffic. It may be possible to estimate the duration but not the direction of vibration. Hanging objects may swing slightly. Standing motorcars may rock slightly.

MM IV: Generally noticed indoors, but not outside. Very light sleepers may be wakened. Vibration may be likened to passing of heavy traffic, or to the jolt of a heavy object falling, or striking the building. Walls and frames of buildings are heard to creak. Doors and windows rattle. Glassware and crockery rattles.

Liquids in open vessels may be slightly disturbed. Standing motor cars may rock, and the shock can be felt by their occupant.

MM V: Generally felt outside, and by almost everyone indoors. Most sleepers awakened. A few people may be frightened. Direction of motion can be estimated. Small unstable objects are displaced or upset. Some glassware and crockery may be broken. Some windows cracked. A few earthenware toilet fixtures cracked. Hanging pictures move. Doors and shutters may swing. Pendulum clocks stop, start, or change rate.

MM VI Felt by all. People and animals alarmed. Many run outside. Difficulty experienced in walking steadily. Slight damage to masonry D*. Some plaster cracks or falls.

Isolated cases of chimney damage. Windows, glassware and crockery broken. Objects fall from shelves and pictures from walls. Heavy furniture moved, unstable furniture overturned. Small church or school bells ring. Trees and bushes shake, or are heard to rustle. Loose material may be dislodged from existing slips, talus slopes or shingle slides.

*See categories of non-wooden construction at end of appendix.

MM VII: General alarm. Difficulty experienced in standing. Noticed by drivers of motorcars. Trees and bushes strongly shaken. Large bells ring. Masonry D cracked and damaged. A few instances of damage to masonry C. Loose brickwork and tiles dislodged. Unbraced parapets and architectural ornaments may fall. Stone walls cracked. Weak chimneys broken, usually at the roof line. Domestic water tanks burst.

Concrete irrigation ditches damaged. Waves seen on ponds and lakes. Water made turbid by stirred up mud. Small slips and caving-in of sand and gravel banks.

MM VIII: Alarm may approach panic. Steering of motorcars affected. Masonry C damaged, with partial collapse. Masonry B damaged in some cases. Masonry A undamaged. Chimneys, factory stacks, monuments, towers, and elevated tanks twisted or brought down. Panel walls thrown out of frame structures. Some brick veneers damaged. Decayed wooden piles broken. Frame houses not secured to foundation may move.

Cracks appear on steep slopes and in wet ground. Landslides appear in road cuttings and unsupported excavations. Some tree branches may be broken off. Changes in the flow or temperature of springs and wells may occur. Small earthquake fountains.

MM IX: General panic. Masonry D destroyed. Masonry C heavily damaged, sometimes collapsing completely. Masonry B seriously damaged. Frame structures rocked and distorted. Damage to foundations general. Frame houses not secured to the foundations shifted off. Brick veneers fall and expose frame Cracking of the ground conspicuous. Minor damage to paths and roadways. Sand and mud ejected in alluviated areas, with the formation of earthquake fountains and sand craters. Underground pipes broken. Serious damage to reservoirs.

MM X: Most masonry structures destroyed, together with their foundations. Some well built wooden buildings and bridges seriously damaged.

Dams, dykes, and embankments seriously damaged. Railway lines slightly bent. Cement and asphalt roads and pavements badly cracked or thrown into waves. Large landslides on river banks and steep coasts. Sand and mud on beaches and flat land moved horizontally. Large and spectacular sand and mud fountains. Water from rivers, lakes and canals thrown up on the banks.

MM XI: Wooden frame structures destroyed. Great damage to railway lines. Great damage to underground pipes.

MM XII: Damage virtually total. Practically all works of construction destroyed or greatly damaged. Large rock masses displaced. Lines of sight and level distorted. Visible wave-motion of the ground surface reported. Objects thrown upwards into the air.

CATEGORIES OF NON-WOODEN CONSTRUCTION

Masonry A: Structures designed to resist lateral forces of about 9.1 g*, such as those satisfying the New Zealand Model Building By-law, 1955. Typical buildings of this kind are well reinforced by means of steel or ferro-concrete bands, or are wholly of ferro-concrete construction. All mortar is of good quality and the design and workmanship is good. Few buildings erected prior to 1955 can be regarded as in Category A.

*Lateral accelerations of about 89.2 m/s^2

Masonry B: Reinforced buildings of good workmanship and with sound mortar, but not designed in detail to resist lateral forces.

Masonry C: Buildings of ordinary workmanship, with mortar of average quality. No extreme weakness, such as inadequate bonding of the corners, but neither designed nor reinforced to resist lateral forces.

Masonry D: Buildings with low standards of workmanship, poor mortar, or constructed of weak materials like mud brick and rammed earth. Weak horizontally.

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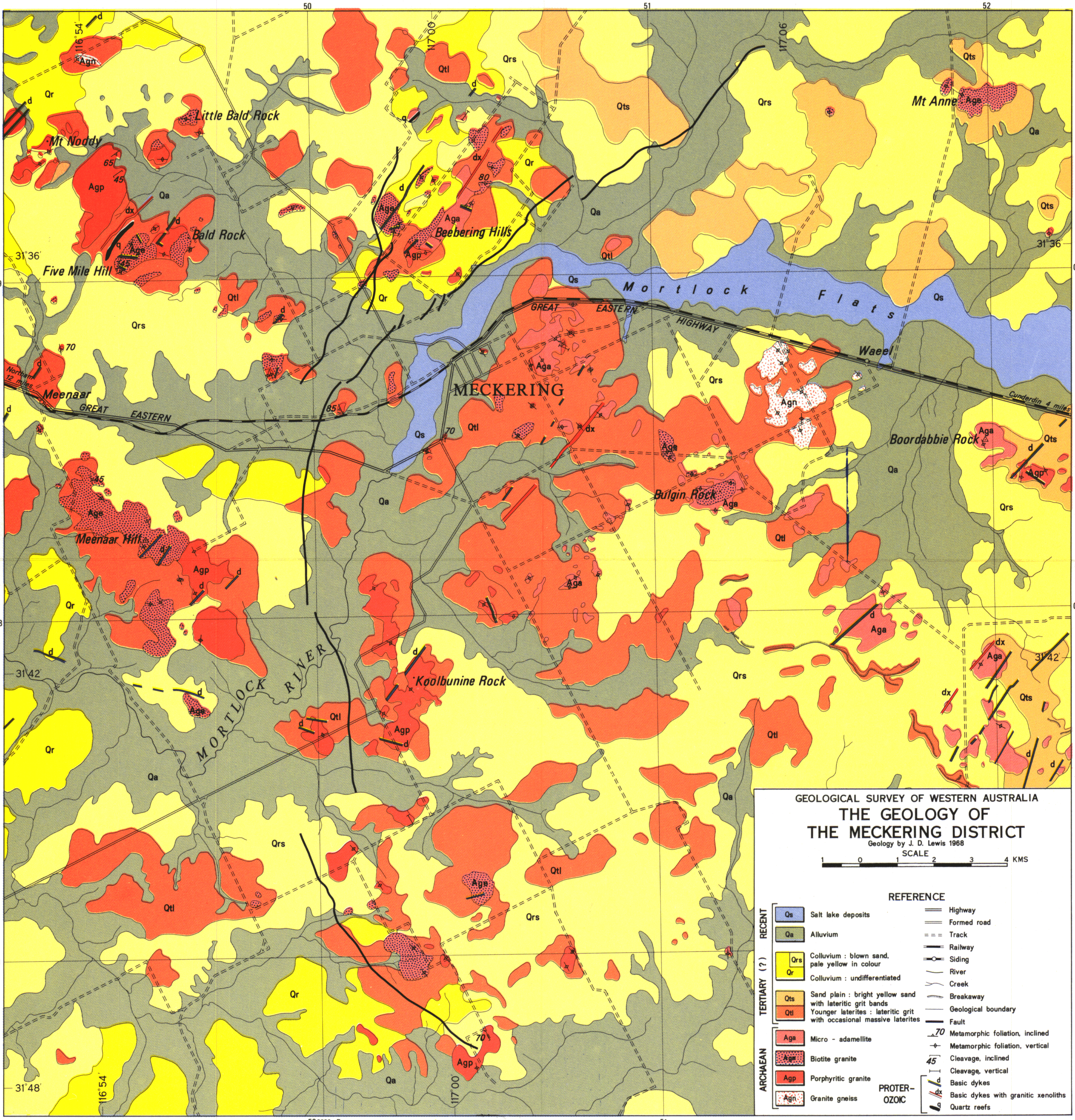
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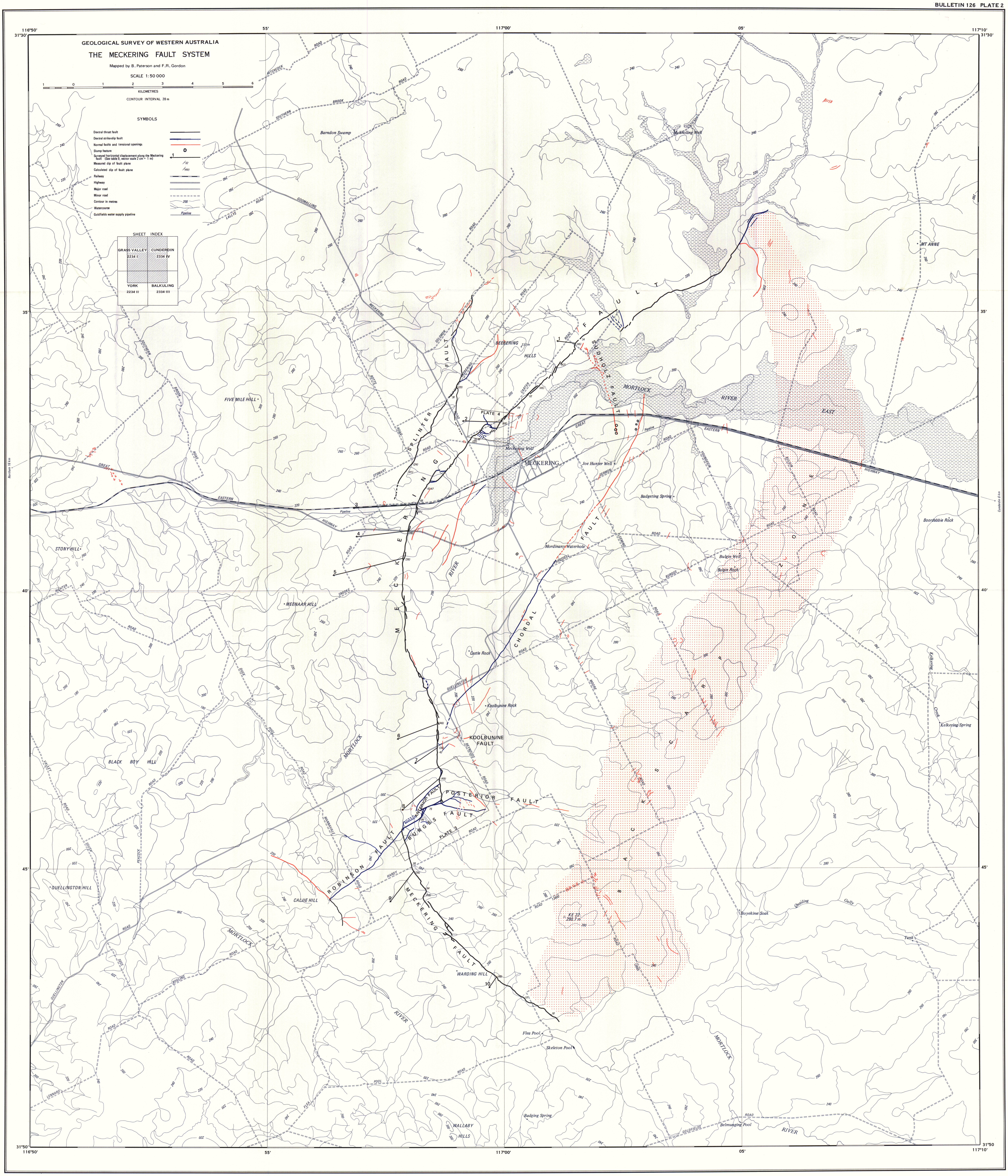
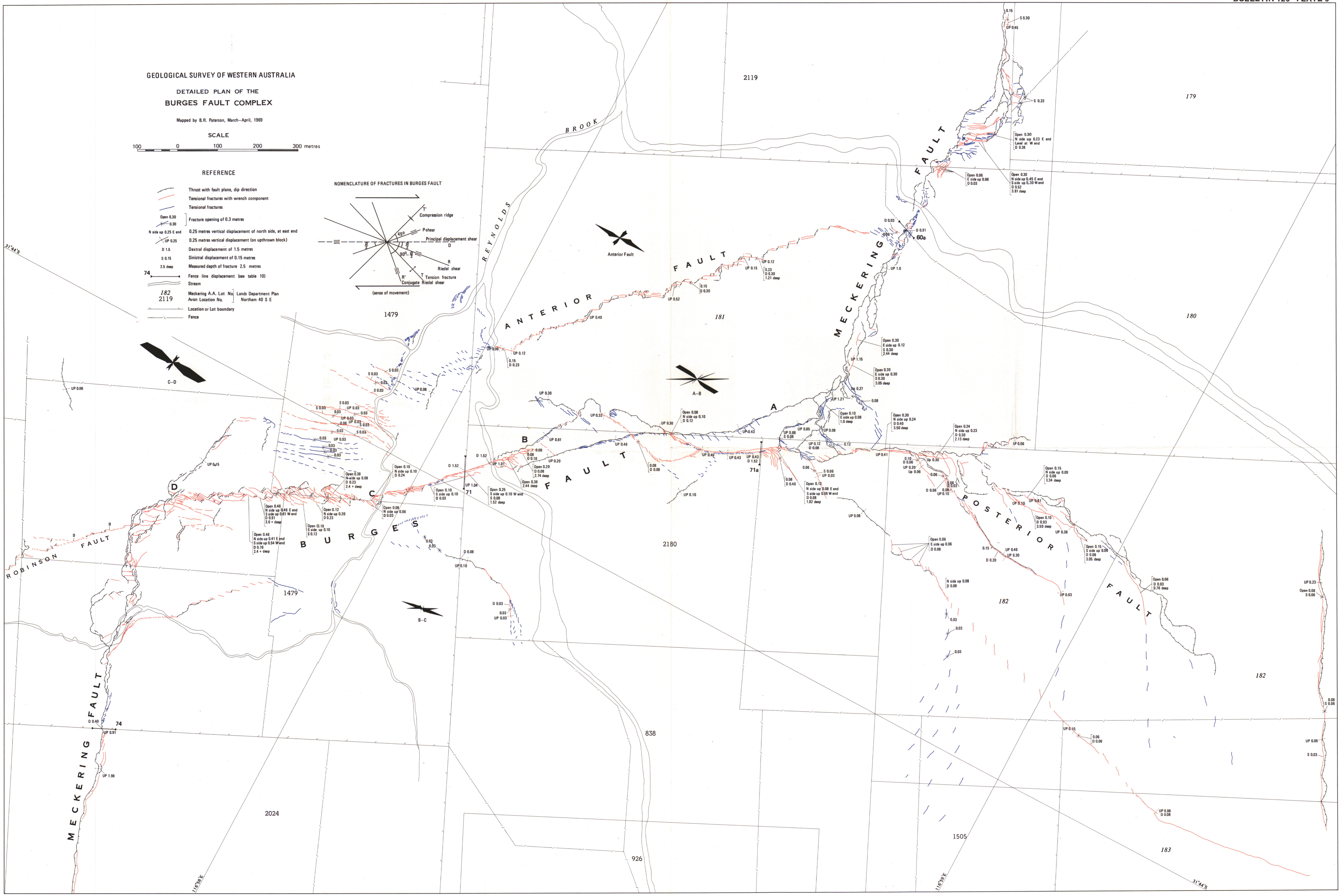
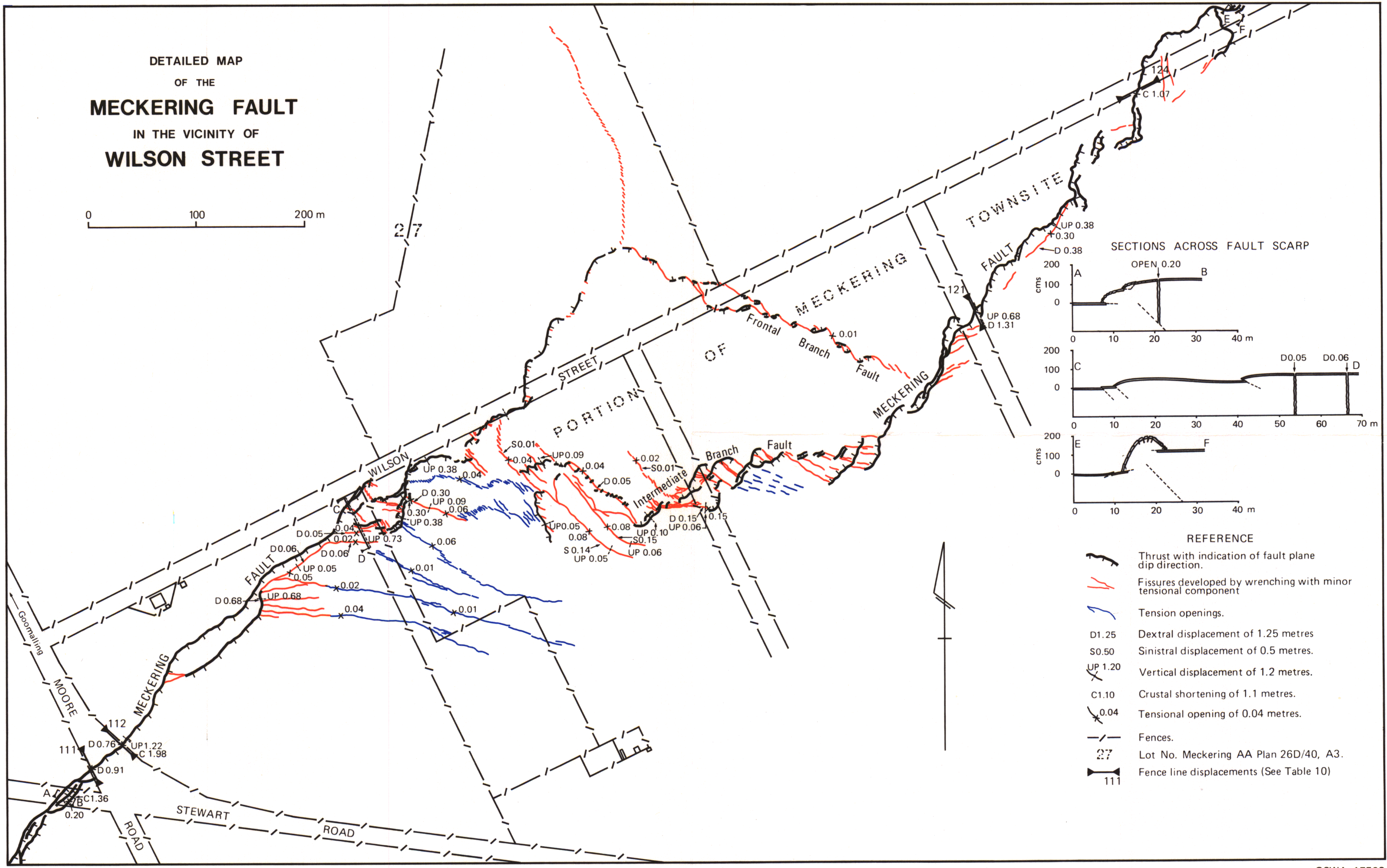
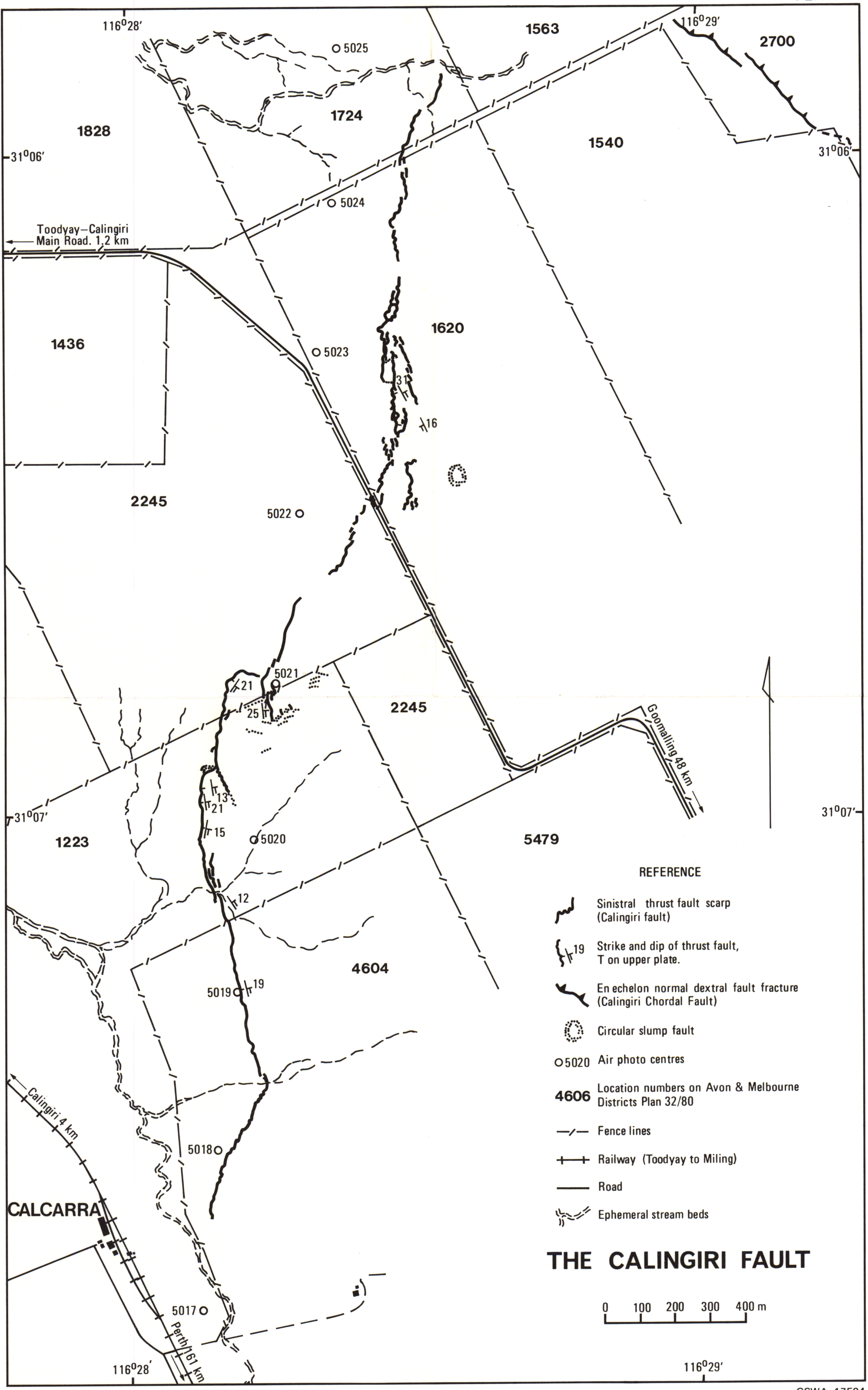
REFERENCE
RECENT
Qs Salt lake deposits
Qa Alluvium
TERTIARY (?)
Qrs Colluvium : blown sand, pale yellow in colour
Qr Colluvium : undifferentiated
Qts Sand plain : bright yellow sand with lateritic grit bands
Qtl Younger laterites : lateritic grit with occasional massive laterites
ARCHAEAN
Aga Micro - adamellite
Agb Biotite granite
Agp Porphyritic granite
Agn Granite gneiss
PROTER-OZOIC
Highway
Formed road
Track
Railway
Siding
River
Creek
Breakaway
Geological boundary
Fault
Metamorphic foliation, inclined
Metamorphic foliation, vertical
Cleavage, inclined
Cleavage, vertical
Basic dykes
Basic dykes with granitic xenoliths
Quartz reefs
MECKERING
Mortlock Flats
MORTLOCK RIVER
GREAT EASTERN HIGHWAY
Little Bald Rock
Mt Noddy
Bald Rock
Five Mile Hill
Beebering Hills
Mt Anne
Meenaar
Northam 12 miles
Waeel
Cunderdin 4 miles
Boordabbie Rock
Bulgin Rock
Meenaar Hill
Koolbunine Rock
116°54'
117°00'
117°06'
31°36'
31°42'
31°48'
50
51
52
09
08
1070000 yN
500000 yE



GEOLOGICAL SURVEY OF WESTERN AUSTRALIA
THE MECKERING FAULT SYSTEM
Mapped by B. Paterson and F.R. Gordon
SCALE 1:50 000
KILOMETRES
CONTOUR INTERVAL 20 m
SYMBOLS
Dextral thrust fault
Dextral strike-slip fault
Normal faults and tensional openings
Slump feature
Surveyed horizontal displacement along the Meckering fault (See table 9, vector scale 2 cm = 1 m)
Measured dip of fault plane
Calculated dip of fault plane
Railway
Highway
Major road
Minor road
Contour in metres
Watercourse
Goldfields water supply pipeline
Pipeline
SHEET INDEX
GRASS VALLEY 2234 I
CUNDERDIN 2334 IV
YORK 2234 II
BALKULING 2334 III
116°50'
55'
117°00'
05'
117°10'
31°30'
35'
40'
45'
31°50'
MECKERING FAULT
SPLINTER FAULT
SUDHOLZ FAULT
CHORDAL FAULT
KOOLBUNINE FAULT
POSTERIOR FAULT
BURGES FAULT
ROBINSON FAULT
ANTERIOR FAULT
ZONE OF BACKSCARP
PLATE 3
PLATE 4
MECKERING
MORTLOCK RIVER
MORTLOCK RIVER EAST
GREAT EASTERN HIGHWAY
Barndon Swamp
BEEBERING HILLS
FIVE MILE HILL
STONY HILL
MEENAAR HILL
BLACK BOY HILL
QUELLINGTON HILL
CALJIE HILL
WARDING HILL
WALLABY HILLS
MT ANNE
Meckering Well
Joe Hunter Well
Badgeting Spring
Mordinany Waterhole
Bulgin Well
Bulgin Rock
Boordabbie Rock
Castle Rock
Koolbunine Rock
Kelkering Spring
Boyekine Soak
Quailing Gully
Flea Pool
Skeleton Pool
Badging Spring
Belmunging Pool
KE 27 290.7 m

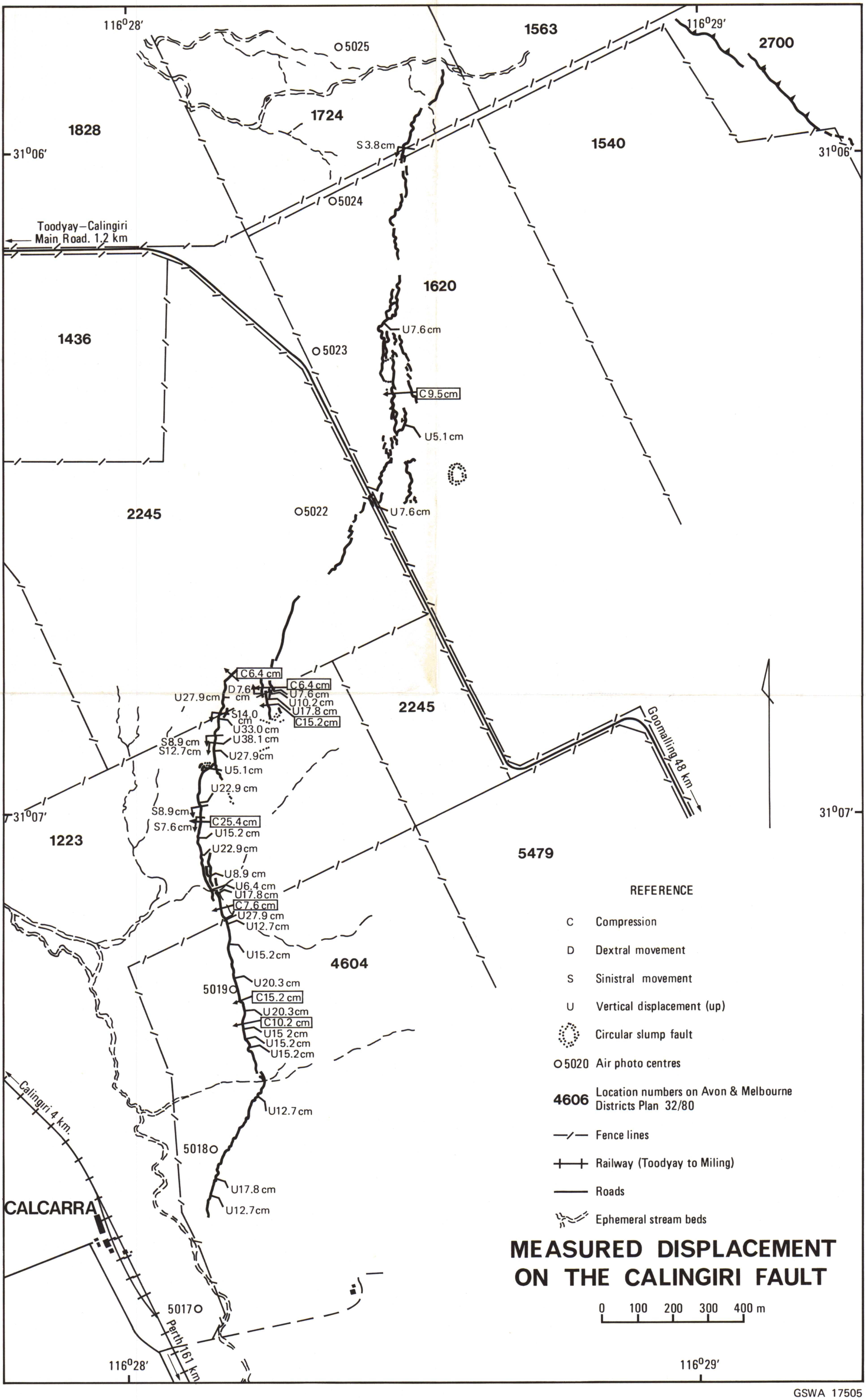

GEOLOGICAL SURVEY OF WESTERN AUSTRALIA
DETAILED PLAN OF THE
BURGES FAULT COMPLEX
Mapped by B.R. Paterson, March–April, 1969
SCALE
100 0 100 200 300 metres
REFERENCE
Thrust with fault plane, dip direction
Tensional fractures with wrench component
Tensional fractures
Open 0.30 / 0.30 — Fracture opening of 0.3 metres
N side up 0.25 E end — 0.25 metres vertical displacement of north side, at east end
UP 0.25 — 0.25 metres vertical displacement (on upthrown block)
D 1.5 — Dextral displacement of 1.5 metres
S 0.15 — Sinistral displacement of 0.15 metres
2.5 deep — Measured depth of fracture 2.5 metres
74 — Fence line displacement (see table 10)
Stream
182 — Meckering A.A. Lot No. — Lands Department Plan
2119 — Avon Location No. — Northam 40 S E
Location or Lot boundary
Fence
NOMENCLATURE OF FRACTURES IN BURGES FAULT
T' Compression ridge
P-shear
45°
Principal displacement shear
D
90° − Ø/2
R Riedel shear
T Tension fracture
R' Conjugate Riedel shear
(sense of movement)
ANTERIOR FAULT
MECKERING FAULT
BURGES FAULT
POSTERIOR FAULT
ROBINSON FAULT
REYNOLDS
BROOK
Anterior Fault
A–B
B–C
C–D
A
B
C
D
60a
71
71a
74
2119
179
180
181
182
183
1479
2180
2024
838
926
1505
31°44'S
116°58'E
116°59'E


DETAILED MAP
OF THE
MECKERING FAULT
IN THE VICINITY OF
WILSON STREET
0
100
200 m
27
WILSON STREET
MECKERING TOWNSITE
PORTION OF MECKERING
Frontal Branch Fault
Intermediate Branch Fault
MECKERING FAULT
MECKERING FAULT
Goomalling
MOORE ROAD
STEWART ROAD
SECTIONS ACROSS FAULT SCARP
cms
OPEN 0.20
D0.05
D0.06
REFERENCE
Thrust with indication of fault plane dip direction.
Fissures developed by wrenching with minor tensional component
Tension openings.
D1.25 Dextral displacement of 1.25 metres
S0.50 Sinistral displacement of 0.5 metres.
UP 1.20 Vertical displacement of 1.2 metres.
C1.10 Crustal shortening of 1.1 metres.
0.04 Tensional opening of 0.04 metres.
Fences.
27 Lot No. Meckering AA Plan 26D/40, A3.
111 Fence line displacements (See Table 10)



THE CALINGIRI FAULT

GSWA 17504



MEASURED DISPLACEMENT ON THE CALINGIRI FAULT

GSWA 17505