GEOLOGICAL SURVEY
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WESTERN AUSTRALIA

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# FOREWORD

While minor earth tremors have been noted frequently in the southwest of Western Australia since European settlement, there have been since 1968 three earthquakes which have caused major loss of property, although, fortunately no loss of life. This report is concerned with the latest of these, the Cadoux Earthquake of 2 June 1979, which had a magnitude of 6.2 and caused damage to property of at least $3.7 million. The Meckering and Calingiri Earthquakes of 1968 and 1971 have been described in Bulletin 126 of the Geological Survey.

The extensive surface faulting and property damage which accompanied the Cadoux Earthquake are recorded and described in this report, together with an account of ground distortion which preceded the event, and the seismic history and regional setting of the affected area. The data used have been gathered as a result of a co-operative effort by State and Commonwealth bodies, a co-operation which will continue in order to assess the seismic risk of the most populous portion of the State

The popular concept of the relative stability of our ancient crustal rocks has been upset by the recurring events of the past decade, and it now appears that damaging earthquakes are a more prevalent phenomenon in Western Australia than was once thought. This report will be of value to researchers in this field, as well as to all concerned with or affected by the design and construction of domestic, public, and industrial buildings in southwestern Australia.

A F Trendall
Director
Geological Survey

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ABSTRACT

The Cadoux Earthquake occurred at 1748 hours local time on 2 June 1979, and registered a local magnitude ($M_L$) of 6.2 on the Richter scale. Considerable damage was caused in the Cadoux area and seismic shaking was felt over a large part of the southwest of Western Australia.

The geology of the area is dominated by a veneer of Quaternary deposits overlying Archaean granitic bedrock, with dykes of quartz and dolerite. The overall structure is obscure. Physiographically the area forms the watershed between east- and west-flowing drainage systems.

Cadoux lies within the South West Seismic Zone, and the area experienced numerous tremors and minor earthquakes prior to the event of 2 June 1979. The seismological details of the earthquake are:

| | | |
|---|---|---|
| Origin time | : | 2 June 1979, at 09 h 48 min 01.1 s Universal Time (U.T.) |
| Magnitude | : | $M_L$ 6.2, $M_S$ 6.4, $m_b$ 6.3 |
| Epicentre | : | Lat. 30°49'48"S, Long.117°09'00"E |
| Depth | : | 15 km. |

A complex pattern of surface faulting developed around Cadoux, and detailed mapping revealed that about 28 km of surface fault traces were present in a zone some 3 km wide stretching over 15 km in a north-south direction. To the south and east of Cadoux faulting took place on a major westward-dipping right-lateral thrust fault about 10 km long and trending north-northeast. Maximum surface displacements of 1.4 m (throw), 0.68 m (heave) and 0.65 m (lateral displacement) were measured near the central portion of this fault. To the north of Cadoux faulting occurred on a conjugate set of reverse strike-slip faults with both right- and left-lateral displacements, trending both northwest and northeast.

Levelling traverses on water-supply pipelines showed that a large tract of country to the east and south of Cadoux had been uplifted by up to 0.36 m. Cadastral surveys on east-west fence-lines showed that in the vicinity of the faults there had been a southward strain prior to the earthquake. The regional deformation was probably caused by east-west compression and the faulting took place on the western margin of the deformed area.

Earthquake damage to the value of at least $3.8 million was reported, nearly half of this within about 15 km of Cadoux township. Most damage was sustained by domestic dwellings, where markedly different responses to the seismic shaking were apparent amongst buildings of differing construction. Serious damage was also caused to the road, railway, electricity, water-supply and telephone networks in the area. Outside the epicentral region only minor damage resulted, mainly the cracking of walls and plaster.

Hydrographs from a number of bores in the southwest of the State were examined to determine if any precursory traits could be recognized. The results were negative, only a few bores recording the earthquake as a 'spike' on the hydrograph.

A comparison of the Cadoux Fault System and earlier faulting at Meckering (1968) and Calingiri (1970) shows a number of similarities and differences. Each fault system is confined to a shallow block and is believed to be a reflection of displacements on unseen deep underlying faults. The surface faulting is predominantly thrusting and results from

compressive stresses throughout the South West Seismic Zone. At Cadoux and Calingiri the surface fault patterns are very similar, but the Meckering Fault is a large arcuate structure. Seismic activity suggests that the South West Seismic Zone is made up of a number of relatively small fault-bounded blocks.

# THE CADOUX EARTHQUAKE, 2 JUNE 1979

## INTRODUCTION

### GENERAL

The Cadoux Earthquake occurred at 0948 hours Universal Time (5.48 p.m. local time) on Saturday, 2 June 1979 and registered a local magnitude ($M_L$) of 6.2 on the Richter scale. The epicentre was at latitude 30°49'48"S, longitude 117°09'00"E, and the depth of focus was 15 km (Gregson and Paull, 1979).

A complex pattern of surface faults developed around Cadoux, a small town in the central wheatbelt some 220 km by road from Perth (Fig.1), and the shaking damaged or destroyed buildings and other structures over a large area. Roads, railways, pipelines and power lines were damaged directly by fault movements.

Field investigations were carried out by the Geological Survey of Western Australia over a period of six weeks following the earthquake. The main objective was to determine the full extent of surface faulting and to assess earthquake-related damage in the Cadoux area before such features were obscured or degraded by agricultural processes, natural weathering and repair. A detailed geological map of the area was also prepared, in order to assess any possible correlation between local geology and seismicity (Plate 1).

The fault-line mapping was carried out by J.A. Bunting and N.A. Daetwyler assisted by J.D. Lewis. Bunting was also responsible for the geological mapping of the area, and Daetwyler, with the assistance of R.P. Mather, for the damage reporting. The seismic history and ground distortion of the area were studied by J.D. Lewis, and J.S. Moncrieff reviewed the literature and carried out local studies on earthquake-related groundwater-level fluctuations. Parts of the text were drafted by each of the authors, Lewis being responsible for collating and finalizing the contributions.

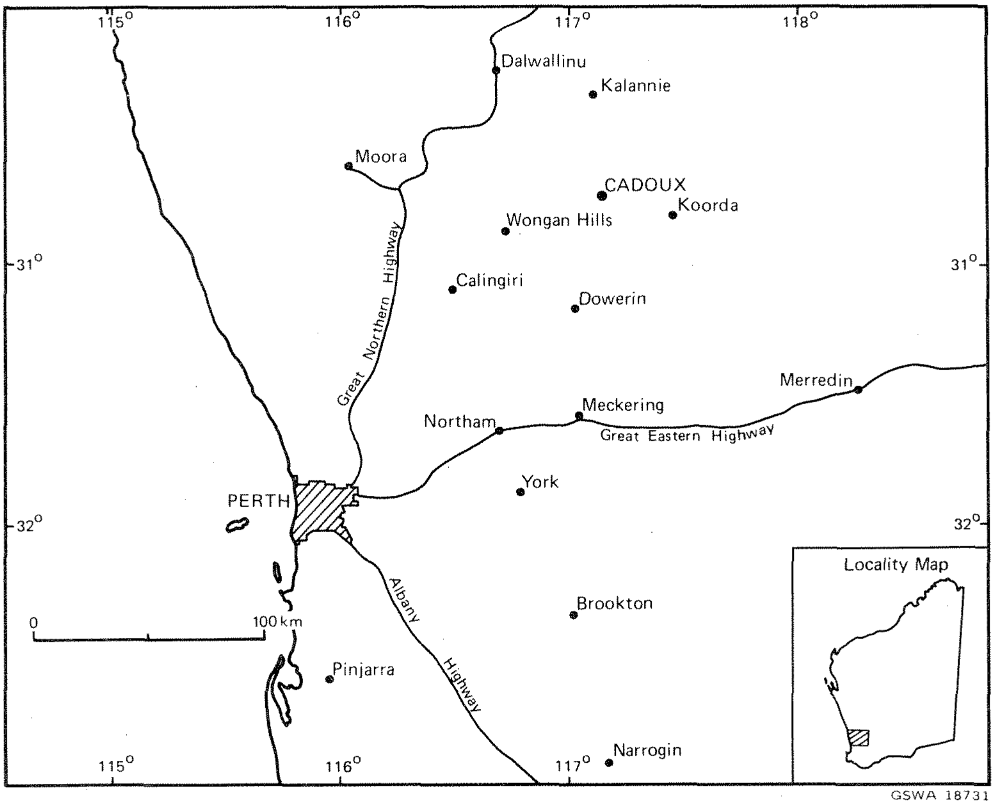


Figure 1. Location map

Mapping of the fault zone was carried out on low-level aerial photography produced by the Western Australian Department of Lands and Surveys. That department, together with the Western Australian division of the Australian Survey Office (Survey and Drafting Section, Commonwealth Department of Administrative Services), also resurveyed several property boundaries affected by the faulting, drew profiles of the fault scarp at selected points, and established two stations to monitor possible future movements of the faults.

This report describes the surface faults produced by the earthquake, and the resulting damage. Physiographic and geological features are briefly described, in order to assess any possible relationships with seismic activity. For a general discussion of earthquake activity in Western Australia, the reader is referred to the Bulletin on the

Meckering and Calingiri Earthquakes (Gordon and Lewis, 1980).

ACKNOWLEDGEMENTS

The Geological Survey of Western Australia would like to acknowledge the assistance of the residents of the Cadoux area, and the co-operation of officers of the Department of Lands and Surveys, the Australian Survey Office, and the Mundaring Geophysical Observatory. The permission of the Director of the Bureau of Mineral Resources to publish seismic data is also acknowledged.

## REGIONAL GEOLOGY

The Cadoux Earthquake occurred near the northern end of the South West Seismic Zone, a well-known active seismic zone extending from Moora and Dalwallinu in the north to Katanning and Albany in the south. A consideration of the geology of this area will provide a basis for comparison between the major earthquakes that have occurred in southwest Australia.

### GEOLOGY OF SOUTHWEST AUSTRALIA

Most of the southwest of Western Australia is underlain by granitoid rocks of the Archaean Yilgarn Block. This is terminated to the west by the Darling Fault, and the coastal areas on the downthrown side of this fault are occupied by a thick sequence of Proterozoic to Tertiary sediments forming the Perth Basin. Although the Darling Fault, which has a downthrow to the west of up to 15 km and is over 1 000 km long, is one of the major tectonic features of the earth's crust, it has been inactive in historic times and seismic activity has been confined to the Archaean block (Playford and others, 1976).

The Southwestern Province of the Yilgarn Block (Williams, 1975) is a roughly triangular area from Carnamah in the north to Ravensthorpe and Bridgetown in the south. A broad belt of schist, gneiss and migmatite traverses the province from Dalwallinu to Katanning and it is within this zone that most earthquake epicentres are located. To the west a group of granite plutons form the Darling Plateau and the western edge of the Archaean Block, while to the east is a mixed granite and gneiss terrain with scattered enclaves of granulites. The Cadoux area is located on the eastern edge of the belt of schists and gneisses.

To the south of the Yilgarn Block is the east-west striking Albany-Fraser Province, a belt of Proterozoic sediments, granitic plutons, and Archaean gneisses.

## GEOLOGY OF THE CADOUX AREA

### *Physiography and superficial deposits*

The area has very low relief, elevations ranging from 300 m to 420 m. A major drainage divide (Fig. 2) separates the west-flowing Mortlock River system to the west, and an east-draining playa-lake system to the east.

Cainozoic laterite (a hard, buff to brown ferruginous duricrust) occurs on higher ground marking the old plateau surface. Some is exposed as small cliffs and hills a few metres high, but most of the laterite surface is covered by residual sandplain. This sand consists of yellow silty or clayey sand containing lateritic pebbles. Laterite and residual sand are each between 5 and 20 m thick.

Recent transported soil (colluvium) forms a blanket deposit up to 30 m thick which covers both the residual sandplain and bedrock areas from which the laterite cover has been removed.

The colluvium passes downslope into brown, sandy clay deposits forming broad alluvial flats. Along the eastern margin of the area (Plate 1) the alluvial flats terminate in a major saline drainage containing small, bare salt lakes and associated gypsum and quartz sand dunes.

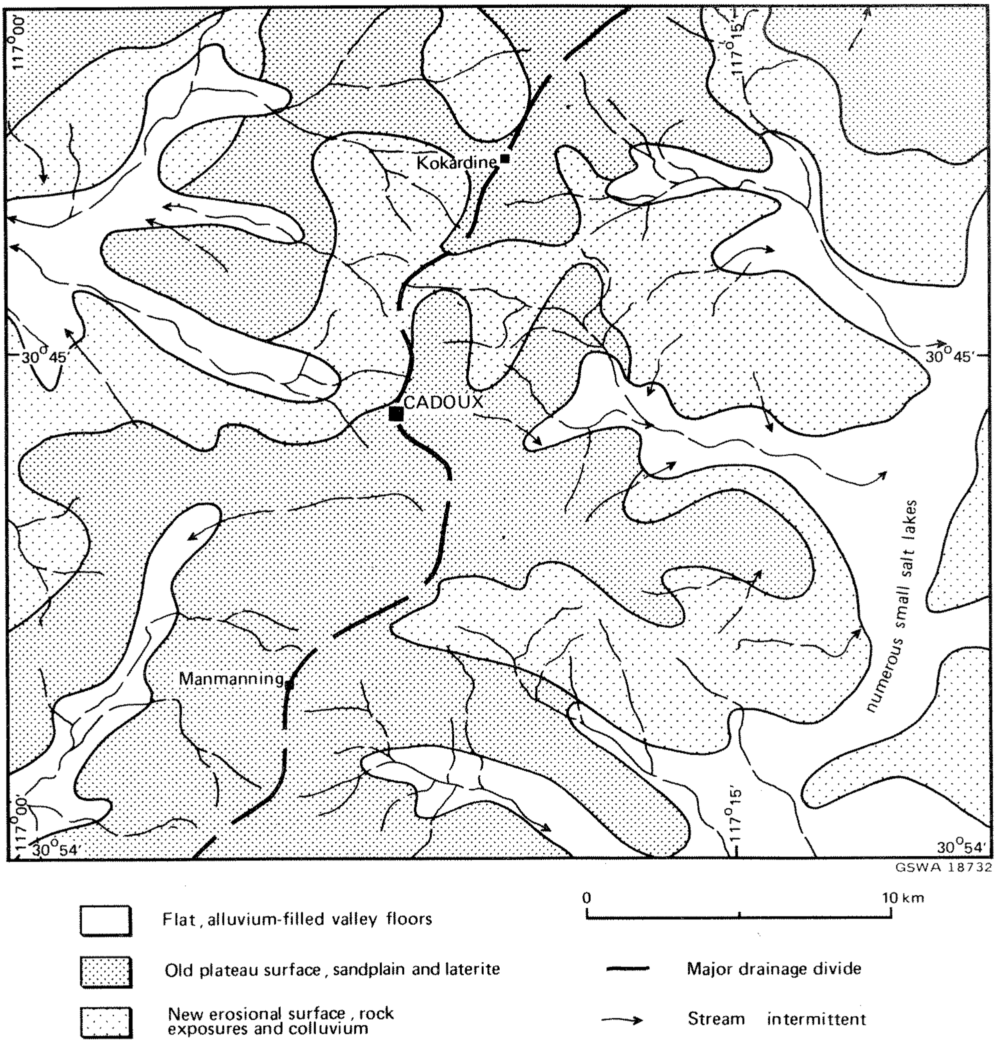


Figure 2. Major physiographic and drainage features of the Cadoux area

*Archaean granite*

Most of the Archaean granite is represented by various textural types of adamellite containing approximately equal amounts of plagioclase and microcline, and up to 5 per cent biotite.

Pegmatite segregations, which can form up to 60 per cent of the total rock, consist mainly of quartz and alkali feldspar, with minor muscovite and garnet. Compositional layering is a common feature. Pegmatite-bearing granite forms a distinctive belt trending southwest from Kokardine. The northern half of the fault system resulting from the Cadoux Earthquake occurs in this belt.

Near the western side of the area of Plate 1, the adamellite contains rafts and xenoliths of gneiss and amphibolite.

*Dolerite dykes and quartz dykes*

Dolerite dykes of presumed Proterozoic age occur in two sets, one trending west, the other northwest. The dykes range in width from a few metres to over 50 m. A distinctive dyke containing granite xenoliths passes just north of Cadoux and can be traced intermittently for nearly 20 km.

A set of quartz dykes trends $080^{\circ}$, slightly oblique to the west-trending dolerite dykes. In addition, a north-northwest-trending quartz dyke passes under the Kokardine water tank. Most quartz dykes probably represent infillings of tensional fractures rather than faults, although the dyke which passes under the Kokardine water tank appears to follow a right-lateral shear fault. It is likely that this fault is of Precambrian age.

*Structure*

In some outcrops the granite shows a weak foliation manifest as either alignment of phenocrysts or compositional layering in pegmatite. In general, this foliation trends northwest to north-northwest; however, in the broad zone corresponding to the pegmatite rocks, which extends southwest from Kokardine, the foliation trend swings from northeast near Kokardine to north-northeast near Cadoux.

Most of the granite outcrops display the widely spaced joints that are typical of granite throughout the Yilgarn Block. One area with unusually abundant joints is the area of pegmatitic granite immediately west of the Kokardine water tank. Two sets are present, both subvertical, and with trends of 040-070° (average 060°) and 300-340° (average 315°). Some of these joints were dilated as much as 2 mm as a result of the earthquake. At one locality immediately south of the Tank Fault, 550 m west of the tank, a group of closely spaced pre-existing joints trending 070° are connected by earthquake-generated oblique tension openings indicative of right-lateral movement. This is the same sense of movement as on the adjacent Tank Fault.

## SEISMIC HISTORY OF THE CADOUX AREA

Since the Cadoux area was settled in the period following the First World War residents have felt the periodic shaking of local tremors, and of larger tremors in other parts of the South West Seismic Zone. However, examination of newspaper reports and the records of the Perth Observatory from 1923-1960 (Everingham, 1968a; Everingham and Tilbury, 1971) reveals no earthquake reports from the immediate vicinity of Cadoux. Seismic activity was recorded, however, in areas to the south and west of Cadoux, particularly near Yerecoin, Calingiri and Goomalling, and many of these events would have been felt in the town, although they apparently caused no damage. The absence of reports does not prove that the Cadoux area was aseismic during this period. The small population, and the lack of an established town could lead to isolated reports being overlooked.

With the installation of the Benioff Seismographs at the Mundaring Geophysical Observatory in 1959 (McGregor, 1966) and subsequent improvements of the equipment, it has become possible to locate all but the smallest seismic events throughout the southwest of the State. Detailed records for the period 1959-1965 have been published by Everingham (1968a), and for subsequent years have appeared regularly in the Annual Report of the Mundaring Geophysical Observatory (Everingham, 1968b; Everingham and Gregson, 1969, 1971a, 1971b; Gregson, 1971, 1972, 1977, 1980; Gregson and Smith, 1973, 1974, 1975, 1976). These reports have been abstracted to produce Figure 3 and Table 1 and are reproduced in full in Appendix No. 1.

TABLE 1. EARTHQUAKES IN THE CADOUX AREA, 1959-1978

| | $M_L$ | | | | |
|---|---|---|---|---|---|
| *Year* | *2.0-3.0* | *3.0-4.0* | *4.0-5.0* | *>5.0* | *Total* |
| 1959-65 | - | - | - | - | 0 |
| 1966 | - | 1 | - | - | 1 |
| 1967 | - | - | - | - | 0 |
| 1968 | 11 | 10 | 2 | - | 23 |
| 1969 | 13 | 3 | 1 | - | 17 |
| 1970 | - | - | - | - | 0 |
| 1971 | - | - | - | - | 0 |
| 1972 | 12 | 3 | - | - | 15 |
| 1973 | 8 | - | - | - | 8 |
| 1974 | 5 | 3 | 1 | - | 9 |
| 1975 | 5 | 2 | - | - | 7 |
| 1976 | 2 | - | - | - | 2 |
| 1977 | 3 | - | - | - | 3 |
| 1978 | - | 1 | - | - | 1 |

(Abstracted from: Mundaring Geophysical Observatory Annual Reports, 1959-1978

The apparently aseismic nature of the Cadoux area prior to 1959 is confirmed by the reports of the Observatory in that only one event, that of 3 October 1966 ($M_L$ 3.6), was located within 25 km of the town between 1959 and 1968. Since 1968, however, seismic activity has been episodic and at times quite intense.

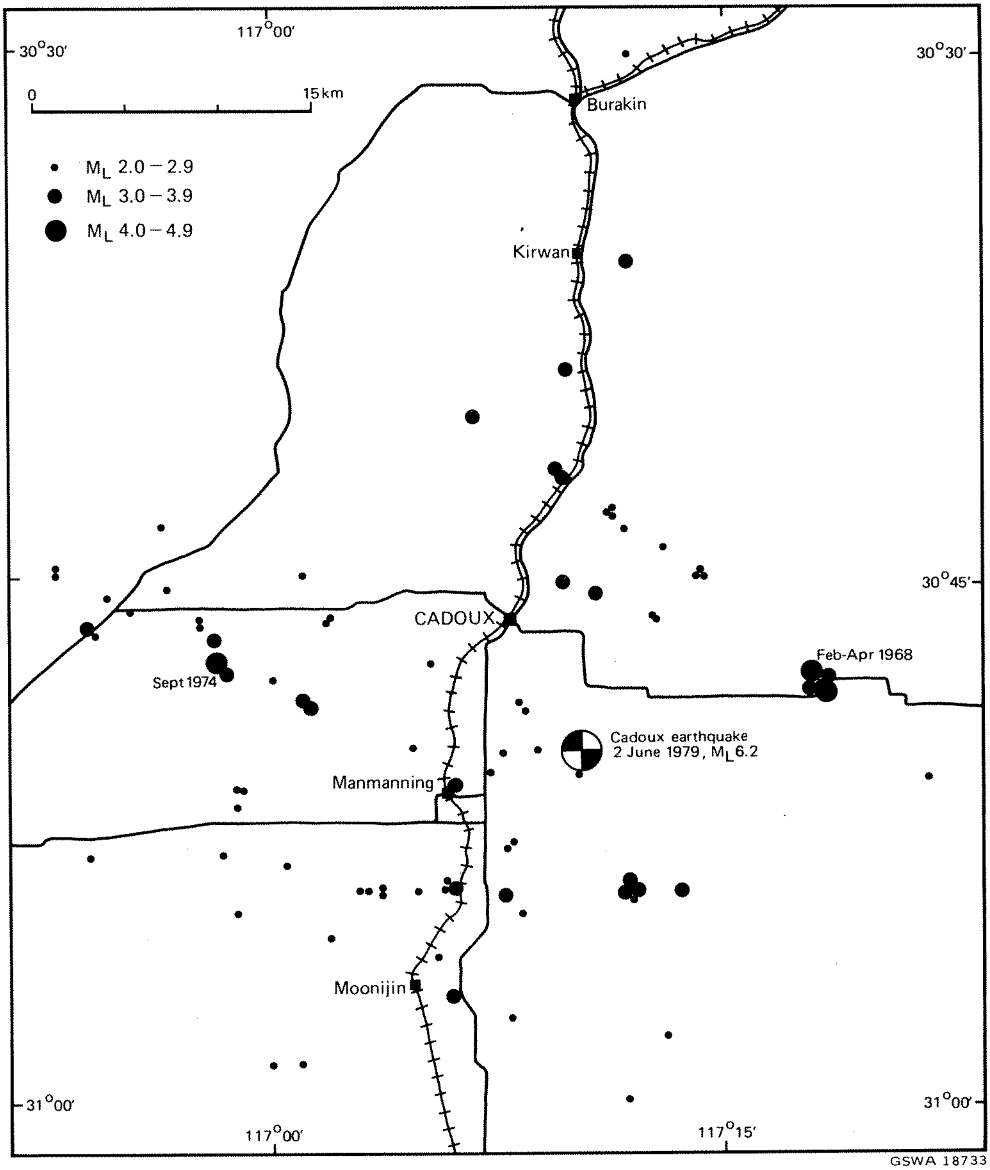


Figure 3. Earthquake epicentres ($M_L$ >2.0) in the Cadoux area, 1959-1978



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In February 1968 a tremor of $M_L$ 4.0 shook the town and this was followed, between 25 March and 18 April, by 20 further tremors, culminating, on 8 April, in a shock of $M_L$ 4.4 which caused minor damage. These events, however, were eclipsed by the major earthquake at Meckering in October 1968. Further series of tremors occurred in 1969, 1972 and 1974, but in the intervening years there were only a few small tremors, or none at all.

Since 1968, therefore, Cadoux had been established as an active seismic area, but at a level no greater than that experienced at many other centres within the South West Seismic Zone.

## THE CADOUX EARTHQUAKE OF 2 JUNE 1979

### FORESHOCKS

In 1978 only one tremor was recorded in the Cadoux area, on 28 October, with a magnitude of $M_L$ 3.6. However, between 13 and 15 March 1979, there were four tremors with magnitudes decreasing from $M_L$ 3.9 to $M_L$ 3.1, the first three of which were distinctly felt in the town. In April and May of 1979 there were three further small tremors (Table 2) and at 5.54 a.m. on 2 June a large tremor of $M_L$ 5.2 was felt in Cadoux with an intensity of MMVI on the Modified Mercalli Scale (see Gordon and Lewis, 1980, p.218 for details). A further five tremors of $M_L$ 3.0-3.8 were recorded in the next six hours. In retrospect, not only the tremors of the morning of 2 June but the whole of the increased seismic activity of early 1979, after an inactive period between 1975 and 1978, can be seen as foreshocks to the major earthquake that followed. The epicentres of the foreshocks are plotted on Figure 5, and it will be noted that they are southeast of Cadoux, in the vicinity of the postulated main fault.

## THE PRINCIPAL EARTHQUAKE

The major shock of the Cadoux earthquake series occurred almost precisely twelve hours after the large foreshock of 2 June. The seismological details (Gregson and Paull, 1979) are as follows:

Origin time: 2 June 1979, at 09 h 48 min 01.1s U.T.
Magnitude : $M_L$ 6.2, $M_s$ 6.4, $m_b$ 6.3
Epicentre : Lat. 30°49'48"S, Long. 117°09'00"E
Depth : 15 km.

The position accuracy is approximately $\pm$5 km in depth, and $\pm$2 km laterally. The earthquake was felt over most of southwestern Australia and was recorded worldwide by at least 120 seismological stations. The earthquake was among the largest recorded in Australia, and, after the Meckering Earthquake of $M_L$ 6.9, the second largest in the South West Seismic Zone.

A preliminary isoseismal map of the earthquake, prepared by Gregson and Paull (1979), is presented as Figure 4. The lower limit for major structural damage is the MMVI isoseismal and this encloses a roughly circular area, 65 km in diameter, around the epicentre. The isoseismal at MMIV, the intensity at which almost everyone recognizes seismic shaking, was approximately 775 km in diameter and encloses most of the principal population centres in the south of the State. At Cadoux itself the destructive effects of the earthquake indicate that an intensity of MMIX was reached. A number of intensity ratings in the epicentral region are plotted on Figure 33 and suggest that the higher isoseismals were elliptical and elongated parallel to the fault zone. The highest intensities, MMVIII-IX, were associated with the group of conjugate faults north of Cadoux and the MMVII isoseismal extends nowhere more than a few kilometres from the fault zone.

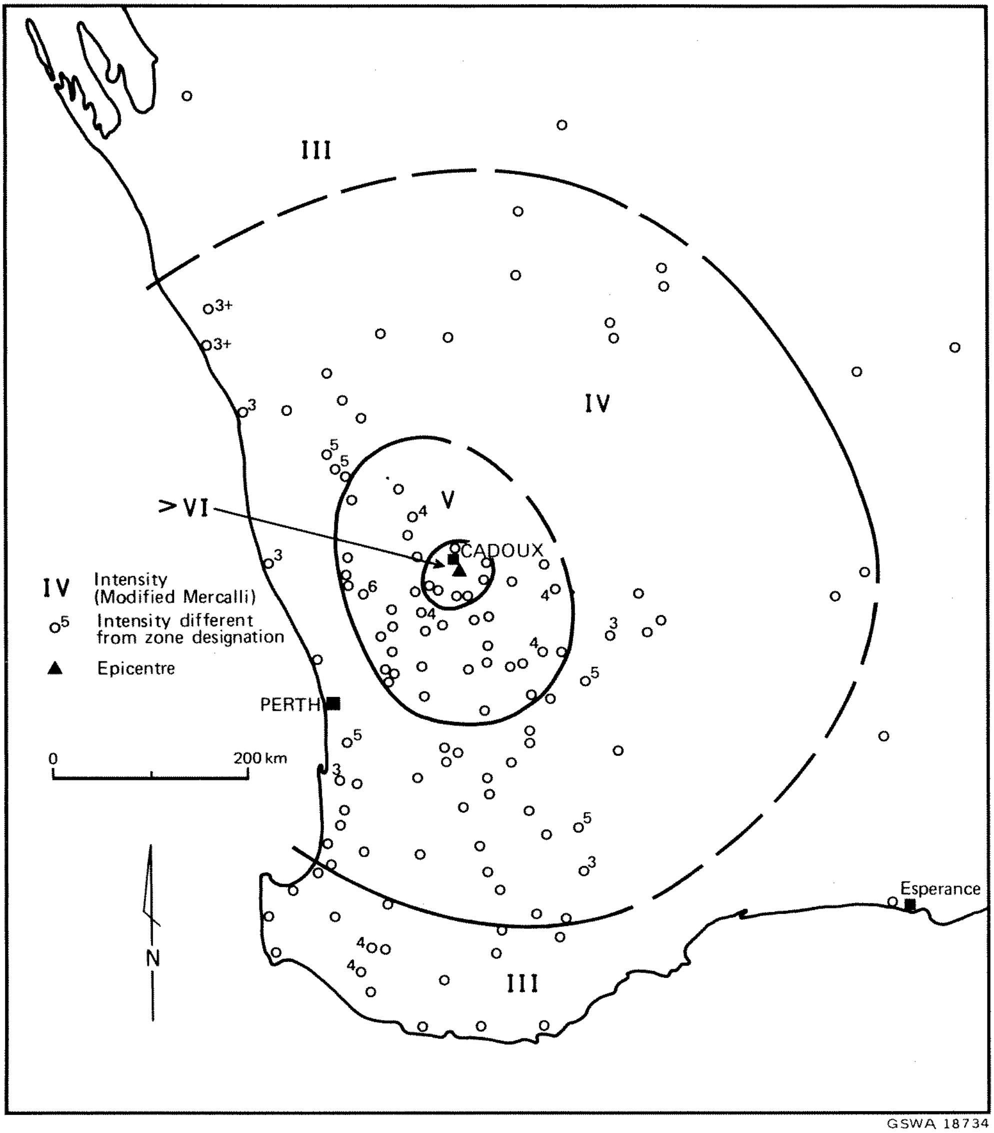



Figure 4. Isoseismal map of the Cadoux Earthquake, 2 June 1979 (after Gregson and Paull, 1979)

## AFTERSHOCKS

In the month following the main earthquake of 2 June there were many aftershocks, two of which, on 3 June and 7 June, registered magnitudes greater than 5 and were widely felt throughout the southwest of the State. Most of the aftershocks were of small magnitude, but 42 aftershocks were of $M_L$ greater than 3.0. There was only one tremor larger than $M_L$ 3.0 in July but between August and December there were a further 13 large tremors, including one of $M_L$ 4.8 on 11 October. In the first six months of 1980 there were a further 3 tremors in the Cadoux area of $M_L$ >3.0. In addition to the larger tremors, the Mundaring Geophysical Observatory has recorded 146 minor tremors of $M_L$ <2.9 in the district during 1979 (Gregson, 1980).

Seismic activity in the Cadoux area for the period 1979 to June 1980 is summarized in Table 2 and fully tabulated in Appendix I. The larger shocks with determined epicentres are plotted on Figure 5.

From Figure 5 it will be seen that the aftershock epicentres all plot in a zone about 5 km wide and 5 km east of the faulted area, not in a narrow zone to the west of the fault as would be expected from the pattern of surface faulting. This discrepancy is in part caused by the complexity of subsurface faulting (Fig. 6), but is mainly the effect of inaccuracies in the instrumental method for determining epicentres. Greater accuracy is not possible without more detailed knowledge of the velocity of earthquake shock waves within the earth's crust.

## MECHANISM OF THE EARTHQUAKE

Earthquakes are caused by movements on faults, movements which need not be reflected accurately by observed surface faulting, or result in surface faulting at all. The nature of the fault upon which the initial rupture occurred can be determined from seismograph records and this work has been carried out for the Cadoux Earthquake by Everingham and Smith (in prep.). Two fault-plane solutions are possible,

TABLE 2. SUMMARY OF EARTHQUAKES IN THE CADOUX AREA, MARCH 1979 TO JUNE 1980

| *Date* | $M_L$ *2.0-2.9* | *3.0-3.9* | *4.0-4.9* | *>5.0* | *Total* |
|---|---|---|---|---|---|
| *1979* | | | | | |
| Mar | 5 | 4 | - | - | 9 |
| Apr | 1 | 1 | - | - | 2 |
| May | - | 1 | - | - | 1 |
| Jun | 103 | 42 | 3 | 4 | 152 |
| Jul | 12 | 1 | - | - | 13 |
| Aug | 15 | 3 | - | - | 18 |
| Sept | 5 | 2 | - | - | 7 |
| Oct | 5 | - | 1 | - | 6 |
| Nov | 7 | - | - | - | 7 |
| Dec | 11 | 5 | - | - | 16 |
| *1980* | | | | | |
| Jan | 7 | - | - | - | 7 |
| Feb | 3 | 1 | - | - | 4 |
| Mar | 1 | - | - | - | 1 |
| Apr | - | 1 | - | - | 1 |
| May | 8 | - | - | - | 8 |
| Jun | 5 | 1 | - | - | 6 |

(Abstracted from Gregson (1980) and unpublished data of the Mundaring Geophysical Observatory)

one trending 018° and dipping 81°E and the other trending 117° and dipping 64°S. As the observed faulting trends approximately north-south the first solution is the most probable, and displacement on this plane was determined to be principally right-lateral strike-slip with a small reverse component. The difficulty with this solution is that the observed faulting dips to the west and shows roughly equal reverse and right-lateral strike-slip displacements.

Further information on subsurface faulting can be obtained by plotting the depths of foci of the aftershocks. This has been done for an east-west section across the Cadoux area (Fig. 6) and, although the number of aftershocks with known depths is not great, it appears to show a major

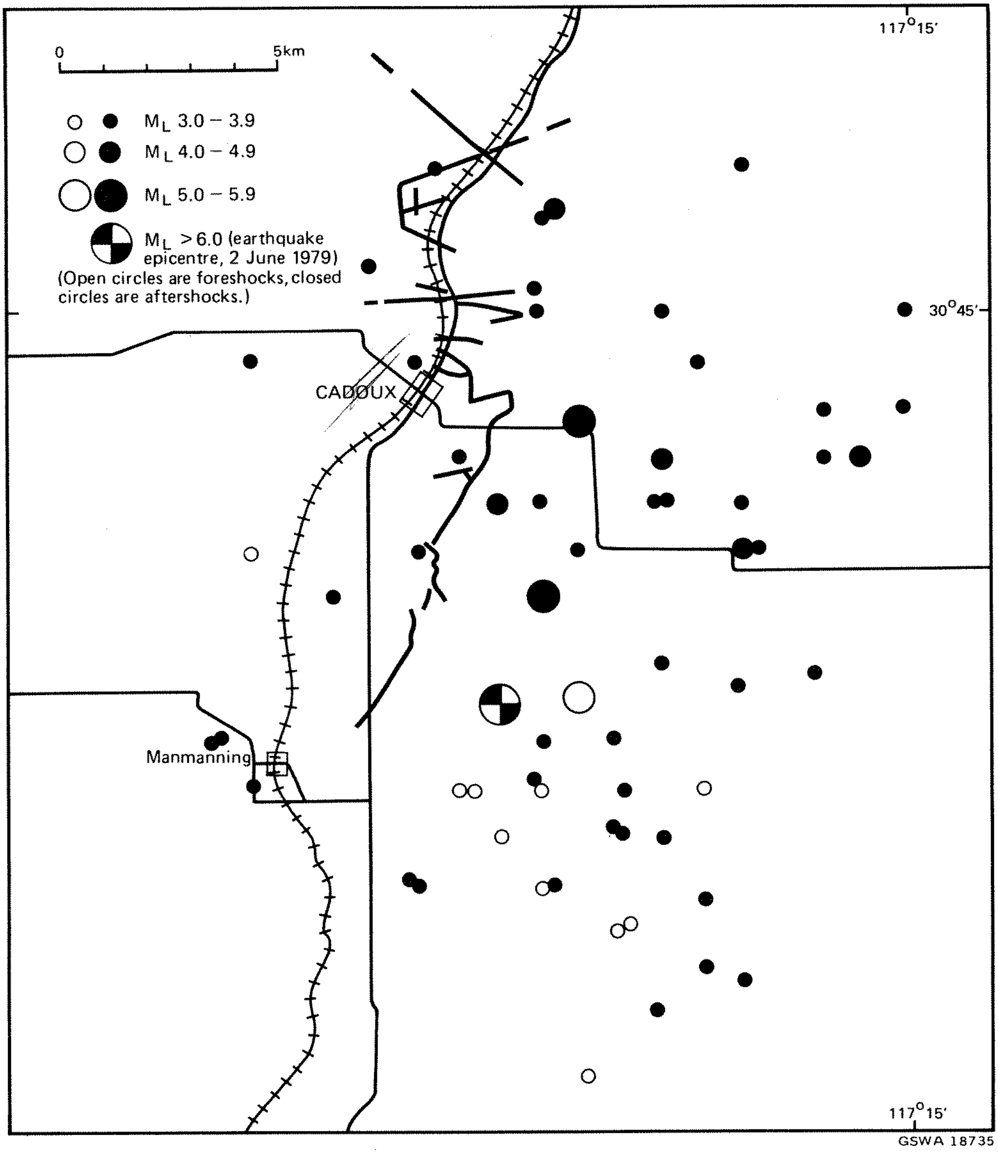



Figure 5. Epicentres of the Cadoux Earthquake and associated foreshocks and aftershocks

fault dipping steeply to the west, intersected by a less well-defined fault plane dipping east. The dip on this postulated secondary plane is much less than the 81° determined from first-motion studies, but this may be due to inherent difficulties in determining the depths of small aftershocks.

Figure 6 does, however, illustrate the relationship between instrumentally determined and observed faulting. Initial rupture took place on an unobserved subsurface fault, while strain in the overlying rocks was relieved by faulting on a conjugate fracture which gave rise to surface faulting.

## THE CADOUX FAULT SYSTEM

The Cadoux Earthquake produced a complex set of faults and superficial fractures within a north-south zone approximately 15 km long and 3 km wide, centred near Cadoux. The total length of the faults is about 28 km, divided between two groups of faults. To the south of Cadoux is a major, north-trending, right-lateral thrust fault about 10 km long, while to the north there are a number of smaller reverse faults forming a conjugate set of fractures and trending approximately 060°, 090° and 120°.

The major faults have been named after the landowners on whose property they occur, or after prominent local landmarks. The faults are permanent features of the local geology, but their surface expression was ephemeral. Ploughing and rain destroyed many of the smaller features within a few weeks, and most of the larger features will be degraded within a year or so.

### FAULT TYPES

Fault movements are conventionally resolved into three components with respect to the fault trace, the line along which the fault cuts the surface. *Strike-slip* movement is a displacement parallel to the fault trace and can be left-lateral, when movement of the opposing block is to the left,

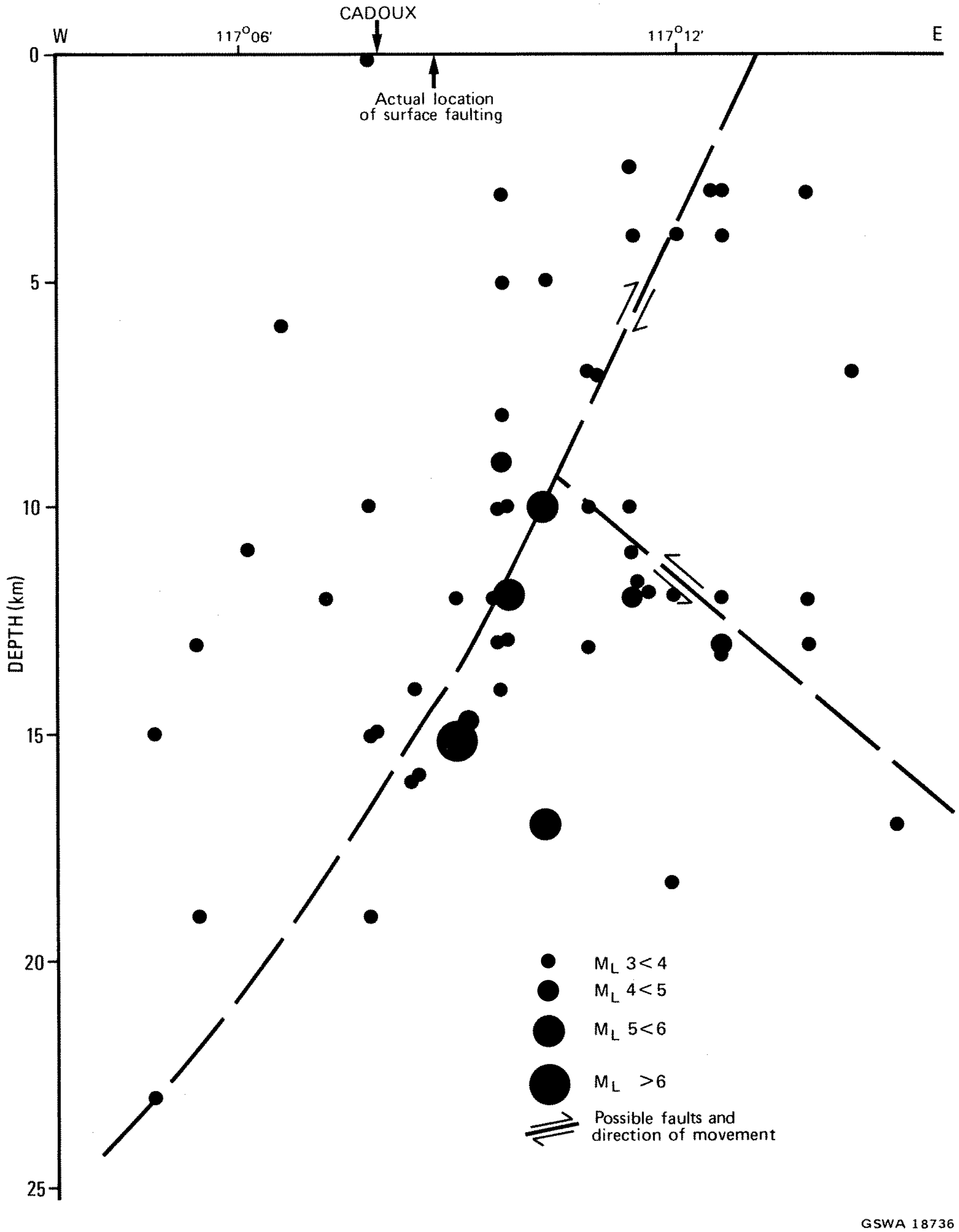



Figure 6. Depths of foci of the Cadoux Earthquake and its aftershocks, on an east-west section

or right-lateral, when movement is to the right. The *throw* of a fault is the vertical difference in height between the blocks on either side of the fault, and the *heave* is the horizontal component of displacement in the dip direction of the fault. Fault movements are rarely simple and usually combine all three components.

In the Cadoux Fault system all faults are compressional and have some component of strike-slip movement, principally right-lateral but sometimes left-lateral (Fig. 7). Only in a few minor faults is this component the major movement. Most faults combine strike-slip and vertical movement, and can be grouped as thrust faults where the fault plane dips at about 45° (Fig. 7d), and high-angle reverse faults where the fault plane dips steeply, commonly at 70°-80° (Fig.7b). For example, the Robb Fault is a right-lateral thrust fault, combining low-angle thrusting with a right-lateral displacement, while the Lone Tree Fault is a left-lateral high-angle reverse fault.

Measurement of fault displacements can be made on any feature that is cut by the fault, including tree roots, plough furrows, pipelines and fences. A fairly accurate measurement of strike-slip can be obtained, although allowance must be made for the angle at which the feature crosses the fault. For example, a simple thrust fault will give an apparent right-lateral or left-lateral strike-slip displacement to a fence line which traverses it obliquely (Fig. 8). The throw of a fault may also be exaggerated where the compressive force has raised a mound of soil higher than the true throw of the fault. Similarly, the collapse of the upthrust block often obscures features on which the heave of a fault may be determined, but this could sometimes be estimated by measuring the slack produced in fence wire. Despite limitations on the accuracy with which many displacements could be measured, it is possible at a number of points to calculate fairly reliable values for the total displacement of the faults, and these have been used in the overall synthesis of fault movements at Cadoux.

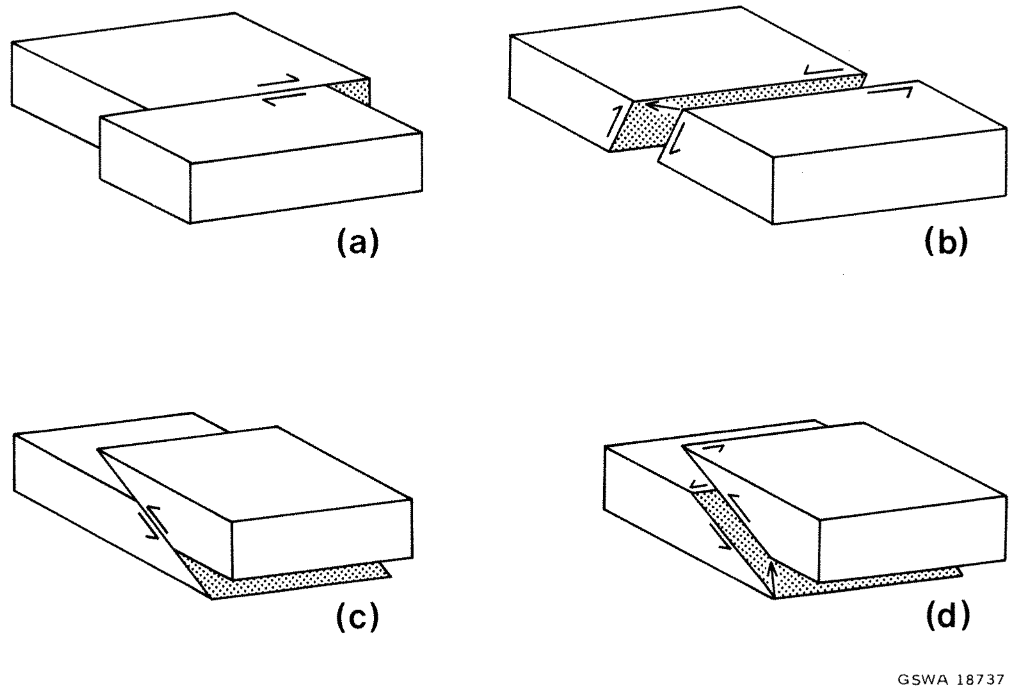



Figure 7. Block diagram of the types of faults present in the Cadoux area: (a) strike-slip fault, (b) strike-slip reverse fault, (c) thrust fault, (d) left-lateral thrust fault

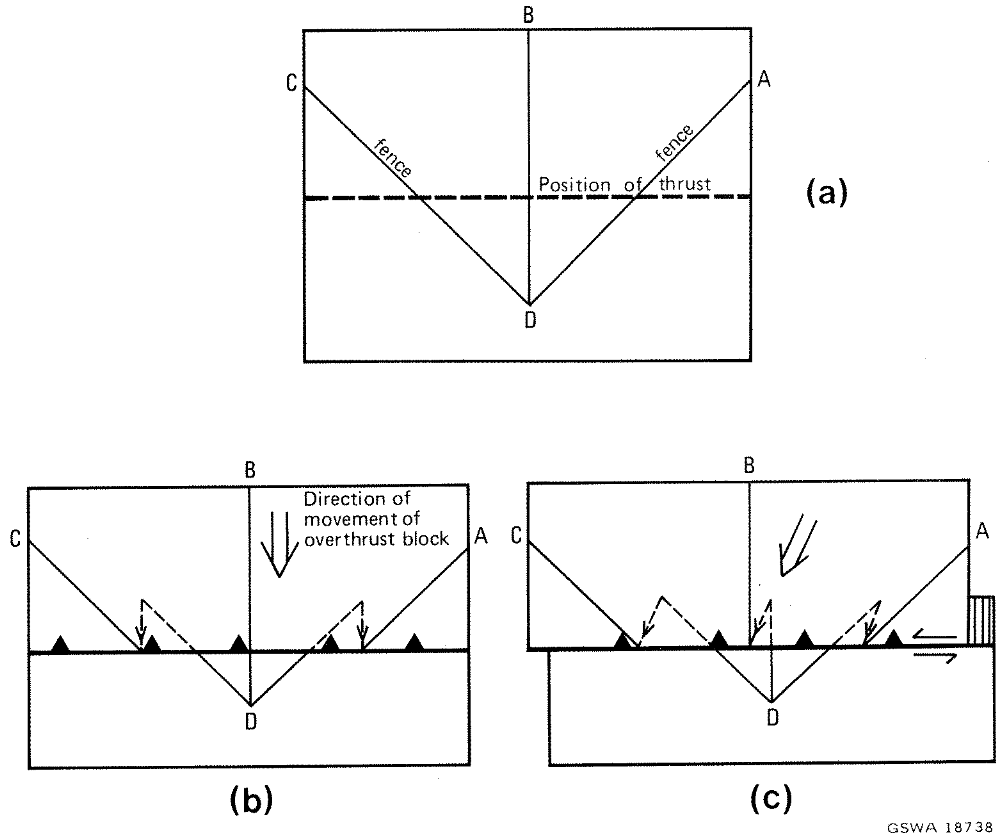



Figure 8. Diagrams showing the effect of thrusting on fences of various orientations: (a) pre-thrust position of fences, (b) apparent displacement resulting from simple thrust movement, (c) apparent displacement resulting from a thrust fault with a strike-slip component

ROBB FAULT

The Robb Fault is a right-lateral thrust, upthrust from west to east, striking at approximately 020$^{\circ}$ for a distance of about 10 km (Plate 2). At its northern end the fault passes into a set of major conjugate faults, while at its southern end the fault diminishes to become a series of minor *en echelon* tension fractures. The displacement of the fault is variable but is generally greatest in the central portion, diminishing to zero at each end of the fault trace. The maximum throw of 1.4 m was measured 1 km north of the Koorda road and the maximum heave and right-lateral displacement, each of about 0.7 m, were measured some 1.5 km south of the Koorda road.

At its southern end, straddling the Cadoux-Dowerin road some 8 km south of Cadoux, the Robb Fault was expressed as a zone of small discontinuous cracks that indicated right-lateral strike-slip movement along the fault. The cracks ranged in strike from 020$^{\circ}$ to 080$^{\circ}$. The trends of the more continuous and linear cracks closely followed the overall trend of the Robb Fault.

About a kilometre from its southern termination the fault was expressed as an indistinct series of hummocks and tension cracks (Fig.9), together with a single small scarp some 150 m long, with a trend of 050$^{\circ}$ and a small downthrow to the southeast. The surface expression of the Robb Fault was more conspicuous to the north, and the more usual thrusted nature of the feature became apparent some 1.5 km northeast of of the Cadoux-Dowerin road.

As a continuous feature the main section of the Robb Fault began in a large paddock, 1.5 km square, southwest of the Shankland farmhouse. Throughout the paddock west-over-east thrust movement was dominant and the scarp form was usually that of a suprathrust with some lengths of formless compressional roll (for fault-scarp terminology see Fig.12). At the southern boundary of the paddock the vertical displacement of the fault was about 0.5 m and the right-lateral movement, measured on fence posts, was about 0.12 m. The thrust front degenerated on the northern side of the

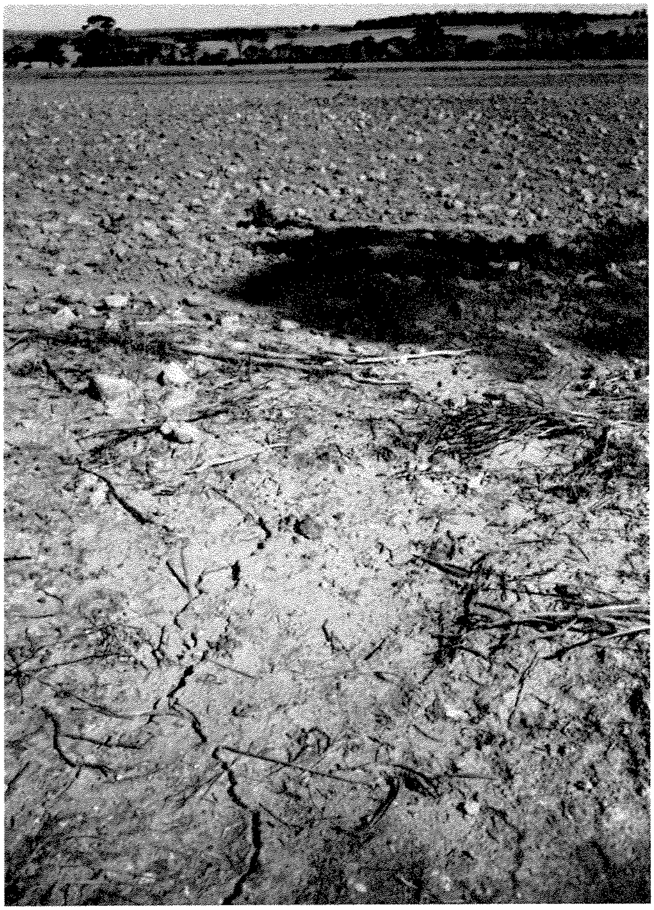


Figure 9. Tension crack 1.2 km from the southern termination of the Robb Fault (GSWA 18739)

paddock and disappeared as it crossed the boundary fence, being replaced by another thrust 270 m to the east. Any smaller earthquake-generated features which were present to the north had been obscured by ploughing at the time of observation.

A feature of this section of the fault was a series of tension fractures in the northern half of the paddock and to the west of the fault. Beginning just to the west of the fault scarp on the northern paddock boundary the fractures formed an *en echelon* series each trending 223°. In the central section of the paddock the fractures trended 188° and formed a linear feature. One of the *en echelon* fractures cut an outcrop of weathered granite (Fig. 10). The fracture appeared to be purely tensional, with no lateral or vertical displacement. The line of tension fractures possibly represented a secondary feature formed by the collapse of a wedge-shaped portion of the uplifted western block.

Figure 10. Tension crack in a granitic outcrop, 3 km from the southern termination of the Robb Fault (GSWA 18740)

Figure 11. A branch of the Robb Fault passing beneath a house on the Shankland property: the right-lateral thrust fault passes between the third and fourth verandah poles and gives a small apparent left-lateral displacement of the stone wall (GSWA 18741)

Some 270 m east of the point where the main fault scarp died out another smaller thrust scarp was developed. This scarp, trending approximately northeast, passed directly through the farmyard of the Shankland property (Fig. 11), and diminished until it disappeared in the driveway, some 160 m beyond the house. The fault scarp, 450 m long but rarely more than a few centimetres high, displayed west-over-east displacement and varied from a suprathrust to a subthrust scarp (Fig. 12).

The major fault displacement in this area was accommodated by a thrust which trended 145° and cut the driveway to the Shankland property some 300 m north of the house. This fault scarp died out 400 m to the southeast but at the driveway it turned northward and became the main feature of

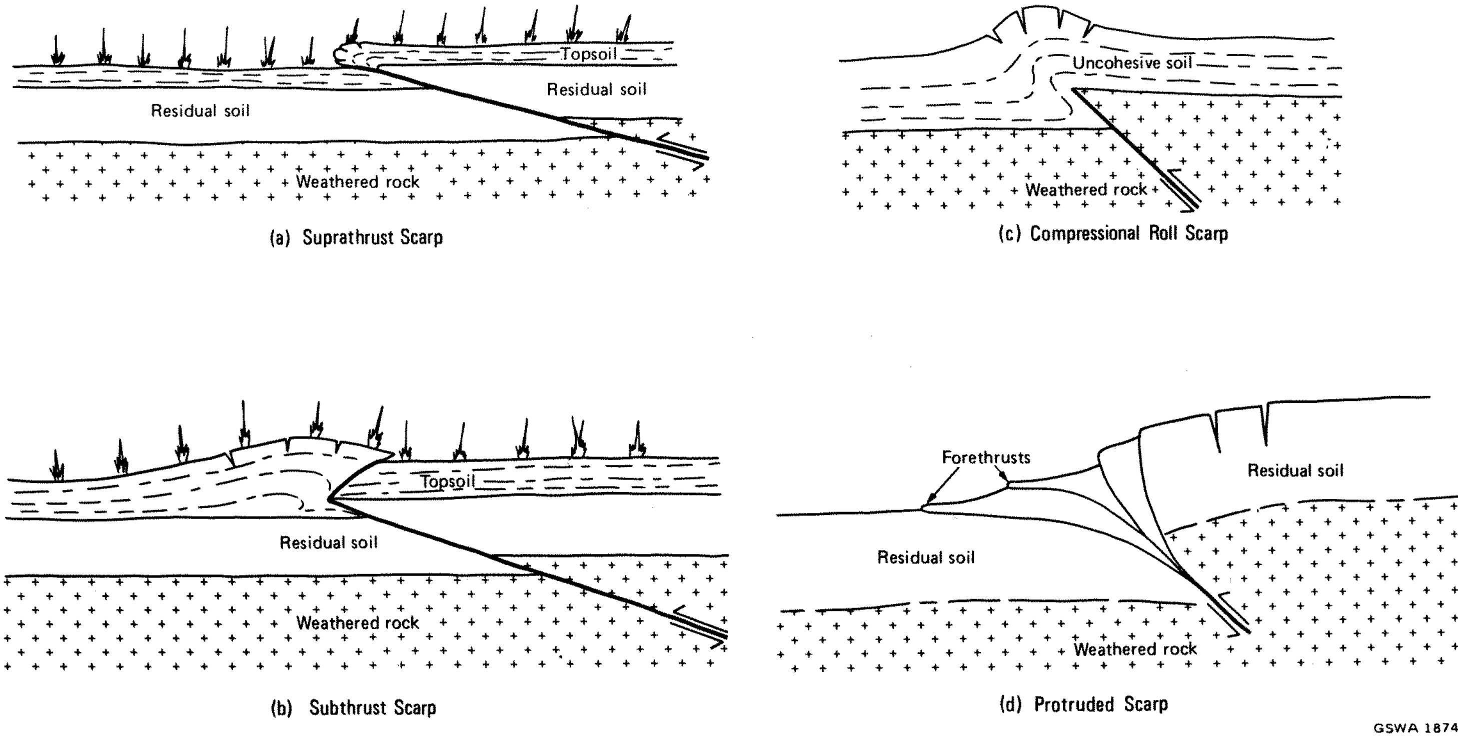



Figure 12. Scarp types typical of the Robb Fault (terminology after Gordon and Lewis, 1980)

the Robb Fault. At the southern end of this fault an anomalous left-lateral displacement was seen (Fig.13a), probably caused by the 145$^{\circ}$ strike of this section relative to the overall strike of 020$^{\circ}$ for the Robb Fault. This section of the fault also provided the only exposure of the plane of the Robb Fault; about 100 m east of the Shankland house it was exposed in cemented laterite gravel and dipped 34$^{\circ}$ to the southwest with a strike of 122$^{\circ}$ (Fig. 13b).

Along the north-south driveway of the Shankland property the thrust fault was lobate and twice intersected the track before resuming a linear course, trending 028$^{\circ}$, to intersect the road along the Dowerin/Wongan-Ballidu Shire boundary. An irregular zone of tension cracks trending southwest from the driveway probably outlined a secondary fracture in the uplifted block and may have represented a continuation of the line of tension cracks mapped in the paddock to the south.

At the shire boundary, repairs to the road and a pipeline had obliterated the fault scarp at the time of observation, but a right-lateral displacement of 0.2 m was measured on the fence-line. Across the road the fault died out within a few metres but was replaced, 200 m to the west, by another thrust scarp. The two sections of the fault were joined by an *en echelon* set of tension gashes with an overall trend of 120$^{\circ}$.

The Robb Fault continued as a thrust trending 025$^{\circ}$, and formed an essentially linear feature for some 2.3 km to the north, as far as the Robb house. Near the southern end of this portion and 400 m to the east a small subsidiary thrust scarp ran parallel to the main fault for about 850 m. The maximum throw of this subsidiary thrust in its central section was about 0.2 m.

As far as the paddock south of the Robb farmhouse the fault scarp of the main Robb Fault was a simple suprathrust with the west block uplifted 0.3-0.5 m, but in the thick sandy soil south of the farmhouse the fault trace was varied and complex. At the southern end of the paddock a maximum

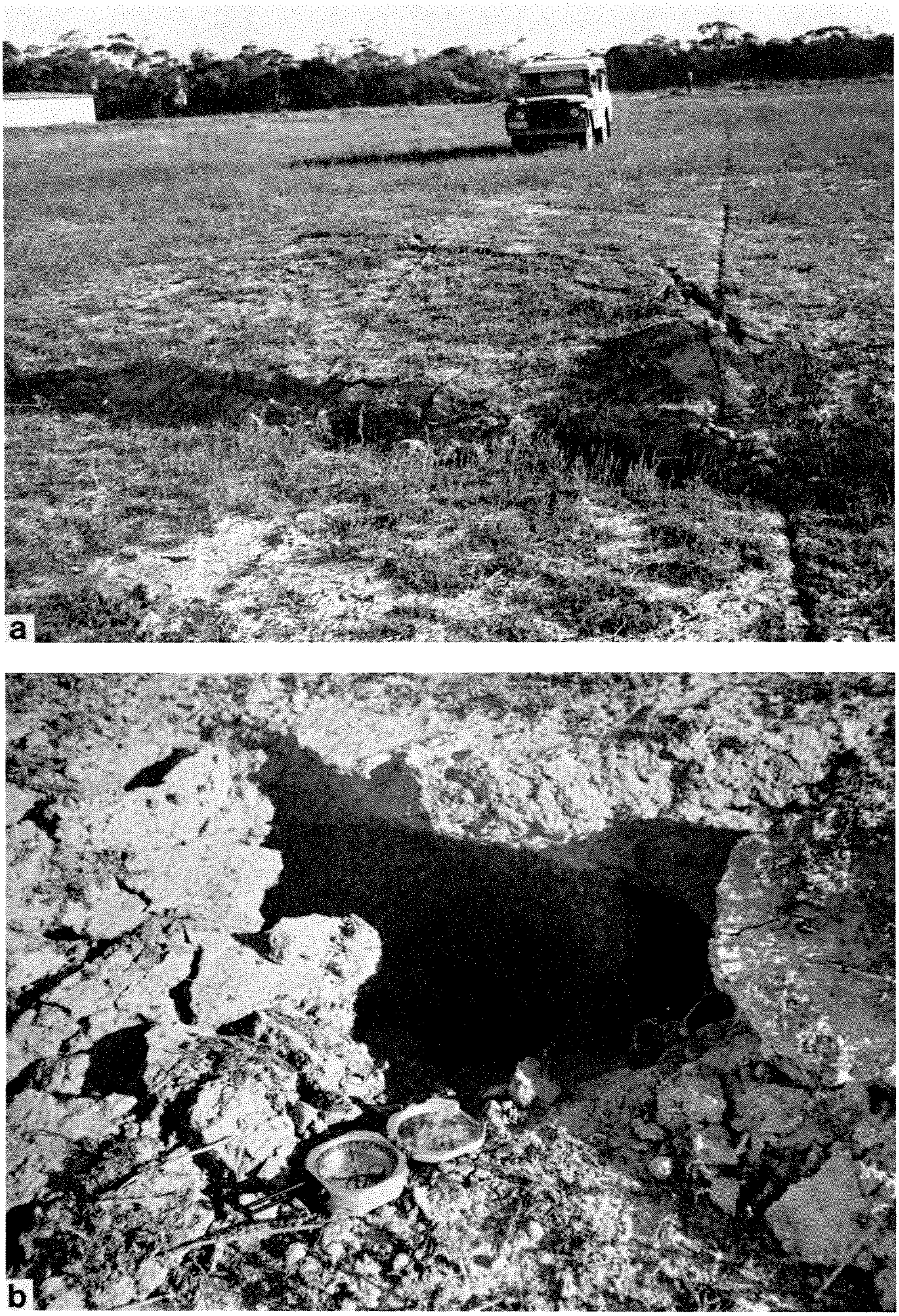


Figure 13. The Robb Fault northeast of the Shankland house: (a) note apparent left-lateral displacement of old wheel tracks and tension cracks to the rear of the collapsed scarp, (b) an exposure of the thrust plane dipping at 34° towards 212° (GSWA 18743)

heave of 0.68 m was measured and the fault scarp, about 0.5 m high, was formed by a subthrust from the west (Fig.14a). Further north the fault trace became a series of complex meandering compressional rolls with tension gashes on the crest (Fig.14c). These rolls were in some cases quite formless, but they often included suprathrust fronts and a subthrust rear. Throughout this section the crest of the fault scarp was often raised above the level of the uplifted block, thus exaggerating the apparent vertical displacement. Towards the northern end of the paddock the pattern of surface fractures became more regular, firstly with a series of *en echelon* thrust scarps joined by tension gashes and then as a zig-zag pattern of alternate thrust and wrench faults each 30-40 m long (Fig.14b). The wrench faults trended 075$^{o}$, were parallel to the resultant movement of the western mobile block, and were simple strike-slip faults with a right-lateral displacement of about 0.3 m. The thrust sections trended more nearly north-south and were purely thrust faults.

About 350 m south of the Robb farmyard the fault split and a small thrust trended 347$^{o}$ to the northwest. The area had been ploughed before documentation of the faults, but it appears that this small thrust linked with a strike-slip fault trending 080$^{o}$ which was traced for some 1.1 km west of the main fault. This is one of a number of small faults on this trend which occur between the Robb house and the northern end of the Robb Fault. It may be the southernmost expression of the conjugate set of faults north of Cadoux.

Between the Robb house and the Koorda road, ploughing had destroyed any earthquake-produced features. However, the reappearance of the fault scarp on the road suggests that the fault trace originally crossed the ploughed area.

Immediately north of the Koorda road the trace of the main Robb Fault disappeared and degenerated into a small right-lateral strike-slip fault trending 075$^{o}$. The maximum observed displacement of the fault was 0.03 m, and at its western end it degenerated into a series of tension cracks.

a

b

c

Figure 14. Complex fault patterns on the Robb Fault: (a) sub-thrust rear of the fault trace 1.45 km south of the Koorda road. Note the vertical displacement of 0.5 m on the fence post and the almost total degradation of the fault trace to the south of the fence, caused by subsequent ploughing, (b) alternate thrust and wrench faults 1.25 km south of the Koorda road. Short thrust sections are joined by minor strike-slip faults trending 075°, (c) meandering compressional roll scarp, alternately sub- and supra-thrusted, to the north of 14(b) (GSWA 18744)

Parallel to this fault and 400 m to the north was another small strike-slip fault about 800 m long, but showing a left-lateral displacement of 0.15 m. At their eastern ends the two parallel faults were joined by a small north-south thrust fault.

From the western end of the northern strike-slip fault the main thrust fault reappeared, trending 010$^{\circ}$, and rose rapidly to a throw of about 0.8 m. Initially, in a very sandy soil, the scarp was a formless slumped mass, backed by large tension fractures 8-10 m to the rear of the scarp. For several hundred metres, however, the fault scarp was well defined and suggested the collapse of the lip of the overthrust western block. A maximum throw of 1.4 m was recorded in this section. At the location of Figure 15a the forward collapse of the scarp produced a tension fracture open 0.2 m and downthrown 0.3 m to the east, and several smaller fractures within the collapsed block which produced a graben-like structure. At this point the toe of the collapsed block extended 22 m to the east of the tension fracture and contained several very low-angle forethrusts. Although the main fault plane was not exposed and the total right-lateral strike-slip could not be measured, the small forethrusts showed a progressive strike-slip movement, which suggests that the major thrust movement preceded the strike-slip movement.

Further north, in the paddock south of the Hopkins' farmhouse, a semi-coherent grass mat had been rolled up by the thrust movement and there were minor tension fractures to the rear of the scarp. On the southern boundary of the paddock the throw was 0.68 m (Fig.15b), but on the Hopkins' entry track the scarp was only 0.48 m high, and in the paddock to the north of the track the fault scarp died away.

A continuation of the Robb Fault could, however, be traced for a further 800 m. The fault changed its essentially north-south trend to the 295$^{\circ}$ trend of the conjugate set of faults to the north. On the west side of the railway a throw of 0.25 m, down to the north, and an apparent left-lateral displacement of 0.1 were measured,

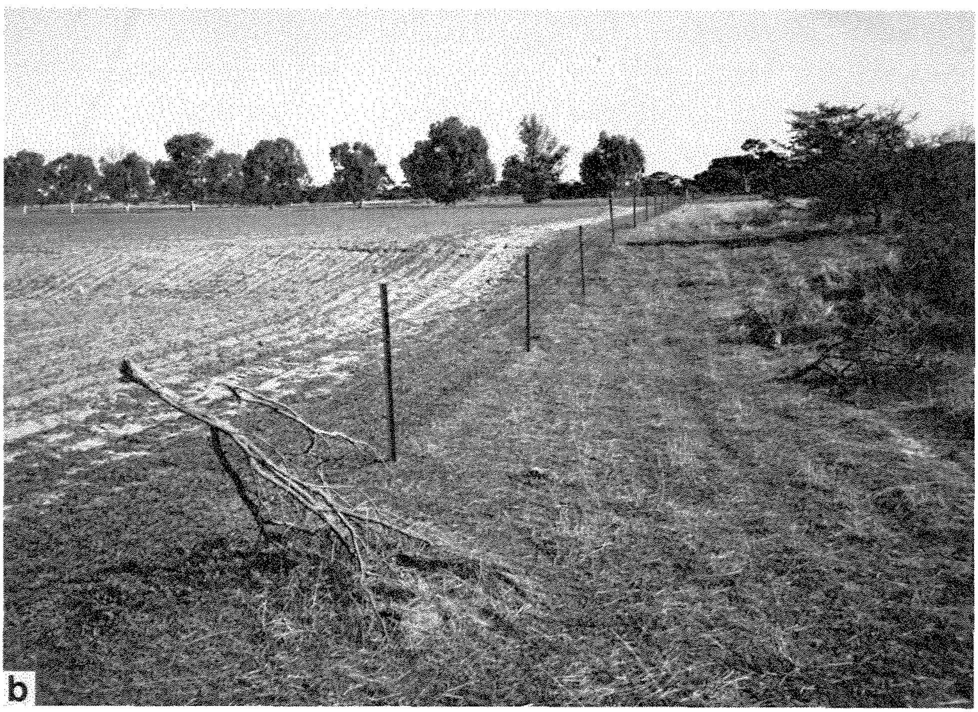


Figure 15. The Robb Fault northeast of Cadoux golf course: (a) collapse of the upthrust block. Note the major tension fracture at the crest and the graben-type structure in the collapsed material. The throw of the fault at this point is 1.4 m (b) Throw of 0.68 m on fence line 0.55 km north of the Koorda road. (GSWA 18745)

but beyond the railway the fault continued for a further 500 m as a small, indistinct, monoclinal warp.

A minor feature was mapped between Cadoux and the northern end of the Robb Fault. It comprised a set of tension gashes trending 115°, which swung to 070° at their junction with the Robb Fault. A small strike-slip fault showing sinistral displacement was present near the eastern end of the feature.

Small dextral thrusts trending 005° were mapped 1 km east of the main fault and southeast of the Hopkins' farmhouse. These faults may be related to the section of the main fault which was offset, north of the Koorda road, by two parallel strike-slip faults.

*Fault displacements*

At no point was the fault plane of the main Robb Fault exposed. Throughout its entire length the fault was obscured by sandy or silty soil. Thus, no direct measurement could be made of the displacement of the fault. Nevertheless, at a number of points along the Robb Fault it was possible to determine from fence lines approximate values for heave, throw and strike-slip. The measurements apply only to the immediate vicinity of the fault and do not take account of distortions which could be spread over a zone many metres wide on either side of the fault scarp. In particular, the throw of the fault was often difficult to measure, as compression often extruded a mound of soil which was higher than the throw of the fault.

At six points along the length of the fault measurements of the displacement of fence lines were sufficient to enable a calculation of the net displacements of the fault and the dip of the fault plane. The field observations must be corrected for the angle at which a fence crosses the fault, and in Table 3 the corrected values are given; the observed values are plotted on Plate 2 with vectors representing the net displacement.

TABLE 3. CALCULATED DISPLACEMENTS OF THE ROBB FAULT

| *Point* | *Throw (m)* | *Right-lateral strike-slip (m)* | *Heave (m)* | *Dip of fault plane* | *Resultant displacement* | |
|---|---|---|---|---|---|---|
| | | | | | *Net slip (m)* | *Azimuth* |
| 1 | 0.50 | 0.22 | 0.13 | $75^{\circ}$ | 0.56 | $063^{\circ}$ |
| 2 | 0.50 | 0.46 | 0.29 | $60^{\circ}$ | 0.74 | $056^{\circ}$ |
| 3 | 0.70 | 0.70 | 0.78 | $42^{\circ}$ | 1.26 | $078^{\circ}$ |
| 4 | 0.20 | 0.20 | 0.08 | $68^{\circ}$ | 0.29 | $065^{\circ}$ |
| 5 | 0.68 | 0.28 | 0.36 | $62^{\circ}$ | 0.82 | $067^{\circ}$ |
| 6 | 0.48 | 0.28 | 0.18 | $69^{\circ}$ | 0.58 | $033^{\circ}$ |

From Table 3 it will be seen that the maximum net displacement of the Robb Fault was 1.26 m in its central portions, diminishing to about 0.5 m near each end. More interesting, however, is the calculated dip of the fault plane. Only in the central portion, at point 3, is it at an angle commonly associated with thrust faulting. Elsewhere it dips at between $60^{\circ}$ and $75^{\circ}$ and is a high-angle reverse fault. It is possible that the scarp form has exaggerated the apparent throw of the fault. Alternatively, considering that the azimuth of the resultant displacement is more northerly than the $075^{\circ}$ direction commonly found in the field, it is possible that the heave has been underestimated. Both sources of error would tend to increase the calculated dip of the fault. Cadastrally surveyed fence lines show that measurements taken at the fault scarp tend to underestimate the heave and strike-slip displacement of the fault. However, a plot of the depth of focus of the aftershocks (Fig.6) provides strong evidence for considering the dip of the Robb Fault as relatively steep. Nevertheless, the scarp forms exhibited by the Robb Fault were characteristic of a low-angle thrust. It seems probable that these scarp forms developed only because the dip of the fault plane was shallower in the thick soil horizon than at depth.

*Minor faulting between the Robb and Cumming Faults*

Four distinct faults have been mapped between the Robb and Cumming Faults. A small compressional ridge trending 090° crossed the road and railway some 1.2 km north of Cadoux Post Office. This feature could not be traced for more than a few metres on either side of the road and railway reserve, and would probably not have been obvious as an earthquake-generated feature but for the minor disturbance caused to the road surface.

The second minor fault was some 300 m north of the first and comprised a south-over-north suprathrust west of the road and railway. Subthrusting was dominant east of the road, although the overall movement was still south-over-north. Tension cracks oblique to the general trend of the feature suggested an overall right-lateral displacement on the fault plane. Although surface evidence of faulting disappeared some 400 m east of the road, a Telecom cable running north-south some 650 m east of the road was severed during the earthquake.

Just south of the Cumming Fault a pair of strike-slip faults was mapped that displayed trends typical of the conjugate set (Fig.16). The two features met at their eastern ends, in what appeared to be a thrusted "nose", but the paddock was ploughed before mapping commenced and the evidence was, therefore, obscured. The more southerly of the two wrench faults had a strike of 070°, and a measured right-lateral movement of 0.04 m. The northerly one, which had a strike of 110°, had a left-lateral movement of up to 0.2 m and could be traced west for a distance of 1.6 km, where it degenerated into a set of tensional gashes.

## CUMMING FAULT

For its full length of 3.2 km the Cumming Fault was invariably expressed as a south-over-north suprathrust. It displayed marked linearity, in contrast to the wavy nature of the other thrusts. The maximum measured vertical displacement on this fault was approximately 0.2 m, measured

Figure 16. Collapse structure on a minor fault south of the Cumming Fault and 400 m south of the Cumming house (GSWA 18746)

some 500 m west of the main road. No lateral displacement was seen where the fault crossed a track 500 m south of the Carter farmyard, although a small apparent left-lateral displacement was evident over the eastern section of the fault.

*Minor faulting between the Cumming and Lone Tree Faults*

A south-over-north thrust trending $100^{\circ}$ ran west from the railway line about 350 m north of the Cumming Fault. This fault swung abruptly south east of the railway line, and connected with the Cumming Fault through a complex series of supra- and subthrusts, tension cracks and strike-slip faults, which appeared to resolve into a general west-over-east reverse movement. This is compatible with a small but consistent left-lateral movement on the section of the fault that trended $100^{\circ}$. A small south-over-north subthrust immediately northeast of the Carter farmyard was probably a continuation of this feature.

All the displacements on the minor faults in this system were of the order of 0.01 to 0.02 m.

LONE TREE FAULT

The Lone Tree Fault is a left-lateral strike-slip fault with a reverse component. It is unusual because the reverse component is north-over-south, contrary to the main movements in the Cadoux area. The fault strikes $115^{\circ}$ and its surface expression was 1.5 km long (Fig.17).

The maximum measured throw was 0.53 m on a contour bank 700 m west of the railway. The throw decreased to both west and east, being 0.25 m where the fault crossed a farm track near its western extremity, and about 0.2 m where it crossed the track immediately west of the railway. Near its eastern extremity the fault had a slight downthrow to the north. Unfortunately the fault plane was not exposed in this area, so it is not clear whether the fault changed from reverse to normal.

Figure 17. The Lone Tree Fault, looking northwest from above the Kalannie road. The scissors fault in the foreground is also shown in Figure 19 (photo: W.A. Newspapers) (GSWA 18747)

An apparent left-lateral displacement of 0.65 m was measured near the western end, but most measured displacements were between 0.3 and 0.55 m.

The fault plane, which was visible in several places, dipped north at between 70 and 85$^{o}$. Consequently, heave on the fault was always small.

The fault was expressed at the surface in two forms. The part west of the "lone tree" was a simple scarp in clayey soil. Some collapse of the scarp had taken place, but in many places the fault-plane surface was still preserved at the time of this study. Short tensional gashes up to 2 m long, and oblique to the main fault are compatible with the left-lateral movement (Fig.18a).

The eastern part of the fault was complex and included numerous, long tensional gashes along which much of the movement had taken place. An unusual feature which was

a

b

Figure 18. Reverse strike-slip fault scarps: (a) the Lone Tree Fault, 400 m from its western end, showing a left-lateral displacement of the contour bank, (b) the Tank Fault, 700 m west of Kokardine tank; the fault plane is exposed in weathered granite and the southern block is upthrust 0.7 m (GSWA 18748)

developed in several places was the presence of conjugate thrusts separated by a scissors fault (Fig.19). This was due to deformation of the soil cover between *en echelon* tensional gashes. A complex zone of thrusting and shearing, or, on a smaller scale, dome-like structures 3 to 4 metres across, were produced.

From measurements on the fault the net displacement has been calculated at two points and plotted on Plate 2. Near the western end of the fault the displacement was 0.57 m towards 278$^{\circ}$ and near the railway 0.23 m towards 282$^{\circ}$.

## CARTER THRUST ZONE

The Carter Thrust Zone is a complex of predominantly low-angle thrusts which joins the western terminations of the Tank and Lone Tree Faults. Together these three structures outline a fault block which moved upwards and westwards relative to the surrounding area.

The three main structural elements of the Carter Thrust Zone are the Carter Main Thrust, the Carter Back Thrust, and the Link Fault which joins the two thrusts (Fig. 21).

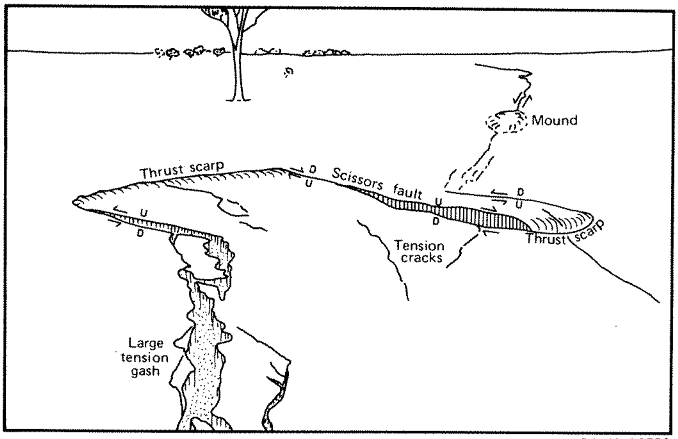
### *Carter Main Thrust*

The Carter Main Thrust is 1.3 km long and has an overall trend of approximately 015$^{\circ}$. The surface trace was very irregular, and offset up to 50 m in several places by small strike-slip faults. The maximum throw and heave (0.5 and 0.4 m, respectively) was measured near the southern end of the thrust, decreasing north of the intersection with the Link Fault. Lateral movement on the thrust was negligible.

The surface expression of the thrust took the form of a lobate thrust front, behind which was a low ground bulge containing tension cracks subparallel to the front. The thrust front itself was usually between 0.05 and 0.2 m high. Near the southern end of the Carter Main Thrust, where the throw on the fault is greatest, the thrust front consisted of up to four small thrusts which gave a terraced effect to

a

b




GSWA 18750

c

Figure 19. A complex structure on the Lone Tree Fault, 200 m west of the railway: (a) scissors fault with associated opposing thrusts (GSWA 18749), (b) diagrammatic representation of (a) (GSWA 18750), (c) detail of the northerly thrust front (GSWA 18749). The tension crack in the lower right of the photograph has been partially filled by the advancing thrust front

the scarp. A trench, 1 m deep, was excavated across an apparently simple thrust front 200 m north of the junction with the Lone Tree Fault. This revealed, in the soil profile, several small flat thrusts which steepened and converged at depth to a single thrust plane dipping 20° east in weathered bedrock (Fig.20).

In most cases the Carter Main Thrust was backed by tension cracks, usually between 5 and 15 m from the thrust front. These crevasse-style cracks were open as much as 0.2 m, and in some cases showed a downthrow (due to slumping) in the direction of the thrust front. Large tensional openings were developed, with graben-collapse structures up to 0.8 m across and 0.3 m deep. Other tensional cracks formed perpendicular to the main thrust. Some of these were probably tensional gashes associated with small right- and left-lateral faults which offset the Carter Main Thrust.

*Link Fault*

The Link Fault, so named because it links the Carter Main and Back Thrusts, has a length of 1.7 km. East of the Carter Back Thrust, it appeared to be a steep reverse fault, dipping north, with 0.1 m of north-over-south throw and a

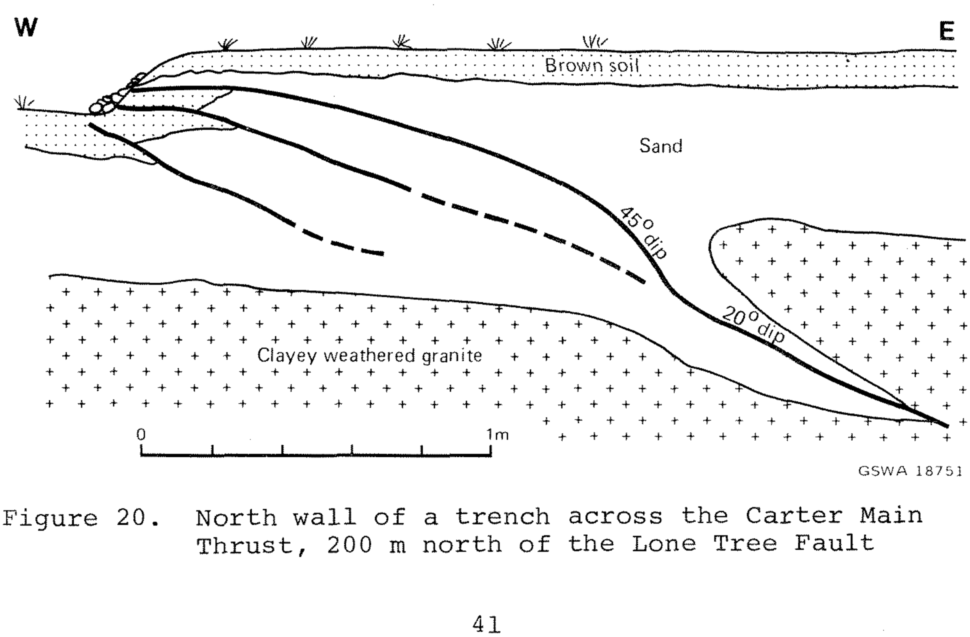



Figure 20. North wall of a trench across the Carter Main Thrust, 200 m north of the Lone Tree Fault

slight right-lateral displacement. Between the Carter Main and Back Thrusts, the Link Fault was expressed as a series of small *en echelon* fractures and in this *en echelon* zone, the throw of the fault changed to south-block-up and the fault plane dipped south. Here the throw was about 0.25 m and there was a right-lateral displacement of some 0.10 m.

The Link Fault continued for 200 m to the west-southwest, past the intersection with the Carter Main Thrust, but with a much diminished throw. It turned sharply east-southeast and rejoined the Carter Main Thrust by a series of small fractures and tension cracks.

*Carter Back Thrust*

The Carter Back Thrust is 700 m long, trends approximately 350$^{\circ}$, and has a west-block-up movement. Like the main thrust, a lobate thrust front was developed, backed by tension cracks. Maximum measured throw was 0.15 m and heave 0.3 m. Pressure ridging was a common feature along the scarp.

At the northern and southern extremities of the Carter Back Thrust, the amount of movement gradually decreased, and the thrust ended in a series of west-trending tension fractures. These were more prominent in the north than the south.

A diagrammatic representation of the relative block movements is given in Figure 21. The size of the arrows is approximately proportional to the magnitude of the relative movements.

*Secondary effects in the Carter Thrust Zone*

A feature of the Carter Thrust Zone was the presence of circular or elliptical holes up to 1 m across and 1 m deep (Fig.22). They were unrelated to tension cracks, although they did occur in the vicinity of major tension cracks a few metres back from the thrust scarps. The holes, of which three were found, were probably caused by the collapse of a cylinder

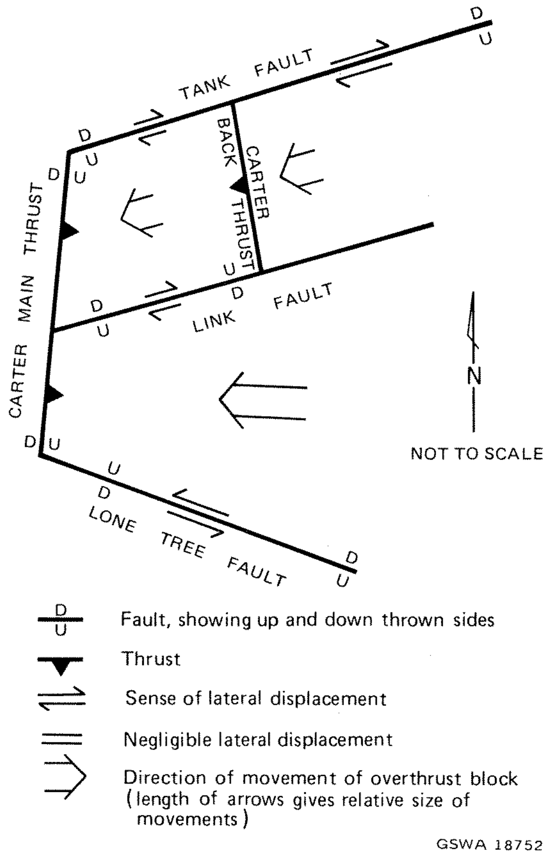



Figure 21. Block movements in the Carter Thrust Zone

of poorly consolidated soil into a cavity formed by movement along the irregular thrust plane. Such a cavity was preserved in a creek near the mid point of the Carter Main Thrust, where the thrust plane had left a subhorizontal cavity at least 5 m x 2 m and 0.3 m deep.

For at least 2 km to the west down the same creek, the creek banks, which range in height up to 0.4 m, showed evidence of tensional cracking parallel to the channel, and up to 10 m from it. The cracks were probably due to incipient collapse during shaking.

Figure 22. Collapse structure 0.6 m across behind the Carter Main Thrust (GSWA 18753)

TANK FAULT

The Tank Fault has an average trend of 070$^{\circ}$ and could be followed intermittently for 3.5 km. For most of its length the fault crosses shallow kaolinized granite bedrock with thin soil cover. At the eastern end of the fault the weathering profile is thicker, and the fault crosses laterite.

Many granitic outcrops showed secondary effects due to the shaking, such as cracking of granite slabs, opening of joints, and spalling of boulders.

The fault is a strike-slip fault with a reverse component, and a right-lateral movement which reached a maximum of 0.4 m about 900 m west of the tank. At the western termination, where the fault turns sharply south to become the Carter Main Thrust, the lateral displacement was 0.22 m, and where the fault crosses the railway, the lateral movement was 0.15 m.

The throw on the fault, which is always up to the south reached 0.7 m at a point west of the tank, reducing to 0.2 m at the western termination and 0.1 m at the railway. The heave was difficult to determine in most cases, but was probably about 0.1 m where the other components were greatest. Tensional openings on the upthrown side of the fault led to inaccuracies in measuring the heave.

As the fault plane was well exposed at a number of points and dipped at $70^{\circ}$ to $80^{\circ}$, the total displacement was easily calculated. Three displacement vectors have been plotted on Plate 2, the most westerly being at a point where the fault crossed a contour bank; here the net displacement was 0.48 m towards $264^{\circ}$. At the point of maximum displacement the vector was 0.83 m towards $260^{\circ}$, and near the tank it was 0.40 m towards $260^{\circ}$. These results are consistent with those found on the Lone Tree Fault.

The fault plane was well exposed 700 m west of the tank, where weathered granite bedrock gave rise to a single scarp 0.7 m high (Figs 18b and 23a). The plane dipped south at $80^{\circ}$, although this was seen to become shallower some 1.5 to 2 m beneath the surface. The exposed fault plane contained a layer, 1 mm thick, of fault gouge material (in this case sheared kaolin) with slickensides. Most slickensides plunged between $55^{\circ}$ and $80^{\circ}$E. A second phase of movement was indicated by slickensides plunging $30^{\circ}$E which were superimposed on the earlier slickensides.

More typical than the simple scarp just described, was a complex scarp in which a steeply dipping main scarp, with some frontal collapse, formed behind a low-angle thrust (Fig. 23b). The thrust scarp, which was usually only a few centimetres high, is thought to have been a secondary feature produced by the forward heave of the steep reverse fault when it reached the unconsolidated soil horizon. In plan, the reverse fault had a secondary thrust lobe several metres in front of the main scarp.

Immediately north of the tank, the fault cuts the quartz dyke and weathered granite which forms the ridge on which the tank stands. The scarp here was between 0.1 and

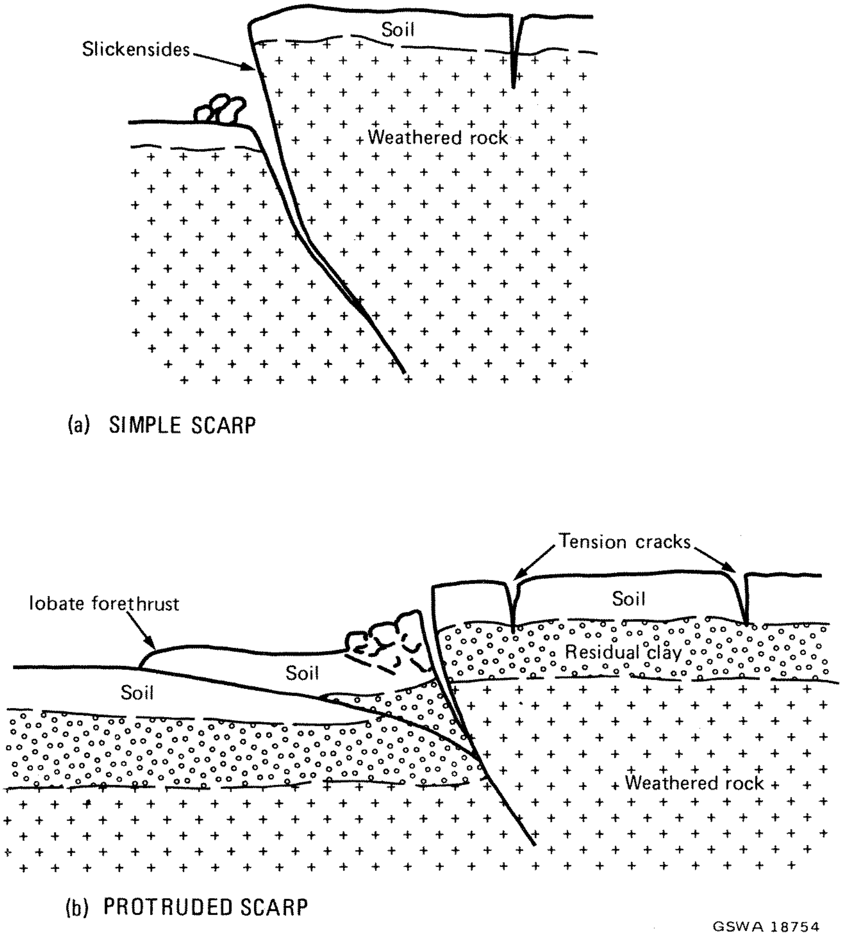



Figure 23. Scarp types on the Tank Fault

0.2 m high and fairly simple in morphology. A trench dug across the fault, 100 m northwest of the tank and 50 m from the nearest exposure of the quartz dyke, revealed that the fault plane dips at 78°S and follows the wall of a pre-existing quartz vein, about 0.3 m thick. This, along with a faint photo-lineament which the fault seems to follow, constitutes evidence that this part of the Cadoux Fault system has been controlled by a pre-existing structure.

Small splay faults were common along the entire fault, and in places these had an *en echelon* arrangement. In some areas of splay faulting, the fault system degenerated into a series of tension gashes and hummocky ridges. For a distance of 600 m west of the tank, there was a zone of tension gashes behind and subparallel to the main fault. This tension zone was up to 100 m wide. A major tension gash extended eastwards, immediately south of the tank, where it had a very small right-lateral displacement and has been termed the Tank Subsidiary Fault.

The eastward extension of the main Tank Fault was completely obscured due to erosion by water from the damaged tank. Consequently it is not clear whether that part of the fault that cuts the railway is connected to the main Tank Fault or the Tank Subsidiary Fault.

## KALAJZIC FAULT

This fault is of particular interest because of its damage effects (Public Works Department tank, pipeline, railway, road and farmhouse), and by the manner in which it is partially controlled by pre-existing structures. The fault trends 305$^{\circ}$, and was well exposed for 3 km. Tension cracks were seen around paddock boundaries (the intervening areas having been ploughed) and these indicate that its length was at least 5 km. The fault crossed an area of shallow sandy colluvium with rock fragments, overlying thin residual clay. Weathered and fresh bedrock occur within a few metres of the surface, and in several places the fault passes close to fresh granite outcrop. Between 200 and 300 m northwest of the tank the fault follows a quartz dyke, and has fractured the dyke.

The surface expression of the fault was a simple subvertical scarp showing downthrow to the north. Along much of its length the fault was expressed as a series of oblique tensions cracks and a gentle warp in the ground surface. The Kalajzic Fault is left-lateral reverse with a maximum throw of 0.2 m and a lateral displacement of about 0.3 m. The fault plane was nowhere visible but probably dips steeply southwest. Assuming a dip of 75$^{\circ}$ on the fault plane the net displacement at two points has been calculated and plotted on Plate 2. At the pipeline 600 m northwest of the tank the displacement was 0.41 m towards 117$^{\circ}$ and at the railway it was 0.27 m towards 110$^{\circ}$. These vectors are parallel, but in the opposite direction, to the local displacement on the Lone Tree Fault.

## SURVEYED DISPLACEMENTS IN THE FAULT ZONE

Immediately following the Cadoux earthquake a number of surveys were carried out in the area by the Western Australian Department of Lands and Surveys and the Australian Survey Office, with the object of gaining some appreciation of ground distortion that may have taken place at a distance from the known fault traces. The Department of Lands and Surveys was mainly concerned with geodetic surveying and the Australian Survey Office with cadastral surveys and levelling.

Unfortunately, no geodetic stations had been established in the area prior to the earthquake and it is therefore impossible to assess any large-scale ground distortion in the Cadoux area. However, a complete geodetic triangulation of the western half of the Bencubbin 1:250 000 sheet area has now been established and will be suitable for monitoring any further distortion of the area. In addition, a closer spaced second-order geodetic network has been established in the Cadoux area to monitor future local distortions. This network includes legs which cross the Robb Fault and small triangulations across the Tank Fault.

Cadastral surveys were carried out by the Australian Survey Office along the major roads and railway and on several paddock boundaries. These indicate only horizontal distortion. A level traverse of benchmarks along the main water pipeline gives some indication of the vertical distortion in the area. In this work the Australian Survey Office was assisted by the Department of Surveying, Western Australian Institute of Technology.

## SURVEY RESULTS

### *Levelling traverse on water-supply pipeline*

The only traverse in the Cadoux area for which reliable levels were known prior to the earthquake is along the Public Works Department (PWD) water-supply pipeline network. Benchmarks at 1.6 km (1 mile) intervals were relevelled along approximately 200 km of this network between Cadoux and Koorda, and south to Cunderdin. A few of the benchmarks could not be relocated, and the benchmark at Kokardine tank had been damaged beyond use. Diagrammatic representation of the results of this relevelling are shown in Figure 24 and full details are given in Appendix II.

From Figure 24 it will be seen that a large block of land between Cadoux and Koorda has been uplifted by as much as 0.36 m; the most dramatic uplift recorded, however, is 0.59 m at a benchmark 1.3 km east-southeast of Kokardine tank. Uplift in this area is the direct result of movement on the Tank Fault. Displacement across the fault itself in the area of the tank measured 0.7-0.8 m. A little over 3 km to the west of the Tank Fault the uplift reduces to zero and further to the west levels remain undisturbed. Eastward, as seen on the section between Cadoux and Koorda, the uplift rises fairly steadily to 0.36 m at a point about 17 km east of Cadoux. Thus, over a distance of about 20 km the uplift of the block has a slope of 1.8 cm per km and it was along the foot of this slope that the earthquake, and faulting, occurred. The Cadoux Fault zone probably marks the western margin of the uplifted block.

The eastern margin of the uplifted block is not known. A traverse north from Koorda shows a consistent uplift of 0.16 to 0.18 m, with peaks up to 0.29 m. Five kilometres west of Koorda the uplift is 0.35 m and 7 km east of the town it has fallen to 0.15 m, a similar slope to that of the western margin of the block, suggesting that the eastern margin of the uplifted block is about 15 km east of Koorda.

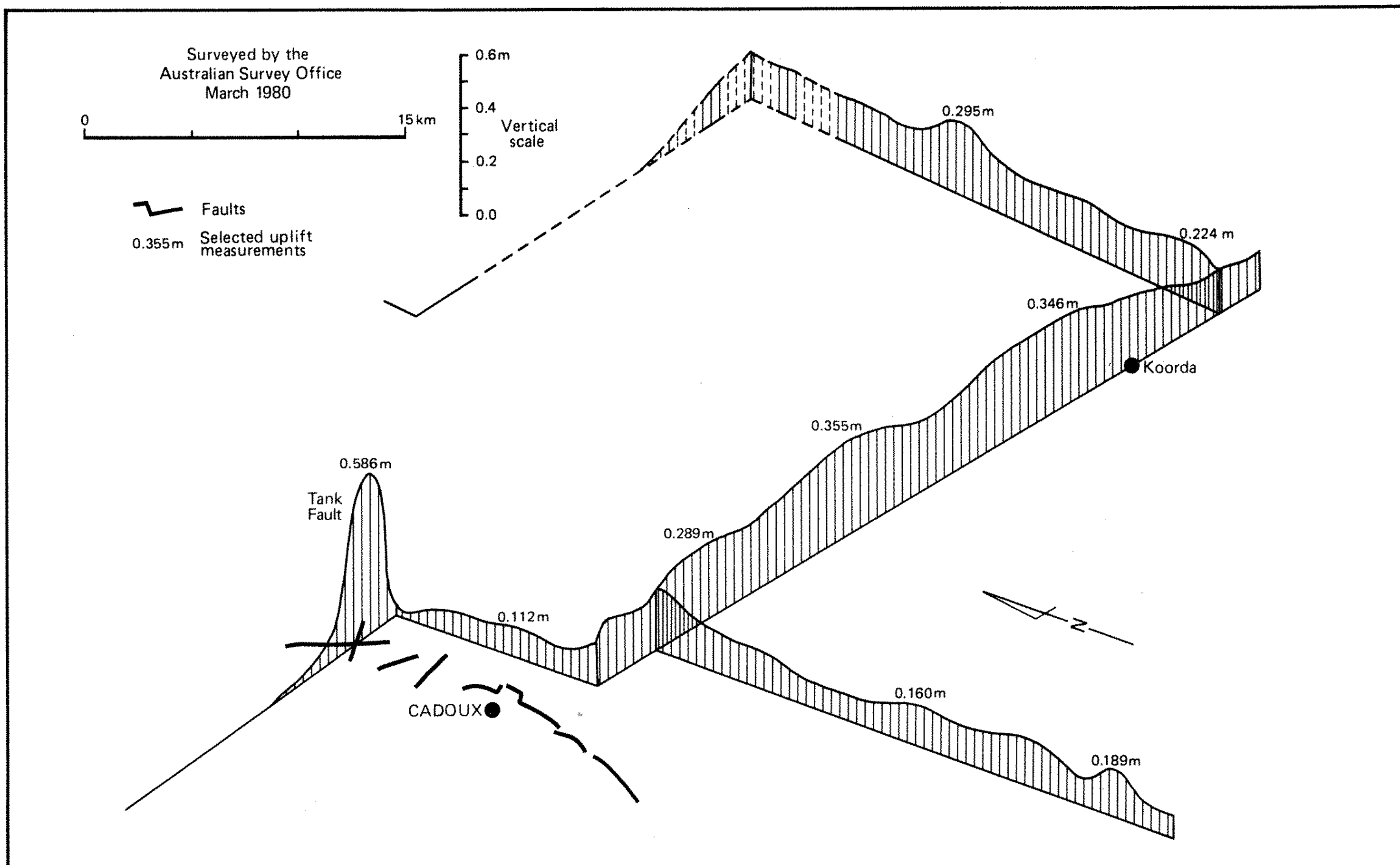
The northern margin of the uplifted area is similarly indeterminate, but benchmarks 27 km northeast of Cadoux show no uplift. Westward from the northern end of the traverse north from Koorda the uplift also diminishes to zero within about 5 km and it appears that uplift did not extend far to the north and northeast of Cadoux.

South from the Cadoux-Koorda traverse uplift continues for about 63 km to a point about halfway between Cunderdin and the main Dowerin-Wyalkatchem road. The maximum uplift is in the order of 0.16-0.18 m, and this reduces steadily to zero over the full distance of 63 km, giving a slope of only 2.6 mm per 1 km.

A feature of this traverse is that two groups of salt lakes are traversed, the Cowcowing Lakes between Dowerin and Cadoux, and the Salt River, a tributary of the Mortlock River, between Dowerin and Cunderdin. In both instances the uplift is greater than would be expected from the general slope of the ground distortion. Between benchmarks CK 48 and CK 45 (Table 12) the uplift is about 0.18 m, with values of 0.15 m and 0.10 m either side of the anomaly; similarly, at benchmark CK 23 (Table 13) the measured uplift is 0.07 m, with benchmarks either side uplifted about 0.04 m. The probable explanation for anomalously high values of uplift being found in topographically low areas is soil creep, but to what extent this was aided or caused by seismic shaking is unknown.

From the limited information available it is impossible to determine the shape, or full extent, of the area of ground distortion associated with the Cadoux Earthquake. However, the area is at least 90 km long from north to south and 45 km east to west. This large block of country, almost entirely to the east of the Cadoux Fault system, has been uplifted by at least 0.36 m.

The other unknown factor is the full amount of the uplift. The original survey of the pipeline, with which the post-earthquake levelling was compared, was made in 1963-4, but the process might have begun at any time before or after this date. Undoubtedly the uplift had accumulated over a period of time, in response to the nearly east-west stress-field present in the area (Denham and others, 1979);




GSWA 18755

Figure 24. Diagram of uplift along levelling traverses in the Cadoux-Koorda area (for details of benchmarks and measurements see Appendix II)

otherwise the isoseismals of the earthquake (Fig.4) would have been distorted eastwards, and Koorda, which was uplifted more than Cadoux, would have been severely damaged. The earthquake was a result of the uplift, not its cause, but there is only indirect evidence for the length of time over which the uplift may have been accumulating. Prior to 1968 the Cadoux area appears to have been aseismic. The swarm of small tremors recorded in that year was almost certainly connected with the uplift and may have marked its beginning. In the same year, however, following the Meckering earthquake, distortions were noted in levelling traverses through Dowerin (Gordon and Lewis, 1980), which suggests that the uplift might have begun somewhat earlier than 1968.

To the east of Dowerin a number of benchmarks surveyed after the Meckering Earthquake were re-occupied in 1981. In 1968 the deviation of benchmarks CK 34 - CK 40 from the original survey of 1963 was only $\pm$ 0.02 m, whereas in 1981 a nearly uniform uplift of about 0.06 m was measured (Table 13). In the earlier survey distortions of a similar magnitude were found between Dowerin and Goomalling but it appears that to the east of Dowerin the uplift began around 1968. The relationship between the ground distortion which preceded the Meckering Earthquake and that which preceded the Cadoux Earthquake remains unknown. All that is certain is that an uplift of 0.36 m has occurred in the Cadoux area since 1963.

*Cadastral surveys*

A number of east-west traverses across the fault zone were resurveyed (Fig. 25). These were principally along road reserves and were carried out by relocating boundary pegs, originally placed in 1911 at intervals of 200 m (10 chains). In addition, the Australian Survey Office also resurveyed the road through Cadoux townsite and the north-south railway and road reserve north of Cadoux. The Lands and Surveys Department resurveyed the boundaries of blocks within the Cadoux townsite. The data are summarized in

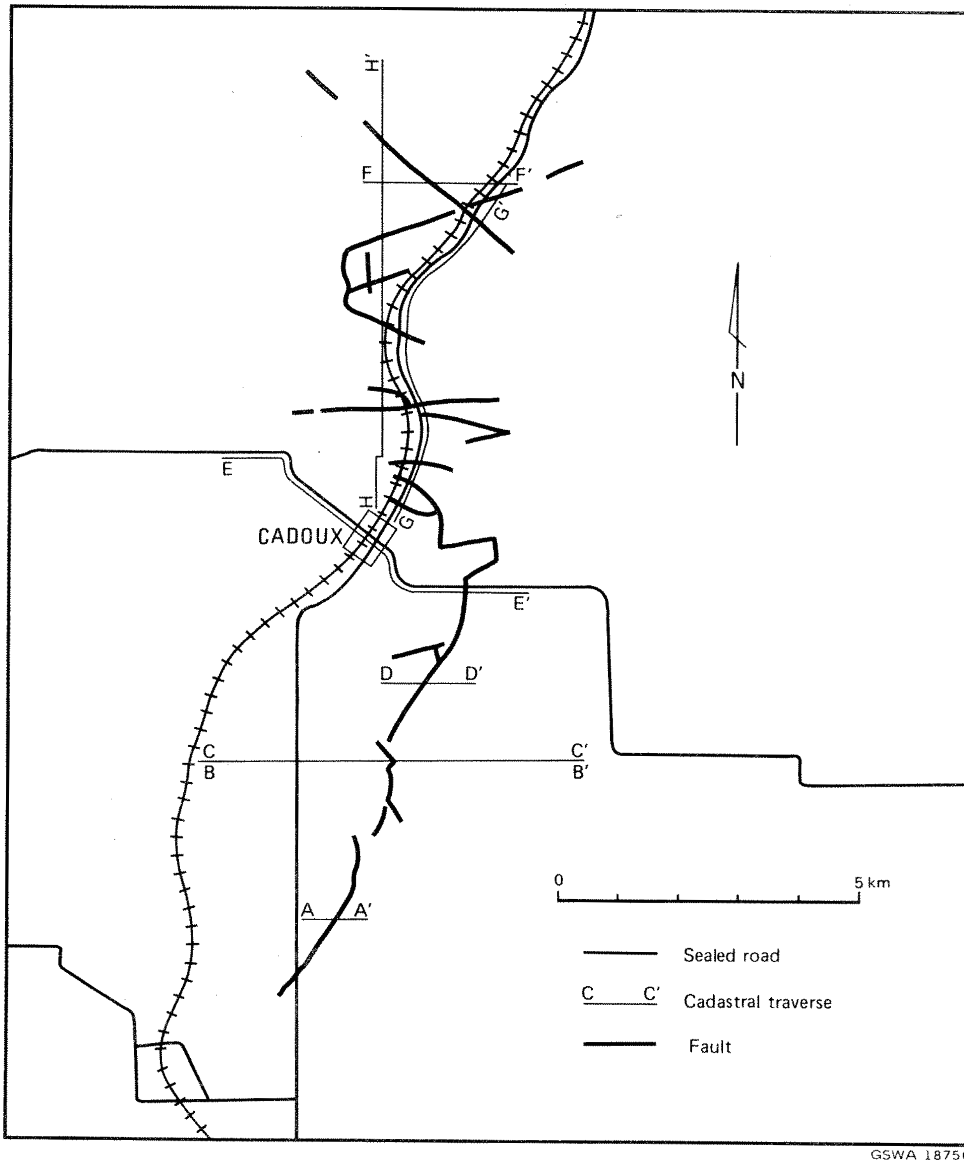



Figure 25. Location of cadastral traverses in the Cadoux Fault zone

Figures 26, 27 and 28, and full details may be obtained from the Australian Survey Office, Commonwealth Department of Administrative Services.

A total of five fence lines were surveyed across the Robb Fault (Figs 26 and 27), the most complete sections being along both sides of the road along the Wongan-Ballidu Shire boundary (Sections B & C) and the southern side of the Koorda road (Section E). Except for the Koorda road section (Fig. 27) all traverses showed horizontal movement at the fault scarp. The traverse along the Wongan-Ballidu Shire boundary was 6.8 km long (Fig. 26, Sections B & C) and at the fault showed a right-lateral translation of 0.20 m. A crustal shortening of about 0.8 m is also shown, mostly in the immediate vicinity of the fault, but including 0.3 m over a distance of 400 m to the east of the scarp. Away from the scarp small increases or decreases of survey length are mainly ascribed to survey errors, but occasional systematic changes on both sides of the road, and both east and west of the fault, probably indicate localized tension or compression. Excluding the fault zone the traverse showed an overall shortening of 0.36 m; including the fault zone the compression was 1.14 m.

The survey confirms the right-lateral strike-slip character of the Robb Fault, and allowing that the fault plane dips west, the simple picture of ground movement is that the mobile west block moved north relative to the east block. However, the survey also shows an apparent southward movement of both blocks, the west block by about 0.05 m and the east block by about 0.25 m, and that a small angle has developed between the two sections. Moreover, there is some curvature in the line, apparently drag induced, particularly on the north side of the road. These features could be explained by regional compressive forces causing buckling in the survey line followed by fracturing which rotated the east block anticlockwise, dragging the west block with it. But, remembering that the regional tilt recorded by levelling on the water supply pipeline was unlikely to be an instantaneous effect of the earthquake,

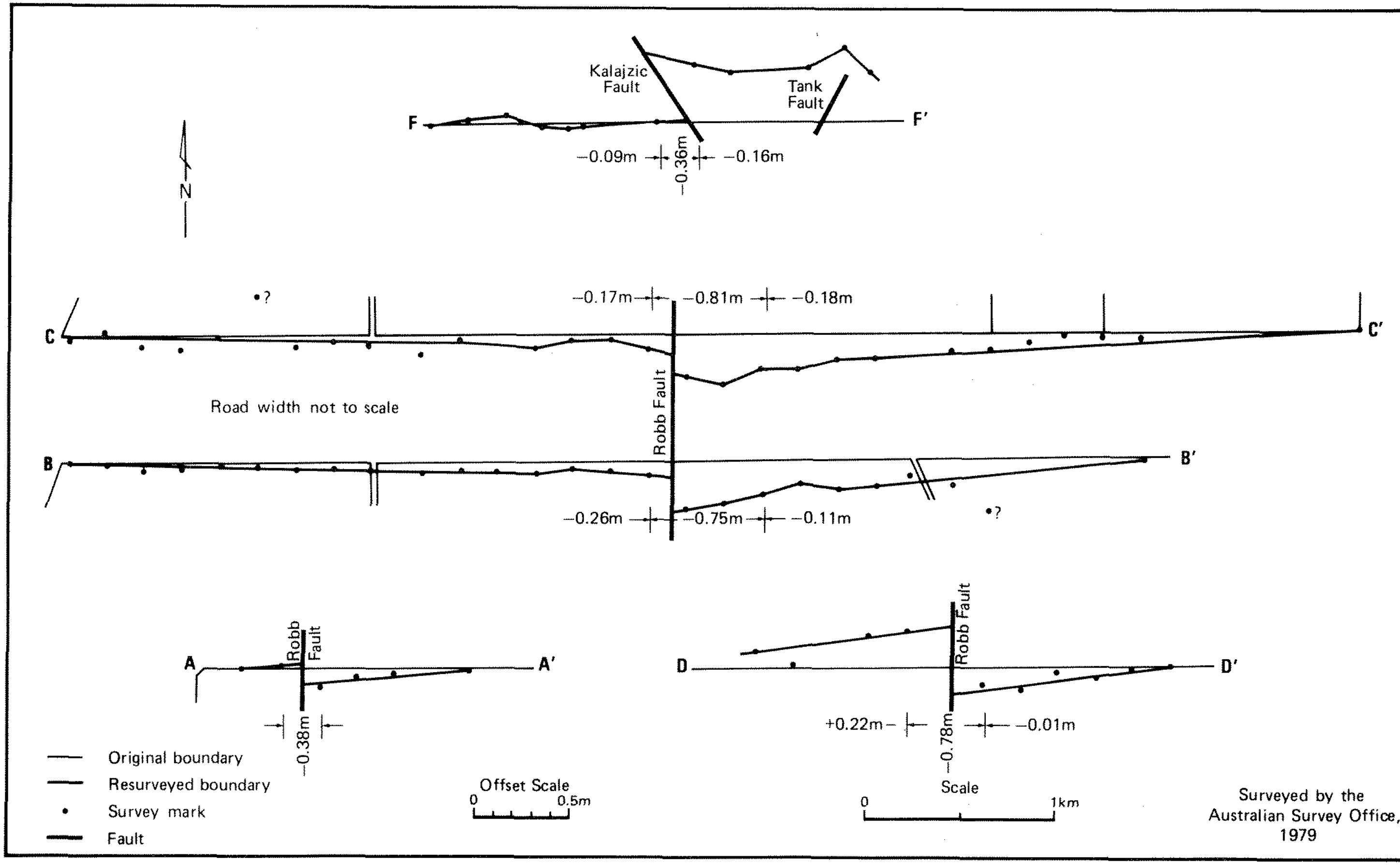



Figure 26. East-west cadastral surveys of lcoation boundaries across the fault-affected area. The offset of the new survey line is exaggerated x 1000 (for locations see Fig. 25).

it appears more likely that both the buckling near the fault trace and the southward distortion of the survey line accumulated over a period of years, and that the earthquake released this strain and allowed the western half to nearly recover its former position.

The angular displacement of survey lines is well seen on the southern side of the Koorda road (Fig. 27). On the northern side of the road a small right-lateral displacement was seen but this was not apparent on the south side. The resurvey confirms that although a shortening of 0.56 m took place there was no lateral displacement. Instead there is a southward distortion of the survey line with a maximum displacement of about 0.4 m east of the fault. From Plate 2 it will be seen that at the Koorda road the main trace of the Robb Fault disappears and is replaced by a right-lateral strike-slip fault trending about $070^{\circ}$.

Figure 27 also shows a ground distortion within the Cadoux townsite area. On the ground this was evidenced by several small fractures in the road surface near the school and by very minor fractures to the northwest of the grain silo. The Department of Lands and Surveys attempted to resurvey property boundaries within the townsite but many markers were not recoverable. The four major corner markers of the townsite, however, showed excellent agreement with the survey of 1929 and it would appear that the distortion noted within the townsite was very localized. Beyond the townsite towards Wongan Hills there appeared to be no further distortion.

North from Cadoux the resurvey of the eastern boundary of the road and rail reserve (Fig. 28, Section G) intersects most of the fractures of the conjugate faults which form the northern half of the Cadoux Fault system. The section extends from the northern boundary of Cadoux townsite to a little north of Kokardine water tank, a distance of 6.2 km, which overall had suffered no change in length. Within the section, however, the line had been compressed, extended, and offset by a number of faults.

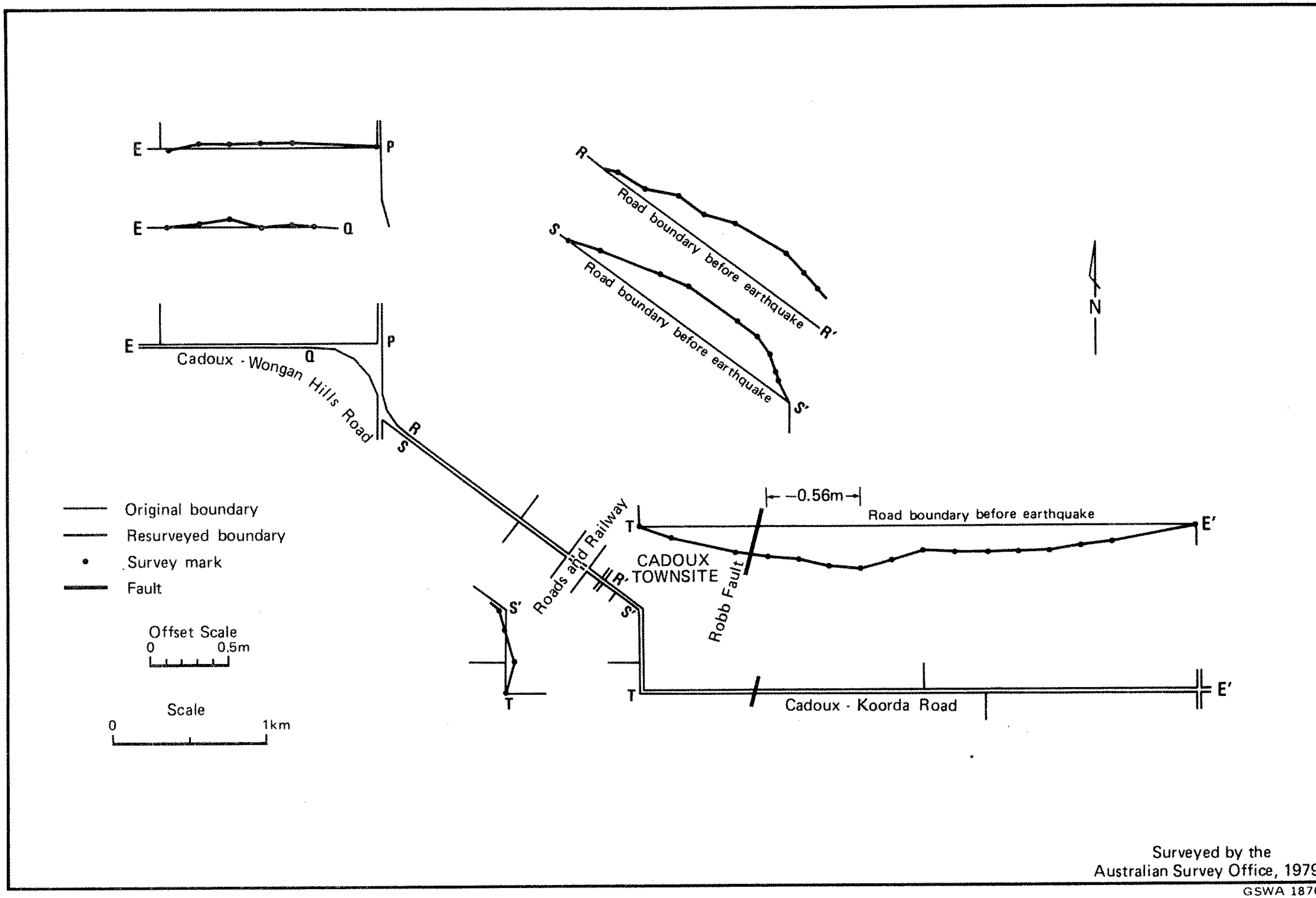



Figure 27. Resurvey of the Wongan Hills-Koorda road through Cadoux. The offset of the new survey line is exaggerated x 1000 (for location see Fig. 25)

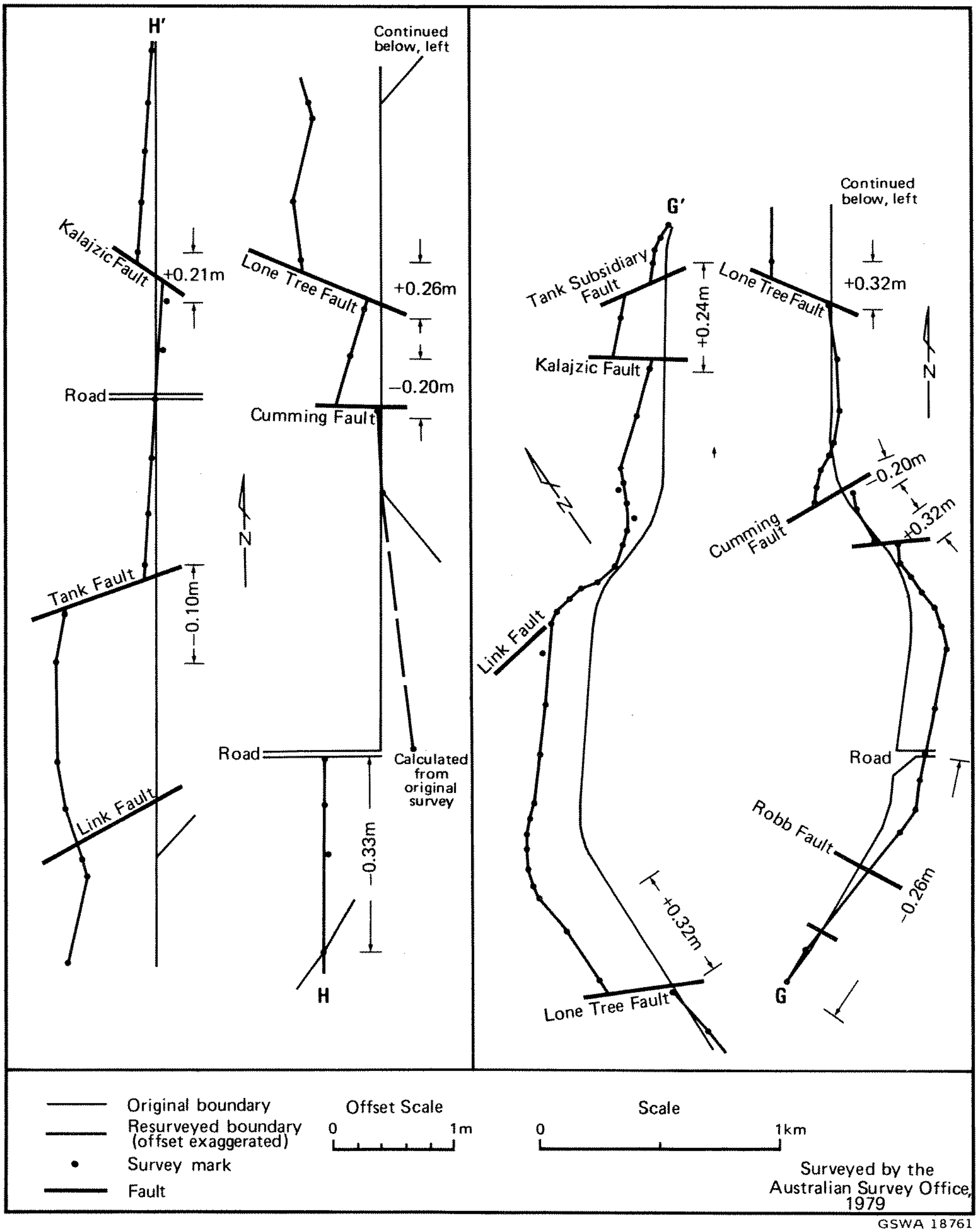



Figure 28. Resurvey of boundaries within the conjugate fault system north of Cadoux. The offset of the new survey line is exaggerated x 1000 (for locations see Fig. 25)

Where the Robb Fault cuts the road it has changed from a right-lateral reverse fault trending 020$^{o}$ to a small left-lateral reverse fault trending 295$^{o}$. An extension of 0.28 m was surveyed south of the fault and a compression of 0.47 m north of the fault. It would appear that most of the northward right-lateral movement of the Robb Fault has been absorbed in this area. No left-lateral step is seen at this point, as the direction of the survey line coincided with the resultant displacement. The direction is 033$^{o}$, the same resultant as calculated a little to the east (Table 3, point 6).

The Cumming Fault is seen to have an apparent left-lateral displacement of 0.29 m, much greater than was observed in the field. However, when allowance is made for the angle at which the survey line crosses the fault, and a shortening of 0.20 m in the same area, the displacement reduces to 0.19 m. The survey, together with an observed throw of 0.2 m enables the displacement of the fault to be calculated and the resultant is a displacement of 0.32 m towards 033$^{o}$ on a fault plane dipping 50$^{o}$ to the south. This result is not easily reconciled with the displacements of the conjugate faults to the north or the Robb Fault to the south and emphasizes the distinctive character of the Cumming Fault.

At all other fault intersections there is an apparent extension of the survey line despite the compressive nature of the faulting. This is because the survey was roughly north-south and the resultant block movement was east-west. Fault planes are steep and the effective north-south compression is negligible compared with the east-west displacement. At the Lone Tree Fault a left-lateral offset of 0.49 m remains for the next 1.5 km until the Link Fault is encountered. The Link Fault did not reach the eastern boundary of the road as a surface fracture and does not distort the survey line, but beyond it the offset decreases until the Kalajzic Fault is intersected.

Finally, the small wedge between the eastern ends of the Kalajzic and Tank Subsidiary Faults is seens to have moved westward, giving a left-lateral offset of about 0.34 m on the Kalajzic Fault and a right-lateral offset of 0.16 m on the Tank Subsidiary Fault.

The survey west of the road and rail reserve (Fig.28, Section H) shows many of the features described above except that the westward displacement of the fence between the Lone Tree Fault and the Tank Fault is up to 0.83 m. The Link Fault is again shown to be a minor feature, causing only a slight local decrease in the westward movement of the fault block. The termination of the Robb Fault and several small faults south of the Cumming Fault, all of which intersected the survey line, appear to have had little effect west of the railway.

The east-west traverse north of Kokardine tank (Fig.26, Section F) also cuts the Kalajzic and Tank Faults. In response to east-west compression the wedge between the two faults has moved relatively northwards and the survey line between the faults has been shortened by 0.55 m.

## REGIONAL DEFORMATION

From a knowledge of the pattern of faulting, surveyed displacements, and the mechanism of faulting, an integrated picture of regional deformation in the Cadoux area can be built up.

The fault pattern, and calculated resultant displacement, shows that on the Robb Fault the west block moved relatively northwards and eastwards over the east block, in the general direction of about 065$^{\circ}$, in close agreement with the direction of the stress field of 077$^{\circ}$ determined by Denham and others (1979) and the maximum pressure axis of 069$^{\circ}$ for the earthquake determined by Everingham and Smith (in prep.). At the northern end of the fault zone blocks within the conjugate fault set moved relatively east or west but with an overall small displacement of the east block westward over the west block. The Carter Thrust Zone is probably a response in the upper layers of rock to this westward displacement. The relative northward movement of the west block of the Robb Fault appears to have been absorbed in small fractures between the northern end of the fault and by the east-west Cumming Fault.

The focal-plane solution for the Cadoux Earthquake shows a steeply eastward-dipping right-lateral reverse fault on the same trend as the Robb Fault, suggesting that the east block is elevated with respect to the west. This is confirmed by the levelling traverse which shows a slope of 1.8 cm per km extending several kilometres east of the fault zone, and the east block, as far as Koorda, elevated by up to 0.36 m. In addition, the cadastral surveys across the Robb Fault indicate that prior to faulting a southward distortion had taken place. A plot of the depths of after-shocks (Fig. 6) shows that the east-dipping right-lateral reverse fault is terminated at several kilometres depth by a west-dipping fault which is presumably the fault seen at the surface.

It is unlikely that the vertical and horizontal ground distortions were formed instantaneously during the earth-quake. Most probably the strain built up over a number of years and the earthquake occurred when the strength of the rock was exceeded and the strain was relieved by fracturing. The process envisaged began with the build-up of the regional stress field which gave rise to creep on a deep-seated east-dipping right-lateral reverse fault. The process possibly began in 1968 and was marked by the occurrence of numerous small tremors. As creep on the deep-seated fault continued the unfractured block above the fault was carried southward by the right-lateral movement to give the distortions found on the Robb Fault by the cadastral surveys, and the regional east-to-west tilt was formed by the reverse movement. Eventually the strength of the surface rocks was exceeded and the strain was relieved by fracturing along the Robb Fault.

For the conjugate faults the dominant influence appears to have been the east-west pressure and the regional tilt. Strain in the surface block was relieved by fracturing along a number of small faults which form a conjugate set of fractures, resulting in a pattern of small interfingering fault blocks. In response to the regional tilt the eastern fault blocks were elevated with respect to the western blocks.

A simplified picture of the process would be that an arch or monocline was formed by east-west pressure and subjected to right-lateral shear from a north-south couple. The Cadoux Earthquake occurred as the arch shattered, and the fault pattern produced depended on the locally dominant force and the presence or absence of pre-existing lines of weakness.

In the conjugate fault set there were indications that faulting may have occurred previously on the same fractures. The whole fault system lies along a watershed and it appears probable that the process of uplift in the Cadoux area implied by the scheme outlined above has been of long continuance.

## EARTHQUAKE DAMAGE

The faulting associated with the Cadoux Earthquake damaged and disrupted a number of public facilities in the immediate vicinity of the town, in particular the water-supply, telephone services, roads and railways. Seismic shaking damaged buildings over a wider area, the damage varying from minor cracks in walls and floors to total collapse. It is clear that the type of structure involved had a greater influence on the damage sustained than did proximity to faults. It is also apparent that all structures of a similar basic construction did not necessarily react in exactly the same manner. For instance, the foundation construction, type of bricks and mortar used, quality of workmanship, and age, all had some influence on the response of unreinforced brick buildings in the area to the earthquake shaking.

CADOUX TOWNSHIP

The town of Cadoux has a resident population of about 30 and consists largely of public buildings servicing the scattered farming community of the district. In addition there are two general stores, a filling station and a small number of private dwellings. The major structure in the township is the grain-storage facility operated by Co-operative Bulk Handling Limited. The construction materials of the major buildings varied from the older asbestos and concrete blocks of the Town Hall, to modern brick-and-tile structures and the reinforced-concrete grain-storage facility. A preliminary appraisal of damage to public buildings was made by the Architectural Division of the Public Works Department (Naismith, 1979), and it was noted that in a number of cases damage was accentuated by poor workmanship.

The eastern section of the Cadoux Town Hall was constructed of a timber framework with fibrous asbestos sheeting and this part of the structure was not extensively damaged by the earthquake (Fig. 29). On the other hand the western end of the building consisted of the roof supported by vertical steel poles along its northern and southern sides, and the western gable end constructed solely of concrete blocks and mortar. The northern and southern walls were also of concrete blocks, but in contrast to the western wall, they were not load bearing. As a result of the earthquake, the southern wall was extensively cracked and disturbed, while the northern blockwork wall collapsed outwards, leaving the steel roof-support still standing alone. The western wall also collapsed, and because this wall was supporting the roof, the roof itself was also extensively damaged.

The Masonic Lodge was constructed of unreinforced silica-bricks with a heavy tile roof (Fig. 30). The building suffered almost total collapse.


Figure 29. Cadoux Town Hall: the western wall and the block wall on the northern side have suffered total collapse. The frame structure at the rear of the building remains intact (GSWA 18762)

The Cadoux Recreation Complex is situated at the southern end of the town and the main clay-brick and corrugated-sheet roof structure was severely damaged (Fig.31)

Cadoux School is of framed construction, and did not suffer major damage. However, the brick chimneys of the building collapsed. They toppled in a northerly direction and fell through the corrugated asbestos sheet roofing into the classrooms. Interior fibrous plaster sheeting to ceiling and walls suffered minor damage and there was some movement of outside walls away from the floor.

Figure 30. Cadoux Masonic Lodge: the western walls collapsed westward causing partial collapse of the roof (photo: W.A. Newspapers) (GSWA 18763)

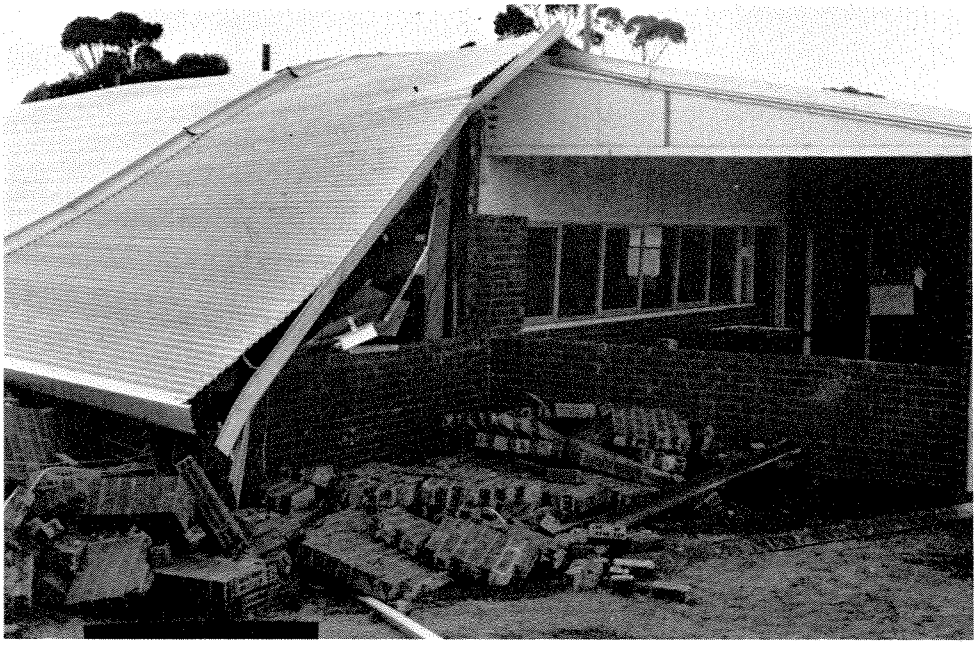


Figure 31. Cadoux Recreation Complex (GSWA 18764)

*Co-operative Bulk Handling Limited grain storage facility*

Damage to the grain-storage and loading facility adjacent to the railway line in Cadoux (Plate 2) was inspected by the consulting engineers to Co-operative Bulk Handling Limited, MacDonald, Wagner and Priddle Pty Ltd. The structures sustained minimal external damage, such as cracking along expansion joints between the concrete wall panels. Internal damage was more significant, although no catastrophic failure occurred. The major damage was done to the steep roof trusses of the main storage area. These trusses are aligned approximately east-west, and appear to have undergone compression (Fig.32). Other minor damage reported at the facility comprised break-up of mortar pads at the junction of the flexible steel members and the relatively inflexible walls, cracking of grouted supports to structural steel members, displacement and loosening of conveyor belt idlers, cracking and spalling of some concrete surfaces, and cracking and heaving of paved surfaces. The seismic shaking also displaced a number of man-hole covers and lifted the heavy steel platform of the nearby weighbridge from its bearings.

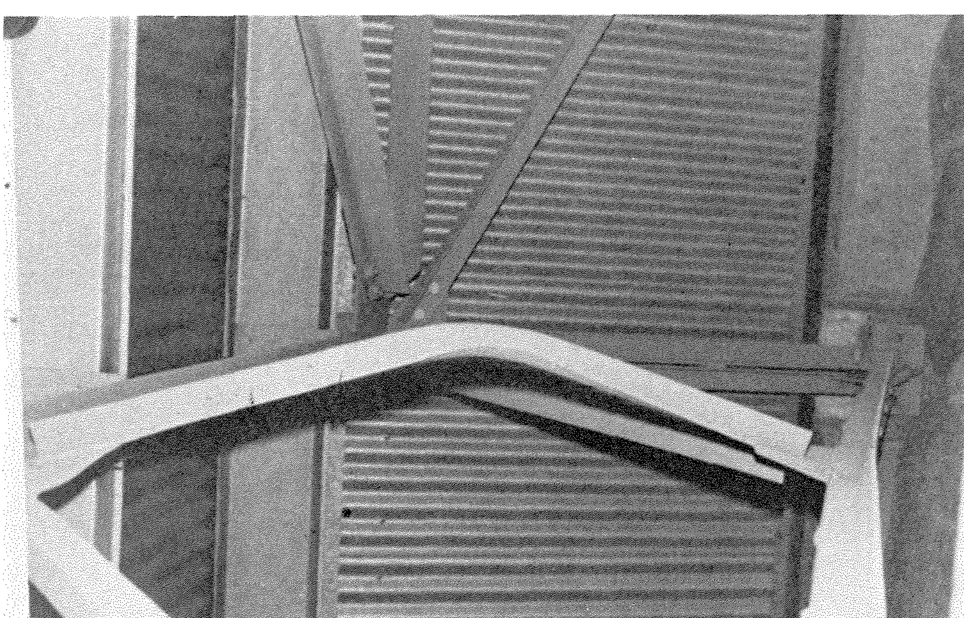


Figure 32. Distorted roof trusses, Co-operative Bulk Handling grain storage facility (GSWA 18765)

Earthquake damage to the facility has been repaired at a cost of $40 000.

## DOMESTIC DWELLINGS

The distribution of houses damaged by the earthquake is shown in Figure 33 and the relationship between type of construction and degree of damage is shown in Table 4. The resilience of frame-type structures to earthquake shock and the susceptibility of unreinforced brick (and concrete/stone block) structures to earthquake damage are well known, and is demonstrated again by the Cadoux Eathquake. Although the categories used in Table 4 are broad it is significant that of 25 masonry dwellings inspected 21 suffered more than minor damage, whereas out of 29 non-masonry frame-type dwellings only 4 suffered more than minor damage.

TABLE 4. DAMAGE TO PRIVATE DWELLINGS IN THE CADOUX AREA

| *Type of Construction* | *No. of buildings surveyed* | *No. demolished, or beyond economic repair* | *No. with extensive damage* | *No. with significant damage* | *No. with minor damage* |
|---|---|---|---|---|---|
| Non-masonry | 29 | - | - | 4 (a) | 25 (b) |
| Masonry | 25 | 6 (c) | 3 | 12 (c) | 4 |
| Mixed | 5 | - | - | 5 | - |
| Total | 59 | 6 | 3 | 21 | 2 |
| Percentage of all dwellings | | 10.2 | 5.1 | 35.6 | 49.1 |

*(a): Includes one steel-frame house and two timber-frame houses where minor associated masonry structures suffered extensive damage.*

*(b): Includes two steel-frame houses and four timber-frame houses where minor associated masonry structures suffered extensive damage.*

*(c): Includes one house of brick veneer with timber frame.*

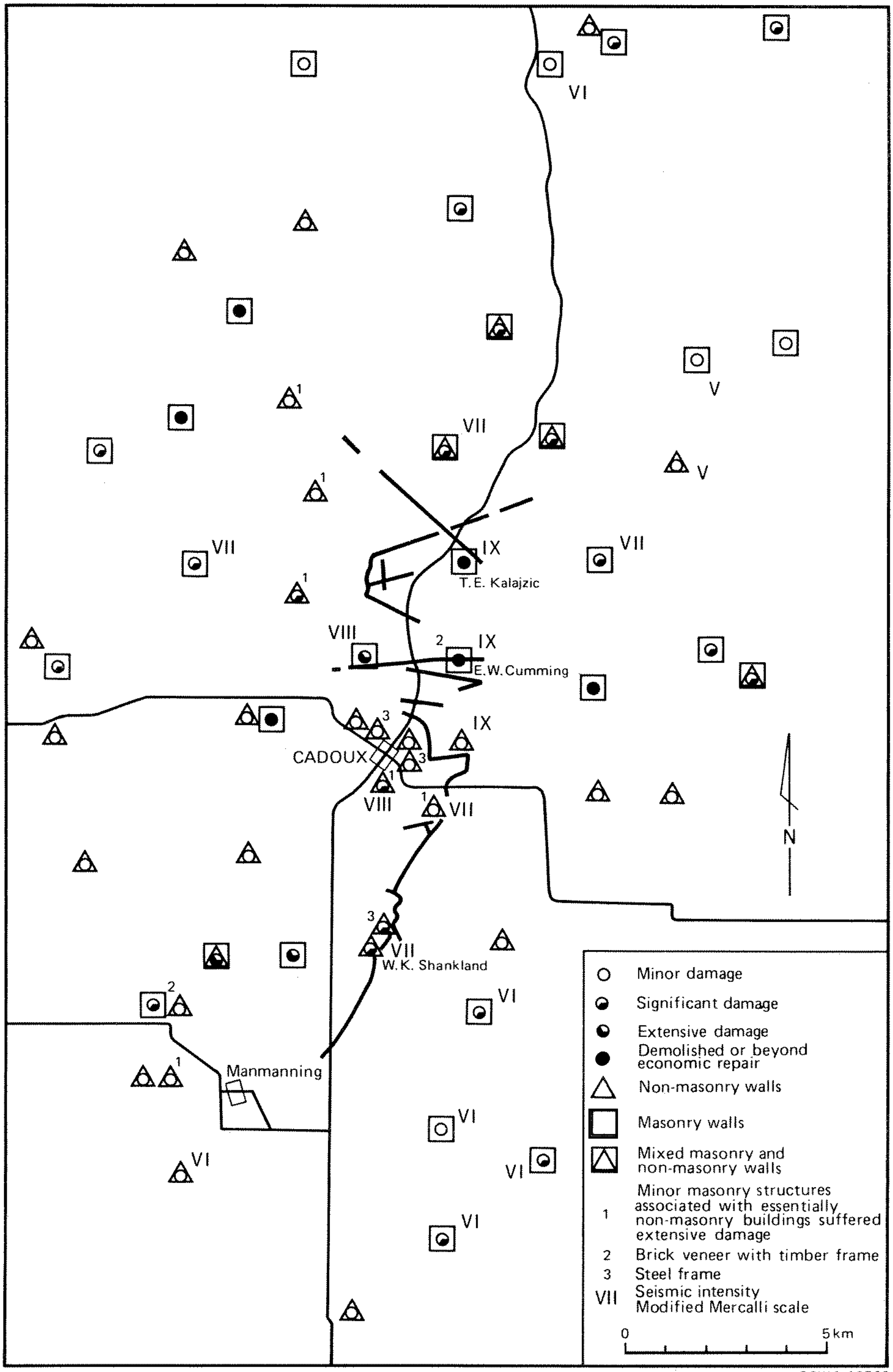



Figure 33. Damage to private dwellings in the Cadoux area

The different responses are illustrated by comparison of the steel-frame transportable home on the property of W.K. Shankland (Fig. 11) and the brick-built house on the property of T.E. Kalajzic. A small thrust fault passes directly beneath the Shankland house and, although the frame is slightly warped, no catastrophic failure occurred. Conversely, the nearest fault is some 150 m from the Kalajzic house, and yet this unreinforced brick-and-tile structure was completely demolished. It was in this house that the only significant injury caused by the earthquake was recorded - a child had an arm broken by falling masonry.

The effect of the earthquake on a dwelling of masonry construction with a lightweight roof is illustrated (Fig. 34) by the house of Mr. E.W. Cumming, under which the Cumming Fault passes. The verandah timbers support the corrugated iron roof intact, in contrast with the brickwork which collapsed.

Figure 34. Damage to the house of Mr. E.W. Cumming: brick-work has collapsed while the timber-framed verandah and roof have remained intact (photo: W.A. Newspapers) (GSWA 18767)

The distribution of damaged property illustrated by Figure 33 shows that major damage, except for a few isolated brick houses, was confined to a small area close to the faulting. Further than about 6 km from the faults damage was minor or negligible. From the Modified Mercalli intensity ratings for the seismic shaking, also plotted on Figure 33, it will be seen that the most damaging shaking, of intensity MMVIII - IX, was confined to a small area from Cadoux northwards.

## PUBLIC WORKS DEPARTMENT FACILITIES

### *Kokardine tank*

A Public Works Department (PWD) water tank of 9 000 $m^3$ capacity at Kokardine, some 6 km north of Cadoux, was severely damaged (Daetwyler, 1979). The tank consists of a circular reinforced concrete wall resting on a reinforced concrete base. To allow for differential thermal movement of the wall, the butt joint between wall and base was sealed by a rubber water stop. The tank failed due to lateral movement of the wall as a whole, which sheared the water stop. (Fig.35). The total movement was 0.42 m in a direction of $348^{\circ}$.

The tank has been repaired by fitting an internal water seal within the tank, after investigations had determined that the tank foundations had suffered no significant damage due to either the earthquake shock or the sudden release of water.

### *PWD pipelines*

Earthquake-induced pipeline damage has been reported by the PWD (Gugich, 1979). Damage included cracking and displacement of the reinforced concrete supports, and dislocation of the pipe itself, resulting in warping and telescoping under compression, and separation of the pipe at welded joints under tension. The location of these damaged areas is shown on Figure 36.

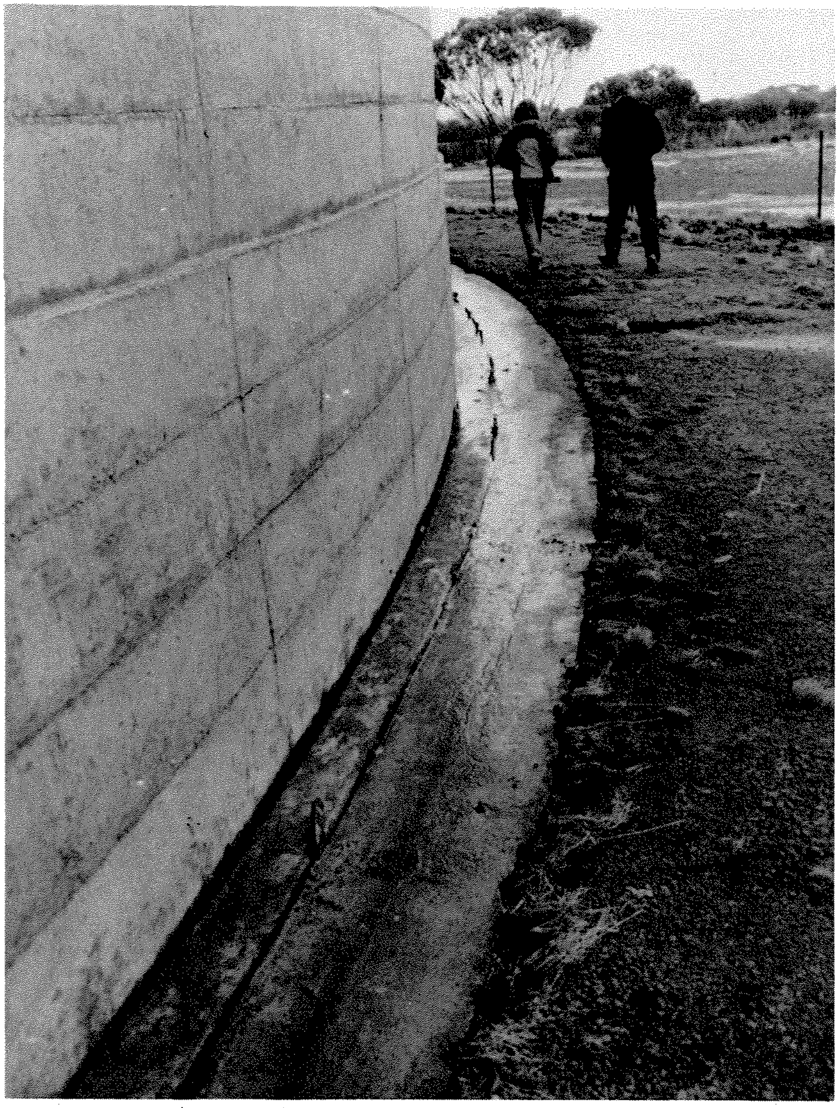



Figure 35. Damage to the Kokardine water tank: note the ruptured neoprene rubber water seal (photo : W.A. Newspapers) (GSWA 18768)

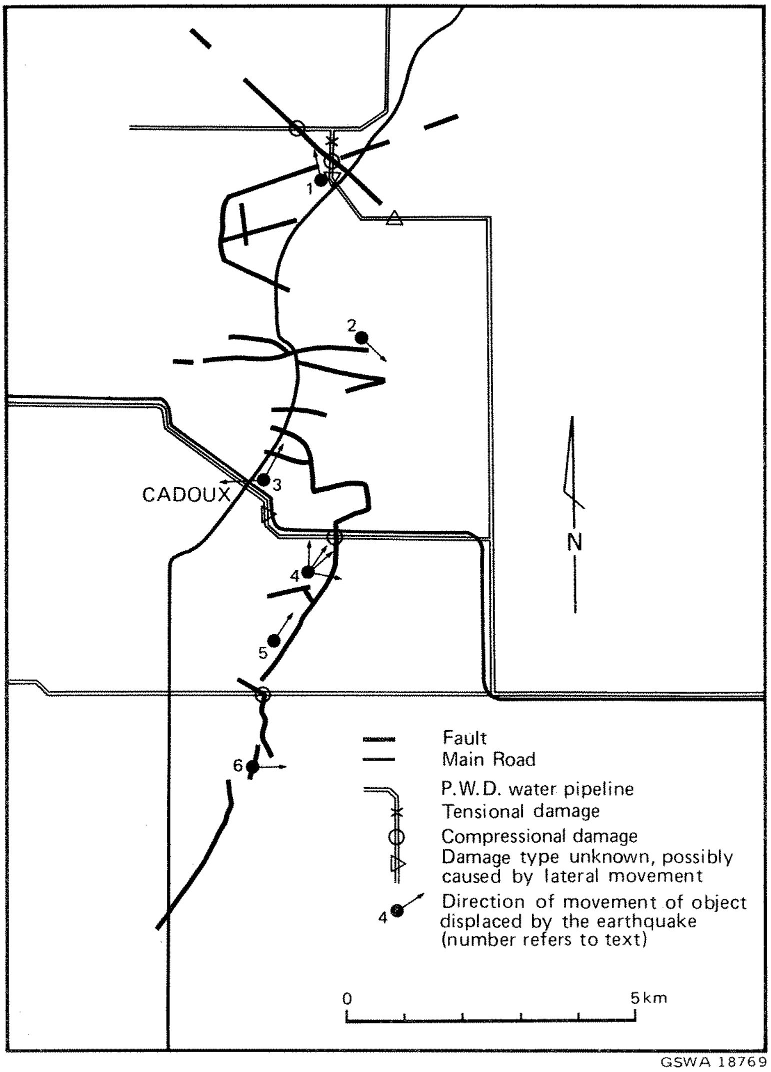



Figure 36. Location of damage to water pipelines, and of objects displaced by the earthquake

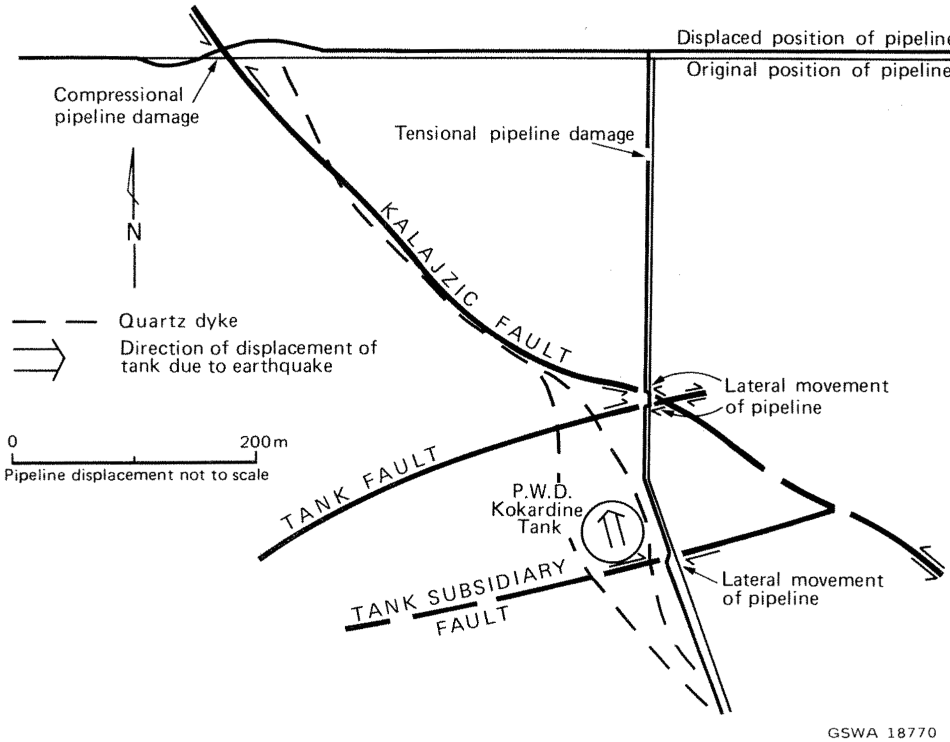



Figure 37. Earthquake damage to PWD pipelines in the vicinity of Kokardine tank. Relative movements are shown assuming the wedge between the Kalajzic and Tank Faults has remained stationary

The damage to the pipework in the vicinity of the Kokardine tank was complex, because of the conjugate fault set in the area (Fig. 37). The principal damage was due to movement on the Kalajzic Fault, which intersects pipelines in two areas north of the tank. The more westerly area showed compressive damage (Fig. 38), as a result of the mechanism illustrated in Figure 39a. The more easterly intersection resulted in a tensile break in the pipeline, some distance from the actual fault which caused the damage. This was due to the pipe failing at its weakest point, which in this case was a factory-produced weld. Minor damage was sustained to pipe supports 1.4 km southeast of the tank where a probable continuation of the Kalajzic Fault again intersects the pipeline (Fig. 36). Pipe-supports were also damaged where the Tank Fault and the Tank Subsidiary Fault intersect the pipeline (Fig. 37).



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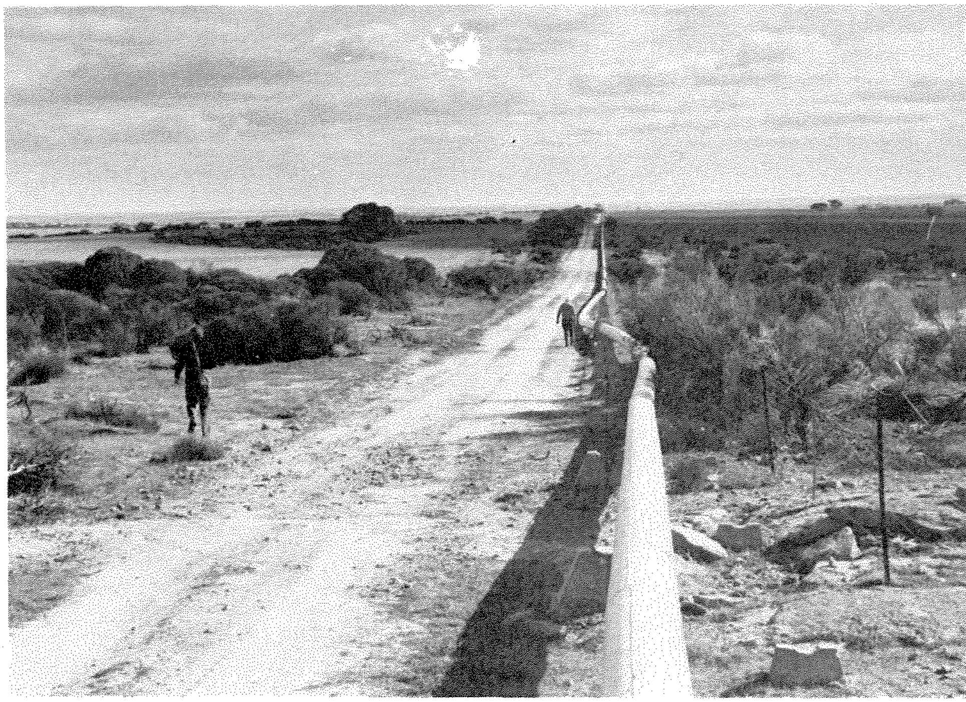


Figure 38. Damage to water pipeline where it crosses the Kalajzic Fault: the pipeline has failed through left-lateral movement and compression (see Fig. 39a) (GSWA 18771)

Pipeline damage occurred at three other locations south and east of Cadoux (Fig. 36). Two of these involved a buried main running parallel to the Koorda road; the more easterly was a compressive break, associated with the Robb Fault, but the more westerly break was not seen to be directly related to any specific fault.

The remaining break in a pipeline occurred in a buried main running parallel to the road marking the boundary between the Wongan-Ballidu and Dowerin Shires. The failure was again directly associated with the Robb Fault and took the form of 'telescoping' of the pipes, and necessitated the replacement of 124 m of pipeline. An estimated 0.175 m of lateral compression occurred over this length. One break occurred on strike with, and to the south of, the minor forethrust in the paddock north of the road. No surface expression of this feature was seen in the vicinity of the pipe break.

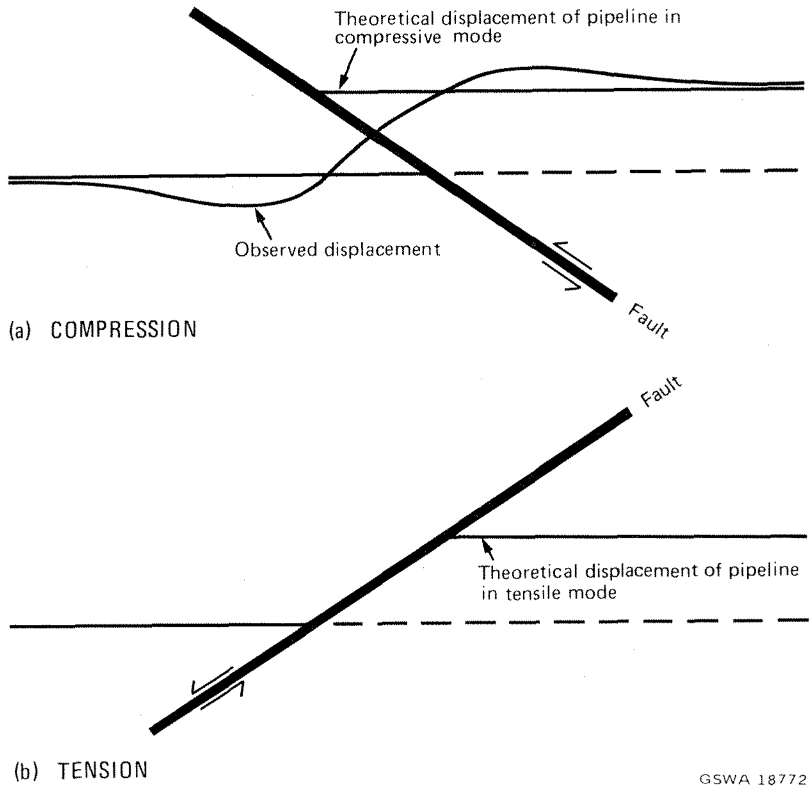



Figure 39. Differing modes of failure for a pipeline crossing a left-lateral strike-slip fault

## TELECOM FACILITIES

### *Cadoux Exchange*

The location of the telephone exchange is shown on Plate 2. The structure consists of a steel-framed transportable hut resting on four metal stumps such that the floor is some 0.3 m above ground level. The earthquake moved the hut off the stumps, causing damage to the internal equipment. The telephone system was quickly restored to working order after the main earthquake, but was disrupted a second time by the major aftershock which occurred on Sunday 3rd June. The exchange building was re-positioned a few days after the main event and was found to have moved 0.77 m in a direction of $027^{\circ}$.

*Telephone cables*

All breaks in the buried cables occurred north of Cadoux, and can be related to individual strike-slip faults. A number of faults intersected cables but did not damage them (Fig. 40). Two cable breaks were caused by the Kalajzic Fault, confirming it as the most destructive feature of the earthquake. A break in the cable serving the Cumming house appears to have been caused by the most northerly of the minor faults between the Robb and Cumming Faults. A fourth cable break occurred on the line to the Hopkins house, and appears to be related to the strike-slip fault which was mapped immediately west of the break. It is interesting to note that this fault failed to break a cable at a point where the fault was conspicuous, yet it broke the same cable where no surface expression of the fault was seen.

The conjugate faults immediately north of Cadoux intersect a buried cable, and no cable damage has been noted. Two thrust faults cross buried cables south of Cadoux without damaging them. The compressive nature of the faulting probably allowed the cable to flex, accommodating the ground movement.

## ROAD AND RAILWAYS

Damage was sustained to the main road and railway north of Cadoux, where the two run parallel. This damage was due to the conjugate reverse strike-slip faulting in the area, which produced dislocations of up to 0.8 m laterally and up to 0.5 m vertically.

*Roads*

A total of 20 disruptions of the sealed road around Cadoux were recorded, ranging from major vertical steps to minor tension cracking. The locations of the disturbed sections of road are shown on Figure 40. Breaks numbered 2, 3, 5, 6, 7, 9, 10, 12, 14, 15 and 19 were all directly related to earthquake faulting.

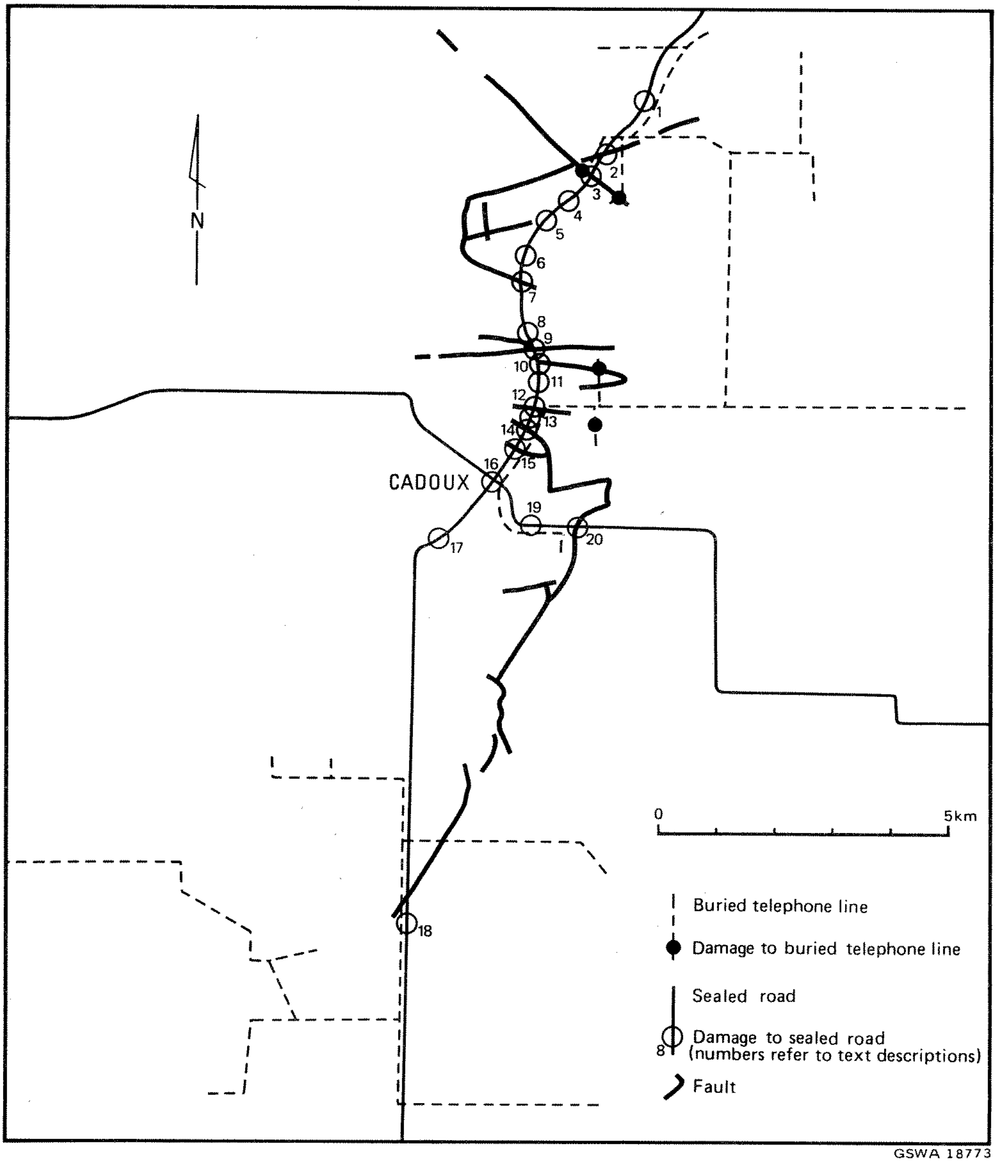



Figure 40. Location of damage to roads and buried telephone cables

Figure 41. Road damage at the scarp of the Cumming Fault (photo: W.A. Newspapers) (GSWA 18774)

Breaks 1, 4, 8, 11, 13, 16, 17, 18 and 20 could not be directly related to any obvious earthquake features in their immediate vicinity. These breaks consisted of small tension cracks and the possibility of some of them pre-dating the earthquake cannot be excluded. Typical road damage is shown in Figure 41.

*Railways*

Considerable disruption was caused to the Westrail track which runs north of Cadoux to Kalannie. Re-levelling and track re-laying was necessary in the wake of the earthquake. Typical damage is shown in Figure 42.

## DISPLACEMENT OF STRUCTURES

A number of structures were displaced as a result of the earthquake and their location and direction of movement

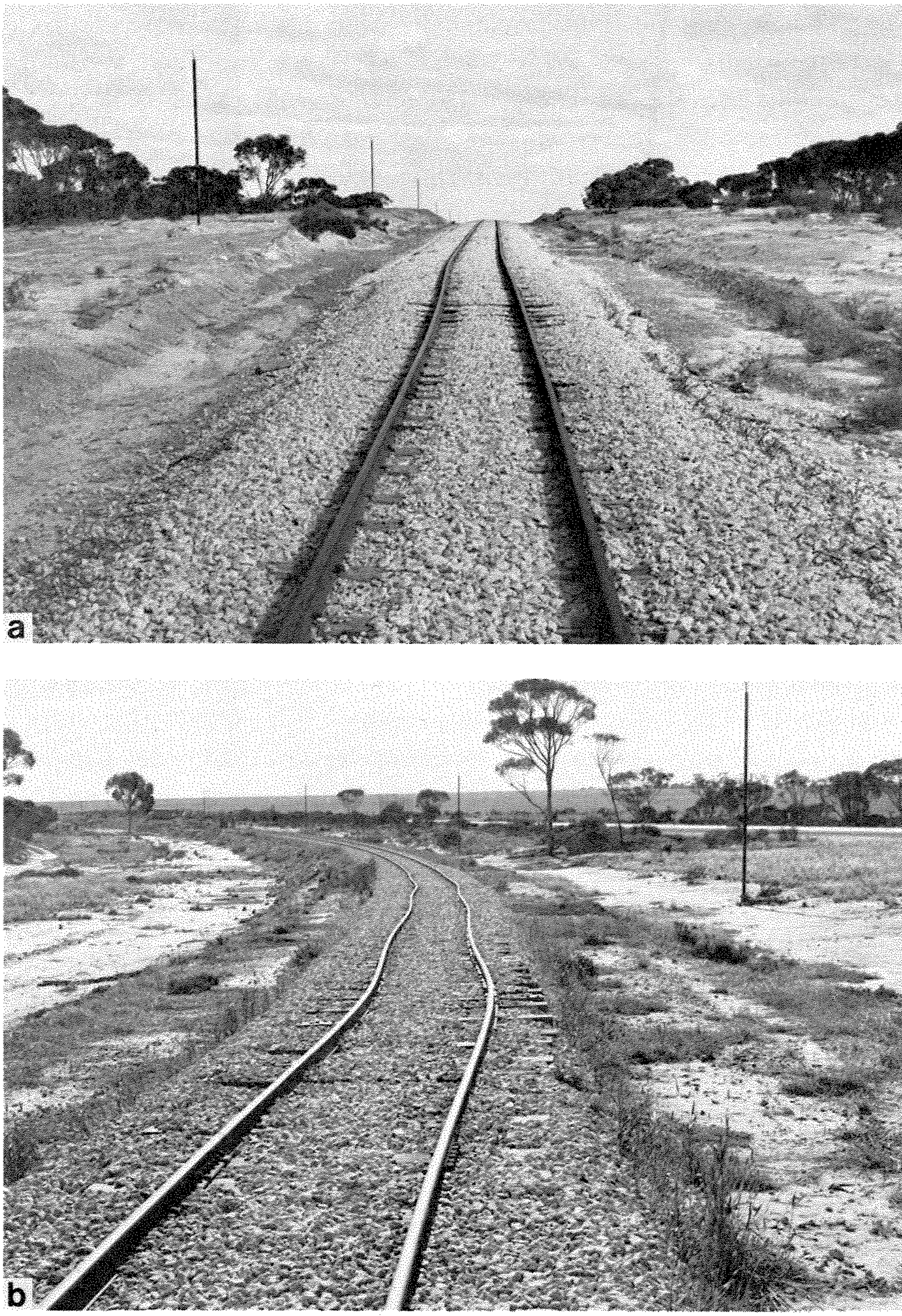
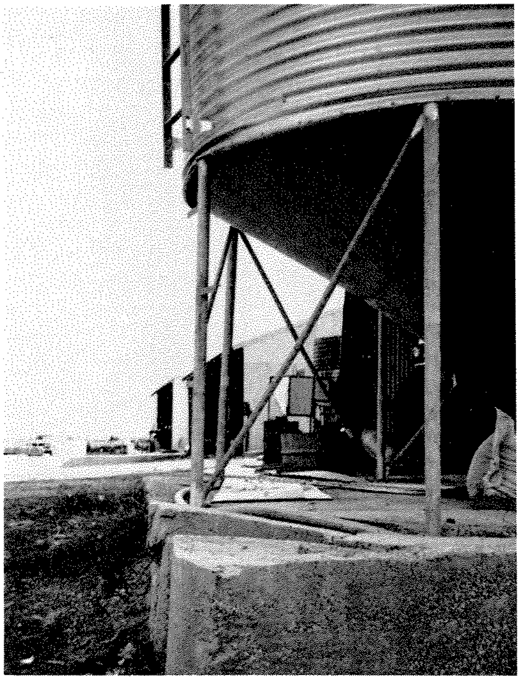



Figure 42. Damage to the railway line north of Cadoux: (a) vertical and left-lateral displacement at the Kalajzic Fault, (b) compressional damage about 1.3 km north of Cadoux (GSWA 18775)

are recorded on Figure 36. The direction of displacement of many structures was constrained by their construction. In Cadoux township the east and west walls of the Town Hall collapsed, leaving the north and south walls damaged but still standing. This suggests a strong east-west component of shaking, but does not give the actual direction. Chimneys were often sheared off at the roof line, probably due to differential movement between the structure and the chimney breast; the direction of fall is therefore probably not diagnostic of the direction of seismic shaking. A number of structures, however, were relatively free-standing and therefore give some indication of the direction of shaking.

Within the conjugate faults north of Cadoux only two structures were displaced. The PWD tank at Kokardine (point 1, Fig. 36) was displaced 0.42 m in the direction of 348$^{\circ}$; this shows no correlation with the displacement of the faults in the area, which was approximately east-west. The preservation, in part, of the original water seal (Fig. 35) may indicate a vertical component in the shaking. Damage to a grain silo on the Cumming property (point 2, Fig. 36; and Fig. 43) may also indicate vertical motion. The concrete slab on which the silo stands was badly damaged and there was a lateral displacement of the silo of 0.15 m to the southeast. The movement on the nearby Cumming Fault was predominantly northwards.

On the upthrust block to the west of the Robb Fault a fairly consistent displacement direction to the northeast is apparent, with a few structures moving northwards and westward. In Cadoux township (point 3, Fig. 36) the Telecom exchange showed a displacement of 0.77 m in the direction of 027$^{\circ}$, and a transportable house moved about 0.06 m westward on its supports. In the Robb farmyard, south of Cadoux, (point 4, Fig. 36) the base of a wheat silo moved in the direction of 001$^{\circ}$, while the tower itself collapsed in the direction of 047$^{\circ}$ (Fig. 44). Nearby, a truck rolled 0.8 m backwards, in the direction 002$^{\circ}$, while its load was lifted out of the tray and displaced 0.2 m westwards. A fuel bowser some 100 m southeast of the silo was found to have



**a**

**b**

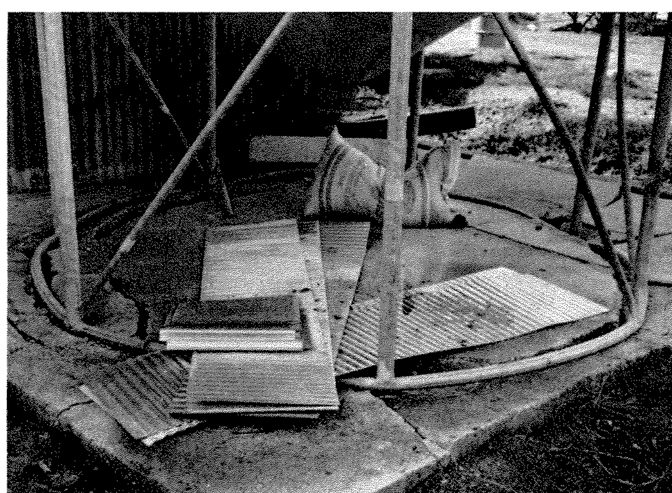


Figure 43. Damage and displacement of a wheat silo on the property of E.W. Cumming: (a) looking west, the concrete slab support has been badly damaged, (b) looking northeast, the silo has been displaced to the right of the photograph (GSWA 18776)

Figure 44. The collapse of a wheat silo on the Robb property: the silo has fallen to the northeast (047°) while the base has moved north (001°) (GSWA 18777)

been displaced a distance of 0.21 m in the direction of 035° (Fig. 45). In the Robb farmhouse a gas cooker had been displaced 0.16 m in the direction of 100°, and rotated clockwise about 6°. About 1 km south of the Robb farmyard a fuel bowser was found to have fallen in the direction of 035° (point 5, Fig. 36; and Fig. 46). Finally, a transportable house, which straddled a branch of the Robb Fault on the Shankland property was directly displaced a small distance eastward by the fault movement (Fig. 11; and point 6, Fig. 36).

The northeasterly displacements on the block west of the Robb Fault are consistent with the simple picture of a right-lateral thrust movement on the fault, but the direction of 027°-047° is more northerly than the resultant displacement of the fault which was generally towards 075°.

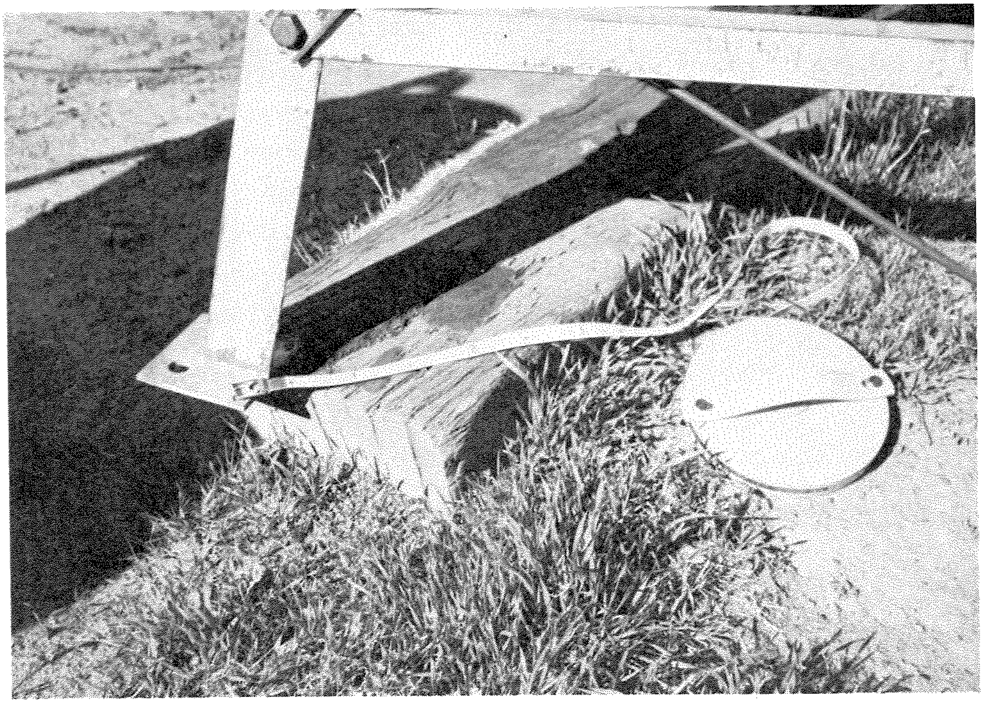


Figure 45. Movement of a fuel bowser in the Robb farmyard: a displacement of 0.21 m is visible for the foot of the structure (GSWA 18778)

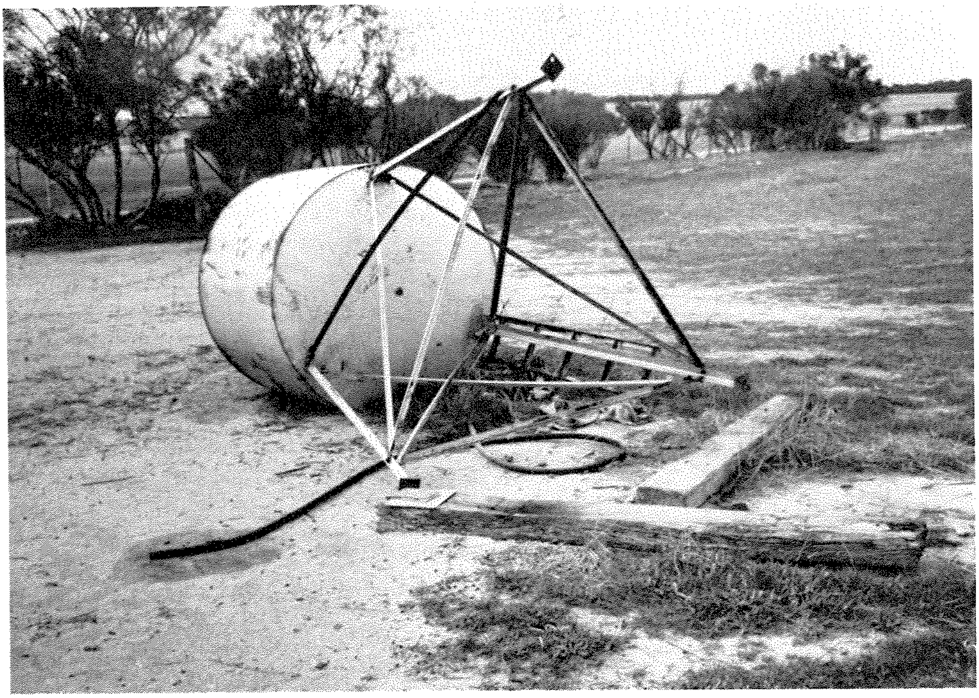


Figure 46. Overturned fuel bowser on the Robb property, looking northeast (GSWA 18779)

The east and west displacement of transportable houses may indicate that these structures were constrained in their direction of movement, but the northerly movement of two structures indicates that there was a stronger northerly component in the initial seismic shaking than in the final resultant movement of the Robb Fault. This may be a reflection of the predominant strike-slip movement of the unseen major fault which is believed to underlie the Cadoux Fault System.

## DAMAGE CAUSED BY AFTERSHOCKS

Aftershocks continued to shake the Cadoux area, with decreasing frequency, for several weeks after the main earthquake. Of these, only one, at about 2.50 pm on 7 June, is known to have produced damage and surface effects. Farm buildings 6 km southwest of Cadoux, on the properties of W. Shankland and J. MacNamara, lost brick chimneys; a silo was damaged; new cracks appeared in walls, and damage from the main earthquake was made worse. Minor damage was also reported from a farm property 10 km west-southwest of Cadoux.

Mr and Mrs Shankland reported that south-southeast-trending cracks opened up in their driveway (5 km south-southwest of Cadoux), and bulges appeared in a field 5 km southwest of Cadoux. Neither of these effects was visible a few weeks later.

Damage due to the aftershock of 7 June defines a linear trend, bearing $100^{\circ}$.

## DAMAGE OUTSIDE THE EPICENTRAL REGION

No examination was made of properties outside the epicentral region that reported damage from the Cadoux Earthquake. Beyond a radius of about 15 km from the epicentre damage was slight; mainly small cracks in walls or plaster. Even in the Perth metropolitan area, 180 km from the epicentre, such damage was commonly reported.

However, much of this damage represented the reopening of cracks that first appeared during the Meckering Earthquake of 1968.

Many tall buildings in Perth swayed during the Cadoux Earthquake but the only damage reported was the loss of mercury from the Rottnest Lighthouse. The lighthouse mirror floats in a bath of over 200 kg of mercury and 56 kg spilled over the side in a westerly direction.

The most notable effect of the Cadoux Earthquake in the Perth metropolitan area was a widespread power blackout caused by the tripping of mercury switches in transformers. Some transformers were also tripped by the major foreshock and aftershocks.

## COST OF DAMAGE

No reliable estimate of the total financial losses caused by the Cadoux Earthquake can be made, but some appreciation of its magnitude can be gained from insurance claims and the estimates for the repair of government facilities. The following table of insurance payments has been provided by the Insurance Council of Australia and is accurate up to 8 October 1979.

TABLE 5. INSURANCE CLAIMS AS AT 8 OCTOBER 1979

| | *Domestic* | | *Commercial* | | *Total* | |
|---|---|---|---|---|---|---|
| | *No. of Claims* | *Amount $* | *No. of Claims* | *Amount $* | *No. of Claims* | *Amount $* |
| Metropolitan | 2 774 | 1 511 078 | 76 | 95 377 | 2 850 | 1 606 455 |
| Country | 705 | 1 392 298 | 113 | 435 610 | 818 | 1 827 899 |
| Totals | 3 479 | 2 903 376 | 189 | 530 987 | 3 668 | 3 434 354 |

These figures by no means represent the total cost of damage to insured properties, as most insurance companies require the policy holder to pay an initial sum towards costs, and no account is taken of underinsured and uninsured damage.

The only other estimates of costs involved for damage caused by the Cadoux Earthquake comes from government departments and instrumentalities such as the Public Works Department, the State Energy Commission and Westrail. After insurance had been paid, expenditure under the Commonwealth/State Natural Disasters Agreement for the financial year 1978/79 amounted to $82 260. During 1979/80 a further $186 681 was spent on the restorations of public assets, and $20 000 allocated in loans to re-establish small businesses. Further work on the Kokardine water tank will be required in 1980/81 at an estimated cost of $25 000.

## EFFECTS OF THE CADOUX EARTHQUAKE ON GROUNDWATER LEVELS

Earthquakes are often preceded by abnormal variations in a number of physical phenomena, including groundwater-level changes. It has also been long known that earthquake shock waves are recorded on hydrographs and the water level in some bores has been shown to give a hydrograph similar to a seismogram. Research in this field culminated in the first successful prediction of a large earthquake, in China in 1975.

In Western Australia water-level recorders are installed on several bores in both confined and unconfined aquifers in the Perth Basin, the northeast Yilgarn Block and the Nabberu Basin. This chapter reviews the literature relating to earthquakes and groundwater-level variations and discusses the fluctuations caused in Western Australian bores by the Cadoux Earthquake.

## LITERATURE REVIEW

Abnormal groundwater-level fluctuations before an earthquake can be expected to result from changes in pore pressure caused by changes in stress of an aquifer (Kovach and others, 1975; Kuo and others, 1974; Sadovsky and others, 1972), but the main problem in recognizing these fluctuations is that of filtering out effects due to other causes (Lamar and Merrifield, 1978). Before eleven major earthquakes in China it was found that such pre-earthquake fluctuations mainly began less than three days before the event, although periods of more than ten days were also recorded (Table 6). However, no correlation could be found between earthquake magnitude and the duration of the preceding fluctuation (Rikitake, 1976). Groundwater-level monitoring is an important tool of earthquake prediction in China (Coe, 1971) and after such observations, amongst other precursors, the 1975 Haicheng earthquake, of magnitude 7.4, was successfully predicted (Hammond, 1976).

A Western Australian example, however, provides an instance of the difficulties involved in using changes in water-level for earthquake prediction. The Meckering Earthquake of 1968, of magnitude 6.9 and located 110 km east-northeast of Perth, affected the hydrographs on some shallow bores at Gnangara, 19 km north of Perth. A sudden rise in water level which began 1.5 hours before the earthquake and reached a peak 5.5 hours later was reported by Gordon (1970) as a possible earthquake precursor. However, on comparing the complete hydrograph with rainfall records Gregson and others (1972) showed that the rise in water level was in response to local rainfall.

Groundwater-level fluctuations during and after earthquakes have been extensively reported (Rikitake, 1947; Parker and Stringfield, 1950; Stirling and Smets, 1971). Usually an earthquake is recorded on the hydrograph either as a sharp 'spike' with about the same amplitude above and below the previous water level, or, less often, as a step.

TABLE 6. PRECURSOR TIMES OF CHANGES IN GROUNDWATER LEVELS IN CHINA (KUO AND OTHERS, 1974, TRANSLATION IN RIKITAKE, 1976)

| *Earthquake* | *Year* | *Magnitude* | *Location (Lat.,Long.)* | *Precursor time* |
|---|---|---|---|---|
| Boundary between Hanfung Country, Hopei Province, and Tsinchiang County, Szechuan Province | 1856 | 6.0 | | several days |
| Haiyuen, Ningsia Prov. | 1920 | 8.5 | 36.5°N 105.7°E | 3 days |
| Taichung, Sinchu, Taiwan Prov. | 1935 | 7.0 | 24.5°N 120.8°E | 14 hours |
| Hanlungchi, Taiwan Prov. | 1935 | 6.0 | 24.3°N 121.3°E | 14 hours |
| Luenyuen,Hopei Prov. | 1945 | 6.3 | 39.7°N 118.7°E | 1 day |
| Hangting, Szechuan Prov. | 1955 | 7.5 | 30.0°N 101.8°E | 2 days |
| Tingchung, Yunan Prov. | 1961 | 5.8 | | 1 day |
| Hsingtai, Hopei Prov. | 1966 | 6.8 | 37.2°N 114.8°E | 1-2 days and 5-10 days |
| Tsunghai, Yunan Prov. | 1970 | 7.7 | 24.2°N 102.7°E | a few to more than 10 days |
| Sichi, Ningsia Prov. | 1970 | 5.5 | 36.0°N 105.8°E | 1-5 days |
| Donan, Tsinghai Prov. | 1971 | 6.3 | 33.5°N 98.1°E | more than 10 days |

This is probably caused by variations in fluid pore pressure, analagous to those which have been shown to occur during fault creep on the San Andreas Fault (Johnson and Kovach, 1973). Sometimes, if the time scale is sufficiently expanded, a recording similar to a seismogram is obtained on which the different earthquake waves can be identified (Blanchard and Byerly, 1935; Rexin and others, 1962). Fluctuations of almost 4 m maximum amplitude which continued for nearly 12 hours were recorded by Rexin and others (1962). The largest fluctuations, from normal depth earthquakes, are produced by surface waves, particularly the Rayleigh waves. Analysis of the hydrographs may provide information on aquifer characteristics, land-surface motions (Bredehoeft and others, 1965) and even earthquake magnitudes (Eaton and Takasaki, 1959; Vorhis, 1965).

Changes between pre- and post-earthquake water level in a bore may be the result of several seismically induced causes. Among these are tectonic raising or lowering of the land, changes in aquifer recharge or discharge and changes in transmissivity or porosity (Waller, 1966a and b). Correlations have been suggested between the sense of water-level change and tectonic strain (Wakita, 1975) or the direction of fault creep (Johnson and others, 1974).

## HYDROGRAPHS FROM WESTERN AUSTRALIA

Hydrographs from 22 monitoring bores were examined for possible effects of the Cadoux Earthquake. The bores are in the Perth Basin and the east Murchison district (Fig. 47) and relevant data are summarized in Table 7. Eleven bores recorded the earthquake and the effects are given in Table 8.

Records from several bores were characterized by step-like water-level changes, apparently caused by the float jamming periodically against the bore casing. Large, sudden fluctuations of the hydrograph from AM35 approximately 41 hours and 12 hours before the earthquake were probably not related to the seismic activity because of the shape of the fluctuation and the length of time before the earthquake. Bore E7B had a straight hydrograph probably because the counterweight on the recorder was too light. With these exceptions it is assumed that all sudden fluctuations of the hydrographs were caused by water-level changes caused by the earthquake. It is possible that direct shaking of the recorders by the earthquake may have produced similar effects in some cases.



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TABLE 7. HYDROGRAPHS EXAMINED FOR EARTHQUAKE-INDUCED WATER-LEVEL FLUCTUATIONS

| *Perth Basin* | | |
|---|---|---|
| *Bore name* | *GSWA No.* | *Aquifer* |
| Unconfined | | |
| Wanneroo CMW | 2034-I-C-61 | Kwinana Group |
| Lake Thompson 90 | 2033-I-B-252 | " " |
| Gwelup CMW | 2034-II-D-615 | " " |
| Baghdad Well | | Herschell Limestone |
| Confined | | |
| Artesian Monitoring (AM) 35 | 2034-II-A- 395b | Leederville Formation |
| Mirrabooka (M) 55 | 2034-II-A-394c | " " |
| Artesian Monitoring (AM) 28 | 2034-II-D-617a | " " |
| Eneabba (E) 7 | 1938-II-D-17 | Yarragadee Formation |
| " (E) 7B | 1938-II-D-19 | " " |
| " (E) 6B | 1938-II-D-26 | " " |
| Quindalup (Q) 7A | 2030-IV-B-27 | " " |
| " (Q) 7B | 2030-IV-3-28 | ?Leederville Formation |
| 0-4 | 2032-I-B-83 | Cockleshell Gully Fm |
| 0-11 | 2032-I-B-90 | Leederville Formation |
| 0-12 | 2032-I-B-91 | " " |

| *East Murchison* | | |
|---|---|---|
| *Bore name* | *GSWA No.* | *Aquifer* |
| Unconfined | | |
| Mt Keith Bore | 3043-I-23 | calcrete Yilgarn Block |
| Paroo Bore | 2845-II-23 | calcrete Nabberu Basin |
| Depot West Bore | 2942-III-41 | calcrete Yilgarn Block |
| Wiluna Well | 2944-I-39 | " " |
| Friday Well | 2941-IV-36 | " " |
| Cherry Well | 2941-IV-33 | " " |
| West Albion Downs Bore | 2943-II-40 | " " |

These bores, for convenience, are named after nearby places and generally are not actually at that locality

TABLE 8. SUMMARY OF WATER-LEVEL DISTURBANCES IN BORES RESULTING FROM THE CADOUX EARTHQUAKE
(Measurements are taken from hydrographs to an accuracy of 5 in the last figure stated)

| *Bore* | *Type of aquifer; confined(C) or unconfined(U)* | *Time of earthquake 2/6/79* | *Apparent time of disturbance 2/6/79* | *Water-level change (m)* | | | *Max. amplitude of disturbance from pre-earthquake water level (m)* | | | *Comments* |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | *Water level before disturbance* | *Water level after disturbance* | *Water level change (+ve up)* | *rise* | *fall* | *Double amplitude* | |
| Wanneroo | U | 1748 | 1850 | 3.574 | 3.590 | -0.016 | 0.0 | 0.051 | 0.051 | Pre-earthquake trend of falling water level took about 2 days to become re-established |
| Baghdad Well | U | 1748 | 1910 | 0.982 | 0.980 | -0.002 | 0.13 | 0.015 | 0.028 | Water level disturbed by rainfall |
| Lake Thompson 90 | U | 1748 | 1810 | 3.865 | 3.866 | -0.001 | 0.025 | 0.025 | 0.050 | |
| Gwelup CMW | U | 1748 | 1755 | 17.259 | 17.257 | 0.002 | 0.003 | 0.0 | 0.002 | |
| AM35 | C | 0554 | 0559 | 1.390 | 1.386 | 0.004 | 0.018 | 0.008 | 0.026 | Water level began falling about 5 minutes before main disturbance on the hydrograph |
| AM28 | C | 0554 | 0558 | 34.790 | 34.780 | 0.010 | 0.012 | 0.001 | 0.013 | Water level took about 12 minutes to stabilize after the disturbance |
| 0-12 | C | 1748 | 1710 | 12.7208 | 12.720 | 0.000 | 0.001 | 0.001 | 0.002 | |
| Mt Keith Bore | U | ?1748 | 1445 | 3.2892 | 3.2895 | -0.00030 | 0.0020 | 0.0060 | 0.0080 | |
| Cherry Well | U | ?1748 | 1706 | 4.002 | 4.001 | 0.001 | 0.023 | 0.024 | 0.047 | Recorder set on stilts |
| Paroo Bore | U | ?1748 | 1220 | 5.0930 | 5.0938 | -0.00080 | 0.002 | 0.002 | 0.004 | |
| Friday Well | U | ?1748 | 1936 | 3.006 | 3.007 | -0.001 | 0.012 | 0.013 | 0.027 | |

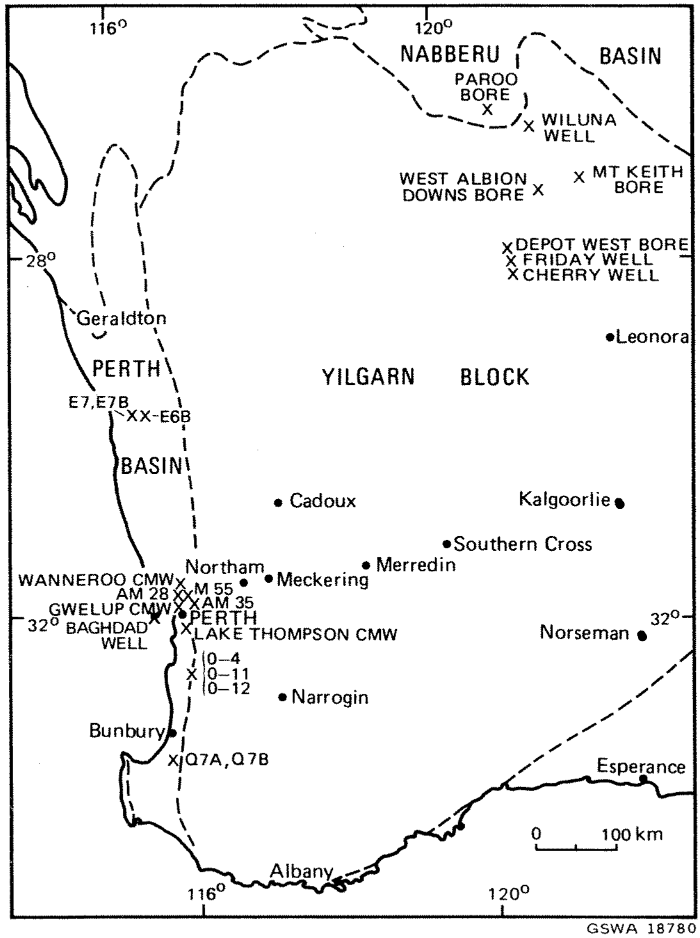


Figure 47. Bore locations

*Perth Basin*

*Unconfined aquifers:* Hydrographs from four bores in the Perth area were examined: Wanneroo CMW (continuous monitoring well), Baghdad Well, Lake Thompson 90 and Gwelup CMW (Figs 48 and 49). All show a disturbance close to the time of the main earthquake of $M_L$ 6.2 but are unaffected by the major foreshocks and aftershocks. In Gwelup CMW the earthquake may have freed the float from the casing to give the small step-like rise in the hydrograph (Fig. 48c).

A rise in the water table in Lake Thompson 90 beginning about seven hours before the earthquake is part of a general seasonal rise. Five millimetres of rain were recorded in

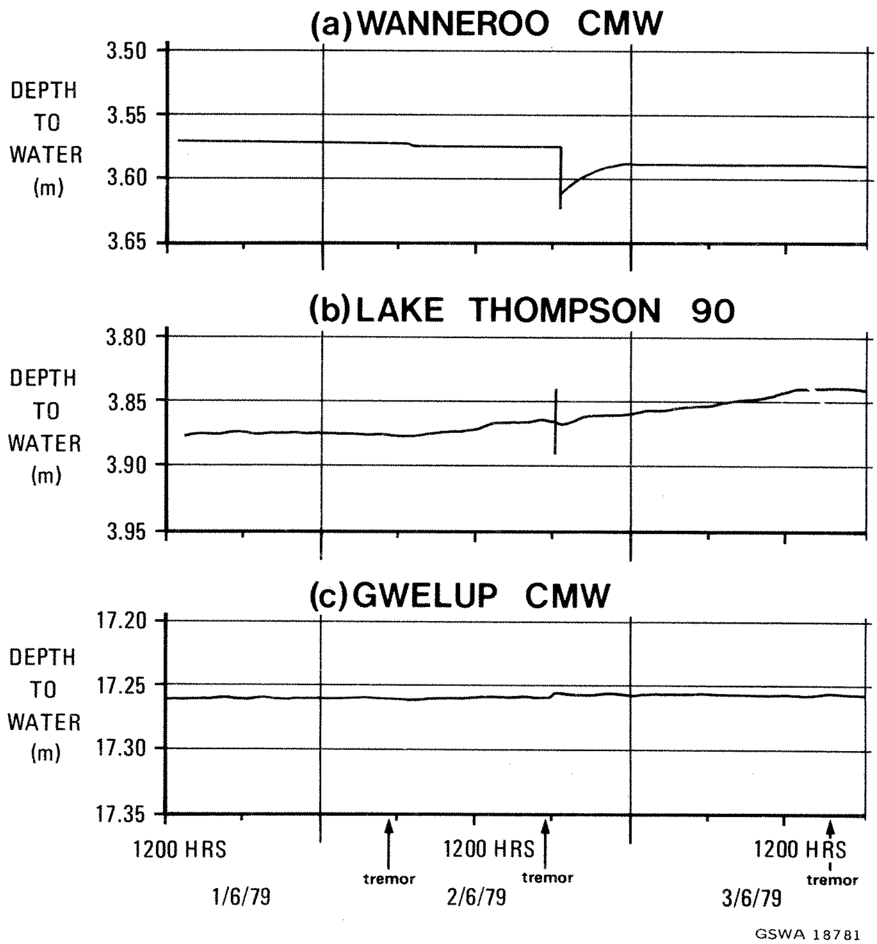


Figure 48. Hydrographs from bores in unconfined aquifers, Perth Basin

the last twelve hours of 1 June at the Bureau of Meteorology in Perth. The earthquake itself is recorded only as a sharp 'spike' of 0.05 m double amplitude* (Fig. 48b).

The hydrograph of Wanneroo CMW (Fig.48a) shows the water level falling before the earthquake and a sharp drop of 0.051 m due to the shock. The water level took about 2 days to re-establish the previous trend. The reasons for this gradual recovery are not known; the hydrograph is similar to that of a bore during recovery after pumping.

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*In this report the maximum double amplitude refers to the maximum distance between adjacent crests and troughs on the recording perpendicular to the time scale.

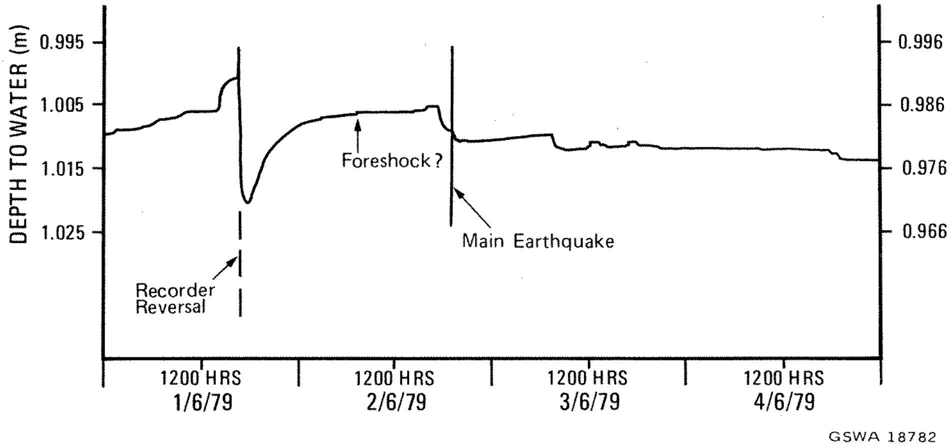


Figure 49. Hydrograph from Baghdad Well, Rottnest Island

Baghdad Well, on Rottnest Island, is a very shallow bore and the hydrograph (Fig. 49) is complicated by rapid response to sporadic rainfall which fell throughout the four days illustrated. The small steps in the hydrograph are caused by rainfall and the large reversal at 1800 hrs on 1 June is caused by the automatic reversal of the recorder mechanism as the pen reached its limit. The main earthquake caused a large spike of double amplitude 0.028 m and there is a possibility that a small step twelve hours earlier might have been caused by the major foreshock.

*Confined aquifers:* Eleven hydrographs were examined but the water level in only three of these was disturbed by the earthquake, two by the major foreshock (AM35 and AM28, Fig. 50) and one by the main shock (0-12, Fig. 51). These bores are all open to the Leederville Formation, but no response was noted from three other bores into the formation. The maximum double amplitude of the disturbance was 0.026 m in AM35; both AM35 and AM28 were recovering from an aquifer test in a nearby bore.

The hydrograph from AM35 (Fig. 50a) shows that the water level began falling about five minutes before the 'spike' caused by the major foreshock. Hydrographs with extended time scales show a similar effect due to the

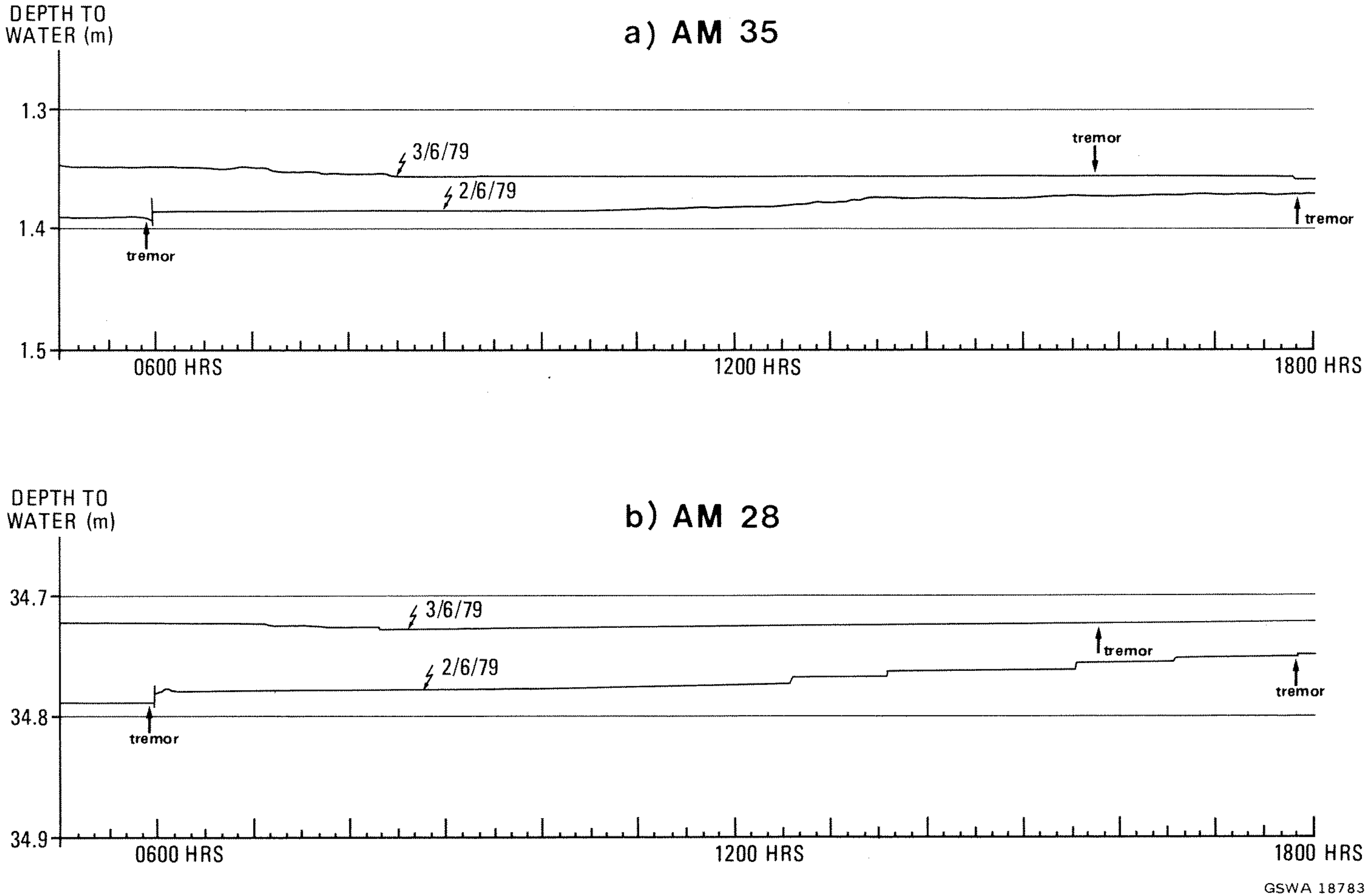


Figure 50. Hydrographs from bores in confined aquifers, Perth Basin

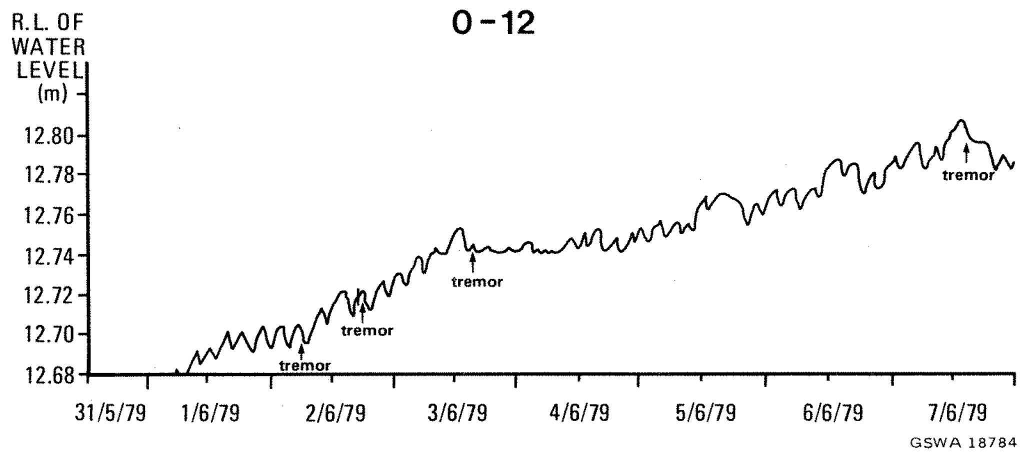


Figure 51. Hydrograph of bore 0-12

differing arrival times of the various types of seismic waves. However, the difference in velocity would account for only about 25 seconds in the arrival time from Cadoux and the disturbance is not thought to be due to this cause. It may have resulted from stress changes before the earthquake, but the short duration of the drop makes this unlikely.

Bore 0-12 is a monitoring bore east of Pinjarra, open in the Leederville Formation. The cause of the two-hourly fluctuations (Fig. 51) is the automatically controlled pumping of water from the underlying Cockleshell Gully Formation. The longer term fluctuations were probably in response to rainfall.

*East Murchison district*

Hydrographs from seven bores were examined and four recorded an earthquake on 2 June between 1200 hours and 2400 hours (Fig. 52). Unfortunately, clock errors could not be calculated but it is suggested that the main earthquake was responsible for each disturbance. The bores affected were Mount Keith Bore, Cherry Well and Friday Well on the Yilgarn Block and Paroo Bore in the Nabberu Basin. Three bores showed a small drop in water level after the shock. The maximum double amplitude of the disturbance was 0.047 m at Cherry Well.

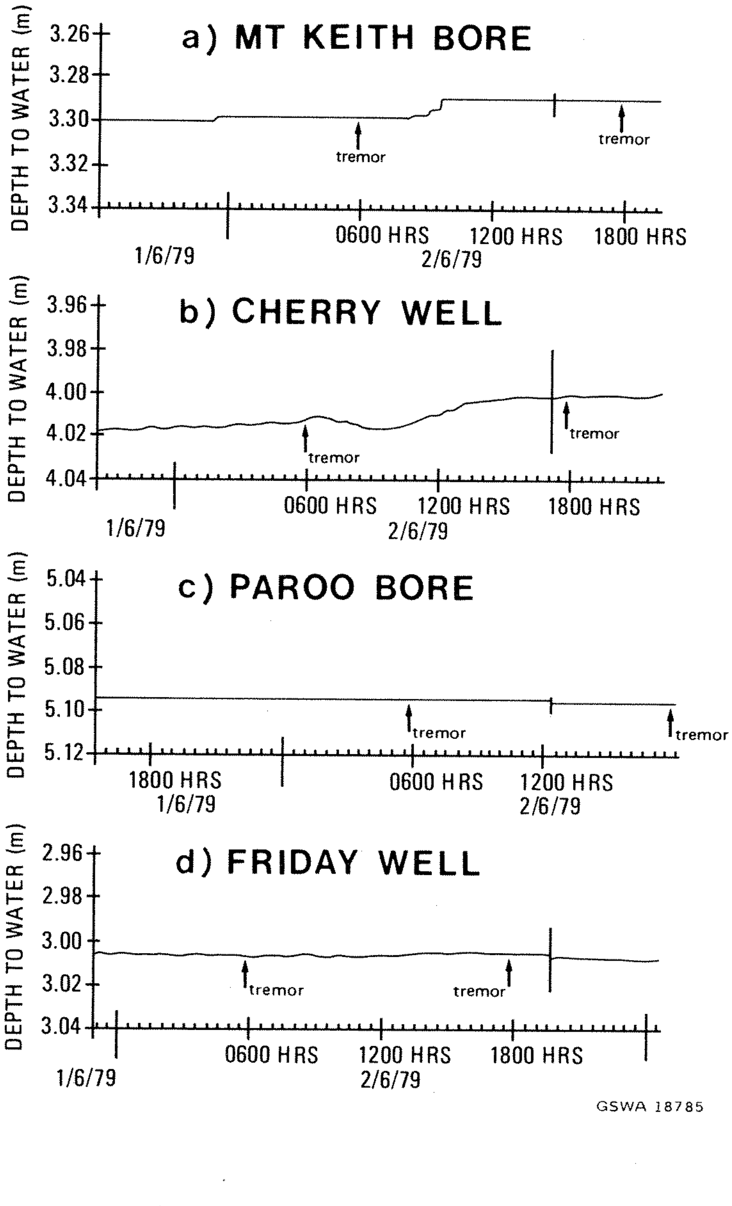


Figure 52. Hydrographs from bores in the east Murchison district (clock errors probably present)

A rise in water level is evident in bores at Mount Keith and Cherry Well, beginning about five hours and seven hours, respectively, before the earthquake was recorded. The rises did not continue up to the time of the earthquake, as would be expected if they were caused by an increase in stress on the aquifers, and are probably not related to the seismic activity. Figure 52b shows that the water level in Cherry Well may have continued to fluctuate for about fifteen minutes after the main disturbance. Both vertical and horizontal scales on the record are too small to substantiate this.

## CONCLUSIONS

The water level in several bores in both unconfined and confined aquifers in the Perth Basin and the east Murchison district were disturbed as a result of the Cadoux Earthquake. However, no hydrograph showed disturbances resulting from more than one of the tremors. Bores in unconfined aquifers responded only to the main earthquake, whereas those in confined aquifers responded either to the major foreshock or the main event. Observations elsewhere have indicated that bores drilled into confined aquifers are affected more strongly than water-table bores (Eaton and Takasaki, 1959). This was not borne out in the present study.

The response of water levels in bores penetrating the same aquifer varied; for example, two of the five Leederville Formation bores were undisturbed by the earthquake. This may be due to differences in bore construction or variations in the physical properties of the aquifer. The lack of response in any of the bores to more than one of the tremors is difficult to explain. Elsewhere, hydrographs which have recorded major earthquakes have also recorded aftershocks (Vorhis, 1967; Costa, 1963). In some bores in the present study the foreshock of $M_L$ 5.2 induced water-level fluctuations while the main earthquake of $M_L$ 6.2 did not.

The advantage, in most areas, of using water bores for the study of changes induced by earthquakes and attempts to find features which would allow the prediction of major shocks lies in their ready availability. Hydrographs from monitoring bores are available for long periods and the cost of improved instrumentation for an existing bore is minimal. However, any changes which could be used for prediction will occur only in a zone relatively close to the epicentre. Bores at a distance from the area under strain may register the earthquake itself but not the precursory changes which might allow of prediction.

In Western Australia the South West Seismic Zone lies entirely in Archaean crystalline rocks with poor large-scale groundwater prospects and a consequent lack of suitable monitoring bores. In addition the zone of distortion for the Cadoux Earthquake was probably not greater than about 50 km by 40 km and it would be economically impossible to cover even the most seismically active areas with suitable bores built for the purpose.

Existing bores in Western Australia with water-level monitoring equipment attached are too distant from any potential epicentre to register more than a 'spike' due to the earthquake, and this study has shown that even this limited response is not always recorded. Furthermore, the time scale on hydrographs from all bores is too compressed to show details of the fluctuations induced by earthquakes. Earthquake prediction, moreover, should be based on careful observation of many phenomena, including groundwater levels, and at present no bores could be recommended for equipping with an extended time-scale recorder.

## REGIONAL SETTING OF THE CADOUX EARTHQUAKE

Earthquakes generally occur in distinct seismic zones, and in Western Australia such zones are located on the northern margin of the Canning Basin, in the Gascoyne region and in the southwest of the State. A number of major earthquakes have occurred in each region but only in the

South West Seismic Zone has surface faulting been observed with earthquakes in historic times. The South West Seismic Zone is also important as it is the only seismically active area close to densely populated areas.

## THE SOUTH WEST SEISMIC ZONE

A map of earthquake epicentres in southwestern Australia (Fig. 53) shows a number of areas of relatively intense seismic activity concentrated in a zone from Dalwallinu to Narrogin. This zone, with extensions north-west to Moora and south to Katanning and Albany to include minor seismicity in these areas, has been named the South West Seismic Zone by Doyle (1971) and is the most active zone in Australia. The western boundary of the seismic zone is well marked along the line of granite plutons which form the Darling Plateau, but the eastern margin is indistinct and a number of tremors have been recorded some distance to the east of the main seismic zone.

Geologically the main part of the seismic zone is coincident with the belt of schists and gneisses which runs parallel to the granites of the Darling Plateau. Physiographically the gneisses are downwarped with respect to the granites to the west and the remainder of the Yilgarn Block to the east. Other geological features which are strongly correlated with the seismic zone are gravity anomalies and a change in crustal thickness. Contours of gravity anomalies trend parallel to the seismic zone and change from between zero and +20 mGal on the Darling Plateau to -40 to -60 mGal in the remainder of the Yilgarn Block. Crustal thickness also changes in the vicinity of the seismic zone, increasing from about 36 km in the Archaean shield to 42 km in the seismic zone, and 46 km beneath the Perth Basin (Everingham, 1965).

The geological and structural changes that occur in the area are probably related causally to the seismicity of the South West Seismic Zone, but detailed knowledge of the relationship is lacking. However, any connection is probably

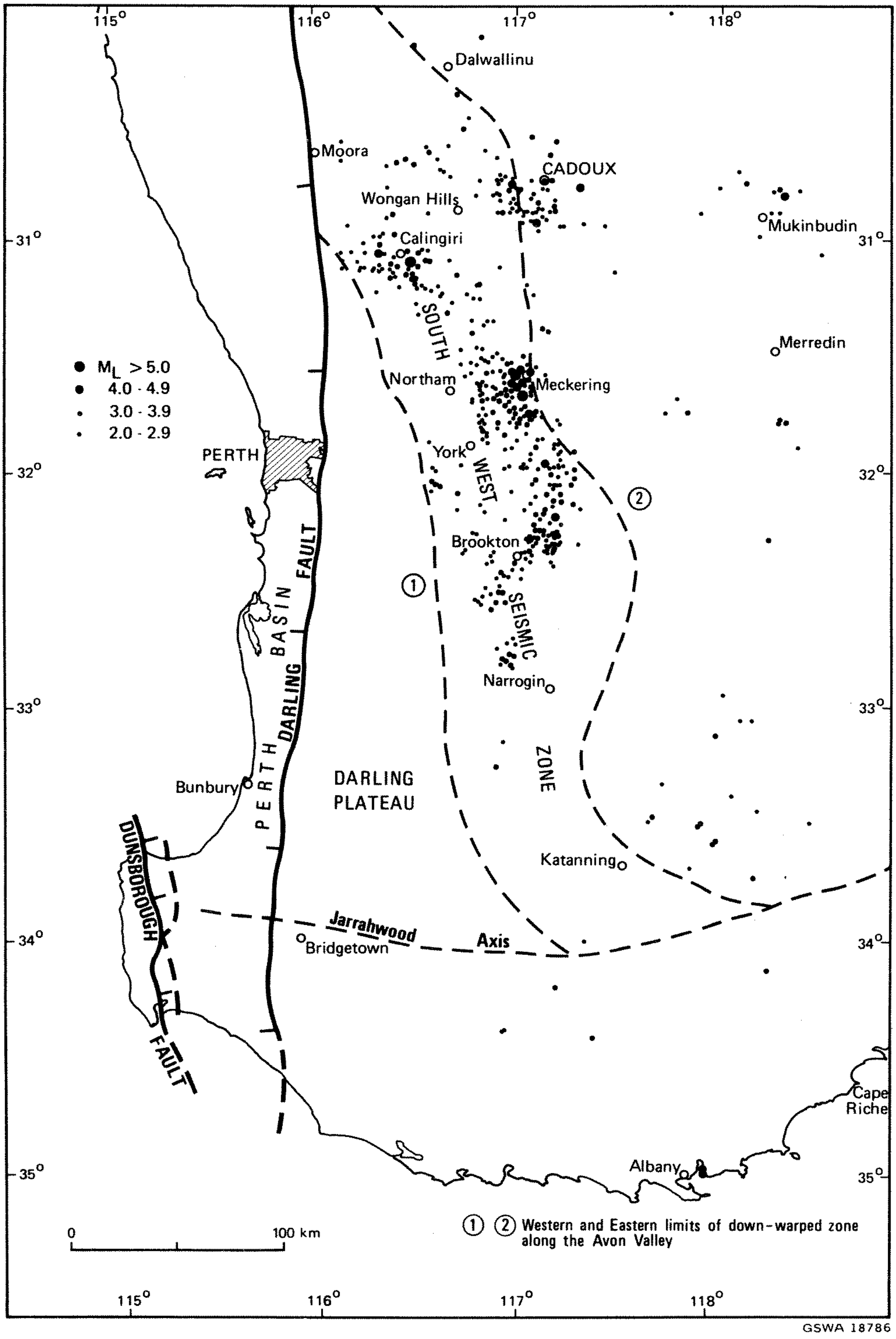


Figure 53. Location of epicentres in the South West Seismic Zone, 1959-1977 (after Gordon and Lewis, 1980)

with deep crustal structures rather than superficial features. It is for this reason that it is possible to extend the South West Seismic Zone to include a number of shocks in the Albany region and offshore in the Southern Ocean despite the changes in geology. Similarly, to the north, the zone can possibly be extended to include tremors near Dongara, and coastline and sea-bed features of the Indian Ocean.

Doyle (1971) has proposed that the South West Seismic Zone marks the boundary of a sub-plate within the major Indian-Australian Plate. On this model the cause of seismicity in the South West Seismic Zone is the stress produced by the continuing activity of continental drift. Sykes (1970) has proposed a connection with a zone of seismicity near the Cocos Islands and tentatively suggested the possibility of a nascent island arc. However, Stein and Okal (1978) have shown that this seismicity is related to the north-south-trending Ninetyeast Ridge, while Weissel and others (1980) have suggested that the high level of intra-plate stress found in the Indian-Australian Plate has arisen since the collision of India with Asia to form the Himalayas.

Alternatively, it is known that there has been extensive uplift of the Darling Plateau during the Tertiary era (Cope, 1975), and Playford and others (1976) have suggested that the seismicity of the area could be a response to localized stresses associated with this continuing epeirogenic upwarping.

Stress in rocks may be determined, both in direction and amount, either directly by such methods as overcoring, or by calculation from surface faulting and the focal mechanism of earthquakes.

In the overcoring technique a number of strain gauges are bonded to the wall of a small diameter borehole drilled into sound rock. These gauges register a change in strain when the section of rock containing the borehole is freed from the rock mass by overcoring with a large diameter core barrel. This change in strain is a function of the *in situ* stress field and the elastic constants of the rock. The elastic constants are determined by laboratory testing, and hence the *in situ* stress field may be determined.

A compilation of available data by Denham and others (1979) shows that the whole Australian continent is under nearly horizontal compressive stress, but that the direction of stress is not consistent from region to region. Within the South West Seismic Zone, however, more detailed work (Denham and others, 1980) has shown that the directions of principal stress as determined from *in situ* measurements and from earthquake focal mechanisms are in good agreement and that the whole region is under a major horizontal east-west pressure, equivalent to an overburden pressure of about one kilometre. Stress measurements were made in 1976 at seven sites in the most active part of the seismic zone, from Manmanning (Fig. 33) in the north to Popanyinning (two sites) in the south. Intermediate sites were located near Goomalling, Meckering, Quajabin Peak and Brookton. The lowest value of maximum principal stress, 4 MPa, was found near Meckering, the site of a major earthquake in 1968. Towards each end of the traverse the stress increased, reaching 23 MPa at Manmanning and 19 MPa at Popanyinning. The stress released by the Meckering and Calingiri Earthquakes is estimated to be about 10 MPa. If this is added to the 4 MPa measured at Meckering it would bring the pre-1968 stress in the area up to the average level of stress for the zone. At Meckering, Quajabin Peak and Brookton, where the principal stress was relatively low, the direction of stress was variable but at the other sites the stress direction ranged only between 065$^{\circ}$ and 095$^{\circ}$. This compares well with 091$^{\circ}$ for the direction of maximum pressure for the Meckering Earthquake (Fitch and others, 1973), 069$^{\circ}$ for the direction of maximum pressure for the Cadoux Earthquake (Everingham and Smith, in prep.), and 065$^{\circ}$ to 095$^{\circ}$ for the resultant displacements of faults at Cadoux.

The direction of the stress field actually found in the South West Seismic Zone is not consistent with the simple plate-tectonic model which suggests that the northward motion of the Indian-Australian Plate should result in a north-south pressure. Denham and others (1980) suggested that a possible source of the east-west compressive force is the gravitational sliding of the Australian continent away from the north-south-trending mid-ocean ridge which separates the Indian and African plates.

The age of the South West Seismic Zone, as a seismic zone, is not known. The geological features noted earlier date from the Archaean, and it is possible that changes in crustal thickness began in Proterozoic times. A tectonic reconstruction by Veevers and Heirtzler (1974) shows the seismic zone as the continuation of a transform fault initiated at the time that India separated from Australia about 120 million years ago. However, if the cause of the present day stress is intra-plate buckling resulting from the collision of India and Asia (Weissel and others, 1980) then it is probable that the seismicity dates only from late Miocene times, about 5 to 10 million years ago. This interpretation is supported by the work of Cope (1975) who has shown that the epeirogenic uplift of the Darling Plateau dates from mid-Miocene to early Pliocene and has continued to the present.

Thus, as a feature of the earth's crust the area of the South West Seismic Zone has long been distinctive and it is possible that present seismicity represents the release of residual strain in an old fracture zone. On the other hand, the lack of large-scale faulting within the zone and the present-day stress field suggests that its seismicity is of recent origin.

Historically the area has only been settled and its seismicity recorded for a little over one hundred years, and it is only within the last decade that the importance of the South West Seismic Zone has been recognized. There is evidence that the Meckering Fault was a reactivated older fault (Gordon and Lewis, 1980) but the overall effect of faulting in the area is minor. The historical and geological evidence suggests that periods of intense seismic activity alternate with long periods of relative inactivity, but it is still probable that the seismicity of the zone is geologically of recent origin.

The style of seismic activity in the South West Seismic Zone, if the period since 1959 (when detailed recording began) is typical, is characterized by a large number of small shallow earthquakes, with occasional larger events, but without periods of quiescence. Richter (1971) described this as continuous seismic activity and suggests that it is caused by the adjustment of relatively small crustal blocks to regional stress.

## MECKERING AND CADOUX COMPARED

In recent years three large earthquakes have produced surface faulting and widespread property damage in the southwest of Western Australia. The Meckering Earthquake of October 1968 ($M_L$ 6.9) and the Calingiri Earthquake of March 1970 ($M_L$ 5.7) have been described by Gordon and Lewis (1980). These two, together with the Cadoux Earthquake all occurred in the northern half of the South West Seismic Zone.

The ultimate cause of each of the earthquakes, and of the general seismicity of the South West Seismic Zone, is probably the mechanism of plate-tectonic movements in the Indian-Australian Plate. More directly, plate-tectonic motions and crustal inhomogeneity have given rise to a nearly east-west compressive stress throughout the seismic zone. All the earthquakes and minor tremors are a result of these compressive forces; thus the Meckering, Calingiri and Cadoux Earthquakes can be seen as individual manifestations of a single underlying cause.

Further similarities between the earthquakes come from their mechanisms. In each case the earthquake is believed to have been the result of movement on an unseen fault at depth which bore little obvious relationship to the surface faulting. At Meckering an arcuate right-lateral thrust fault was caused by movement on an underlying left-lateral reverse fault trending 332$^{\circ}$ and dipping 68$^{\circ}$ east (Fitch and others, 1973); at Calingiri the surface fault was a left-lateral thrust trending 008$^{\circ}$ produced by movement on a deep left-lateral reverse fault trending 337$^{\circ}$ and dipping 76$^{\circ}$ east. At Cadoux, as we have seen, the deep fault is right-lateral reverse, trending 018$^{\circ}$ and dipping 81$^{\circ}$ east. Although each earthquake is classed as shallow, it would appear that major displacements occur only at depth and that surface faulting is confined to a detached cap of rock. No major change is known to occur in the crust at a depth of 5-10 km, but such a change seems to be required by the style of faulting in the seismic zone. Such a discontinuity might also explain the lack of any known large transcurrent faults in the zone.

A difference between the Cadoux and Meckering Earthquakes is the direction and displacement of the underlying fault. At Meckering and Calingiri left-lateral faults trend north-northwest while at Cadoux a right-lateral fault trends north-northeast. The two directions form a conjugate pair and tend to confirm that the seismic zone is made up of a number of small blocks, with seismic activity the result of adjustments between the blocks. The relative independence of the blocks is shown by the seismic records of the Cadoux and Meckering areas. In 1968 Cadoux was seismically active in March and April, while Meckering remained quiet. Conversely, no tremors were recorded at Cadoux between October 1968 and May 1969 during the main period of after-shock activity following the Meckering Earthquake. Seismic activity at Calingiri tended to follow that at Meckering and the Calingiri Earthquake can be regarded as a large and distant aftershock of the Meckering event.

The surface faulting at Meckering and Cadoux was similar in that the types of surface expression seen at Meckering were repeated at Cadoux along the Robb Fault, even though the Meckering Fault is a low-angle thrust while the Robb Fault is much steeper. Scarp forms would appear to be more related to soil and sub-soil conditions than to the dip of the fault plane. However, in most other respects the faulting is quite different. At Meckering an arcuate main fault is accompanied by strong radial and chordal faulting which are absent at Cadoux. Equally, there is no equivalent at Meckering of the conjugate fault set at the northern end of the Cadoux Fault System. Faulting at Cadoux and Calingiri is quite similar; the main faults are only slightly arcuate and the Calingiri Chordal Fault is probably a representative of a partially developed conjugate set,of the type that is well developed at Cadoux.

The long-term physiographic effects of faulting at Meckering and Cadoux are similar. In both areas the effect was to raise the eastern block of the fault. In detail, however, the local effects are different; at Meckering the Mortlock River has been diverted around the mobile cap of rock while at Cadoux the different style of deformation has raised the watershed between two drainage systems.

In summary, the earthquakes at Meckering and Cadoux have the same ultimate cause, are similar in many major aspects and, together with smaller tremors which caused no surface faulting, are the products of the same processes. In detail, however, there are features particular to each event which depend on local conditions.

## THE FUTURE

The South West Seismic Zone has only been recognized as an earthquake-prone area for about 40 years, and adequate recording of the seismicity is only about 20 years old. The area has been settled for about one hundred years and in this period three damaging earthquakes have occurred, all in the last 11 years. Our knowledge of the past history of the seismic zone is very limited; consequently the future of seismicity in the area is not predictable, other than that further earthquakes can be expected to occur. Recent events have spurred research, but this is a long-term project and few results can be expected immediately.

Apparent return periods for earthquakes of a given magnitude have been calculated by Everingham and Gregson (1970), but the data base was small and it cannot be known whether the present activity, which is the most intense for

150 years, will continue. For a magnitude 6 earthquake, using data gathered prior to the Meckering Earthquake of 1968 and its aftershocks, the return period is calculated to be 170 years, but including the Meckering shocks it falls to 46 years. With the Calingiri and Cadoux Earthquakes included the apparent return period would become even shorter. The assumption of this method is that the seismic activity monitored in the past 20 years is representative of a much longer period of time. Experience in the last 150 years suggests that this assumption is not correct, but even if it were correct the return period only gives us an expectation, it cannot predict the occurrence of an earthquake.

Continuing work by the Bureau of Mineral Resources on the regional stress field may eventually be able to define areas of greatest risk. Similarly, surveying might assist in defining such areas, if the model for ground distortion proposed in this report is correct. But with no knowledge of the long-term behaviour of the stress field in the South West Seismic Zone it is impossible, at present, to predict reliably the magnitude, location or time of a future earthquake. Even when such information is available the precision with which the predicted earthquake can be located may be insufficient to avoid the damaging consequences.

In some areas of the world monitoring of water bores has been used to assist in earthquake prediction, but the limitations of this method have already been discussed, and it seems unlikely that it can be applied in the South West Seismic Zone.

For the future it seems feasible that some effective and reliable system of earthquake prediction will be developed and that earthquake risk in southwestern Australia will become better defined. For the present, the community must assume that damaging earthquakes will continue to occur within the seismic zone at irregular intervals and suitable precautions should be taken when erecting commercial or domestic buildings.

# APPENDIX I

## LOCATION OF EARTHQUAKE EPICENTRES IN THE CADOUX AREA, 1959-1980

The following tables have been abstracted from the Annual Reports of the Mundaring Geophysical Observatory and are presented to complete the picture of the overall seismicity of the Cadoux area. The epicentres have been plotted on Figures 3 and 5, but it should be remembered that these locations, although the best available, have been instrumentally determined and are only accurate to a radius of 5 km. This applies particularly to the smaller tremors of $M_L$ <3.0. The equipment at the observatory is being continually updated, but prior to 1978 it was not possible to accurately determine the depth of focus of an earthquake.

TABLE 9. EARTHQUAKES IN THE CADOUX AREA, 1959 TO 1978 ($M_L$ > 2.0)

| *Date* | *Origin time (U.T.)* | *Epicentre Lat. °S* | *Epicentre Long. °E* | $M_L$ |
|---|---|---|---|---|
| NOTE: Between 1959 and 1966 no tremors were recorded within a radius of 25 km of Cadoux. | | | | |
| *1966* | | | | |
| Oct 3 | 21 39 24 | 30.6 | 117.2 | 3.6 |
| *1968* | | | | |
| Feb 22 | 04 40 10.5 | 30.8 | 117.3 | 4.0 |
| Mar 25 | 02 50 31 | 30.75 | 117.24 | 2.8 |
| 25 | 03 21 26 | 30.75 | 117.24 | 2.4 |
| 25 | 03 22 45 | 30.73 | 117.22 | 2.8 |
| 25 | 09 35 49 | 30.75 | 117.24 | 2.9 |
| 27 | 03 57 28 | 30.72 | 117.19 | 2.6 |
| 27 | 06 34 11 | 30.67 | 117.12 | 3.2 |
| 29 | 06 40 08 | 30.75 | 117.24 | 2.6 |
| 29 | 06 47 23.5 | 30.8 | 117.3 | 3.2 |
| 29 | 15 51 58.8 | 30.8 | 117.3 | 3.1 |
| 31 | 00 12 24 | 30.72 | 117.19 | 2.9 |
| Apr 02 | 18 53 46.4 | 30.8 | 117.3 | 3.4 |
| 05 | 19 01 47.6 | 30.8 | 117.3 | 3.0 |
| 05 | 19 48 24 | 30.72 | 117.19 | 2.7 |
| 05 | 23 30 55 | 30.75 | 117.24 | 2.9 |
| 07 | 06 54 18.7 | 30.8 | 117.3 | 3.5 |
| 08 | 01 44 55.4 | 30.8 | 117.3 | 4.4 |
| 08 | 01 48 11.8 | 30.8 | 117.3 | 3.7 |
| 08 | 01 53 40.8 | 30.8 | 117.3 | 3.2 |
| 10 | 22 10 19 | 30.84 | 117.36 | 2.9 |
| 18 | 23 27 41 | 30.70 | 117.16 | 3.3 |
| May 22 | 09 34 48 | 30.70 | 117.16 | 3.5 |
| 27 | 06 46 04 | 30.75 | 117.24 | 2.9 |
| *1969* | | | | |
| May 16 | 04 22 47.9 | 30.9 | 117.2 | 3.7 |
| 19 | 15 29 | 30.34 | 117.17 | 2.7 |

TABLE 9. EARTHQUAKES IN THE CADOUX AREA, 1959 TO 1978 (cont'd)

| *Date* | *Origin time (U.T)* | *Epicentre* *Lat.* °*S* | *Long.* °*E* | $M_L$ |
|---|---|---|---|---|
| Jun 26 | 00 37 | 30.76 | 117.21 | 2.9 |
| 26 | 00 38 09.2 | 30.76 | 117.28 | 3.4 |
| 26 | 06 45 | 30.76 | 117.21 | 2.9 |
| Jul 27 | 08 37 | 30.72 | 116.94 | 2.6 |
| 27 | 09 20 47.3 | 30.95 | 117.10 | 4.2 |
| 27 | 12 46 | 30.88 | 117.15 | 2.9 |
| 27 | 12 54 | 30.87 | 117.13 | 2.9 |
| 27 | 14 04 | 30.75 | 116.95 | 2.4 |
| Aug 21 | 23 57 04.0 | 30.75 | 117.16 | 3.2 |
| Oct 22 | 20 17 | 30.77 | 117.03 | 2.9 |
| 22 | 20 26 | 30.77 | 117.03 | 2.8 |
| 23 | 12 05 16.7 | 30.88 | 117.13 | 2.7 |
| 23 | 12 13 | 30.79 | 117.09 | 2.8 |
| Nov 01 | 05 53 | 30.75 | 117.02 | 2.7 |
| 08 | 08 46 | 30.78 | 117.14 | 2.5 |
| *1972* | | | | |
| Jan 25 | 11 37 54.6 | 30.85 | 117.10 | 3.0 |
| 30 | 02 10 25 | 30.89 | 116.98 | 2.4 |
| Feb 01 | 04 15 28 | 30.90 | 117.06 | 2.7 |
| 02 | 18 20 34 | 30.90 | 117.06 | 2.0 |
| 18 | 07 58 43 | 30.84 | 116.88 | 2.9 |
| 18 | 08 23 52 | 30.83 | 116.89 | 2.3 |
| 24 | 02 16 22 | 30.86 | 116.98 | 2.2 |
| 24 | 06 51 32 | 30.90 | 117.05 | 2.4 |
| 24 | 14 37 16 | 30.90 | 117.05 | 2.2 |
| 26 | 11 15 40 | 30.81 | 117.02 | 3.3 |
| Apr 01 | 15 37 18 | 30.85 | 116.98 | 2.1 |
| 02 | 23 45 08 | 30.85 | 116.98 | 2.1 |
| Nov 08 | 22 54 48.8 | 30.90 | 117.20 | 3.0 |
| 09 | 21 11 39.5 | 30.90 | 117.20 | 2.7 |
| 27 | 06 45 08 | 31.00 | 117.20 | 2.2 |

TABLE 9. EARTHQUAKES IN THE CADOUX AREA, 1959 TO 1978 (cont'd)

| *Date* | *Origin time (U.T.)* | *Epicentre* *Lat.* °*S* | *Long.* °*E* | $M_L$ |
|---|---|---|---|---|
| *1973* | | | | |
| Feb 16 | 13 26 46.4 | 30.91 | 117.14 | 2.3 |
| 17 | 14 27 28.1 | 30.97 | 117.22 | 2.5 |
| 28 | 22 42 06.3 | 30.90 | 117.08 | 2.8 |
| Mar 19 | 00 28 20.5 | 30.96 | 117.13 | 2.2 |
| 25 | 06 14 16.8 | 30.92 | 117.03 | 2.1 |
| 31 | 11 07 21.6 | 30.90 | 117.10 | 2.2 |
| Jun 29 | 13 52 41.2 | 30.82 | 116.90 | 2.3 |
| Sep 23 | 09 09 05.0 | 30 90 | 117.10 | 2.2 |
| *1974* | | | | |
| May 12 | 15 49 46.3 | 30.83 | 117.01 | 2.7 |
| Sep 04 | 23 17 42.4 | 30.79 | 116.97 | 4.5 |
| 04 | 23 20 30.4 | 30.79 | 116.97 | 3.9 |
| 05 | 21 31 37.1 | 30.76 | 116.91 | 2.7 |
| 07 | 12 23 56.4 | 30.82 | 116.97 | 2.3 |
| 09 | 09 42 05 | 30.8 | 117.0 | 2.2 |
| Oct 03 | 04 12 27.2 | 30.77 | 116.96 | 2.9 |
| 03 | 20 41 49.3 | 30.78 | 116.97 | 3.1 |
| Nov 05 | 20 24 50.1 | 30.65 | 117.16 | 3.1 |
| *1975* | | | | |
| Jan 21 | 01 50 07.5 | 30.83 | 117.08 | 2.9 |
| May 01 | 13 33 15.7 | 30.90 | 117.13 | 3.1 |
| Aug 23 | 19 23 00.3 | 30.77 | 116.90 | 3.5 |
| Sep 04 | 20 41 09.7 | 30.77 | 116.90 | 2.5 |
| 19 | 12 54 46.0 | 30.76 | 116.92 | 2.6 |
| Oct 25 | 16 50 38.5 | 30.77 | 116.96 | 2.2 |
| Dec 06 | 15 28 46.3 | 30.93 | 117.09 | 2.1 |
| *1976* | | | | |
| Mar 04 | 16 09 03.9 | 30.9 | 117.0 | 2.0 |
| May 11 | 09 26 49.0 | 30.9 | 117.09 | 2.5 |

TABLE 9. EARTHQUAKES IN THE CADOUX AREA, 1959 TO 1978 (cont'd)

| *Date* | *Origin time (U.T.)* | *Epicentre Lat.* °*S* | *Long.* °*E* | $M_L$ |
|---|---|---|---|---|
| *1977* | | | | |
| May 10 | 10 38 50.3 | 30.75 | 116.88 | 2.3 |
| 10 | 12 52 28.5 | 30.75 | 116.88 | 2.0 |
| Sep 30 | 11 48 13.7 | 30.5 | 117.2 | 2.2 |
| *1978* | | | | |
| Oct 28 | 03 26 01.4 | 30.90 | 117.23 | 3.6 |

TABLE 10. THE CADOUX EARTHQUAKE SWARM OF 1979-1980 ($M_L$ >3.0)
(after Gregson, 1980)

| *Date* | *Origin time (U.T.)* | *Epicentre Lat. °S* | *Long. °E* | *Depth (km)* | $M_L$ | *Remarks* |
|---|---|---|---|---|---|---|
| *1979* | | | | | | |
| Mar 13 | 07 29 42.1 | 30.85 | 117.20 | 16 | 3.9 | Felt MMIII |
| 14 | 23 45 46.8 | 30.88 | 117.18 | 12 | 3.7 | Felt MMIV |
| 14 | 23 49 04.6 | 38.88 | 117.18 | 12 | 3.2 | Felt MMIII |
| 15 | 17 34 45.7 | 30.88 | 117.18 | 12 | 3.1 | |
| Apr 06 | 21 47 23.5 | 30.80 | 117.09 | 12 | 3.0 | |
| May 10 | 19 33 16.8 | 30.91 | 117.17 | 8 | 3.1 | |
| Jun 01 | 21 54 02.9 | 30.83 | 117.17 | 17 | 5.2 | Principal foreshock,MMVI |
| 01 | 22 38 28.9 | 30.86 | 117.15 | 12 | 3.3 | |
| 02 | 01 34 55.4 | 30.85 | 117.16 | 10 | 3.8 | |
| 02 | 02 13 35.3 | 30.85 | 117.14 | 16 | 3.4 | |
| 02 | 02 13 50.0 | 30.85 | 117.14 | 16 | 3.4 | |
| 02 | 03 11 51.3 | 30.87 | 117.16 | 8 | 3.0 | |
| 02 | 09 48 01.0 | 30.83 | 117.15 | 15 | 6.2 | Main earthquake,MMIX |
| 02 | 10 00 17.8 | - | - | - | 3.7 | |
| 02 | 10 05 31.9 | - | - | - | 3.3 | |
| 02 | 10 09 21.9 | - | - | - | 3.0 | |
| 02 | 10 16 52.9 | - | - | - | 3.4 | |
| 02 | 10 33 11.9 | - | - | - | 3.0 | |
| 02 | 10 37 21.8 | - | - | - | 3.6 | |
| 02 | 10 40 53.7 | - | - | - | 3.6 | |
| 02 | 10 44 22.8 | - | - | - | 3.3 | |
| 02 | 11 04 57.2 | 30.80 | 117.21 | 13 | 4.1 | |
| 02 | 11 36 09.6 | - | - | - | 3.3 | |
| 02 | 11 47 52.8 | 30.78 | 117.24 | 7 | 3.8 | |
| 02 | 12 27 28.0 | 30.72 | 117.13 | 10 | 3.4 | |
| 02 | 17 08 54.6 | 30.79 | 117.16 | 13 | 3.7 | |
| 02 | 17 30 39.8 | - | - | - | 3.5 | |
| 02 | 19 24 44.9 | 30.77 | 117.25 | 17 | 3.4 | |
| 02 | 20 08 31.0 | 30.80 | 117.21 | 4 | 3.2 | |
| 02 | 21 00 30.9 | 30.77 | 117.23 | 13 | 3.3 | |
| 02 | 21 28 49.5 | 30.76 | 117.20 | 4 | 3.0 | |

TABLE 10. THE CADOUX EARTHQUAKE SWARM OF 1979-1980 (cont'd)

| *Date* | *Origin time (U.T.)* | *Epicentre Lat. °S* | *Long. °E* | *Depth (km)* | $M_L$ | *Remarks* |
|---|---|---|---|---|---|---|
| Jun 03 | 04 21 33.0 | 30.87 | 117.13 | 15 | 3.1 | |
| 03 | 07 45 34.5 | 30.77 | 117.17 | 10 | 5.3 | Major aftershock, MMVI |
| 03 | 20 54 13.4 | 30.78 | 117.14 | 14 | 3.5 | |
| 04 | 04 13 16.3 | 30.84 | 117.21 | 12 | 3.3 | |
| 04 | 06 03 30.3 | 30.81 | 117.11 | 6 | 3.1 | |
| 04 | 14 30 41.4 | 30.86 | 117.19 | (10) | 3.1 | |
| 04 | 16 27 03.3 | 30.75 | 117.16 | (10) | 3.0 | |
| 05 | 00 23 10.3 | - | - | - | 3.3 | |
| 05 | 10 25 36.5 | 30.85 | 117.18 | 7 | 3.1 | |
| 05 | 11 33 32.5 | 30.86 | 117.18 | 7 | 3.0 | |
| 06 | 05 04 29.5 | 30.84 | 117.16 | 12 | 3.3 | |
| 06 | 06 17 32.9 | 30.78 | 117.23 | 12 | 3.1 | |
| 06 | 17 36 53.1 | 30.73 | 117.16 | 14 | 3.5 | |
| 07 | 06 45 16.1 | 30.81 | 117.16 | 12 | 5.5 | Major aftershock |
| 07 | 22 33 30.4 | 30.73 | 117.16 | 9 | 4.0 | |
| 10 | 18 24 52.6 | 30.78 | 117.19 | 12 | 4.3 | Felt MMV |
| 12 | 02 23 15.0 | 30.86 | 117.18 | (10) | 3.1 | |
| 12 | 22 15 10.9 | 30.87 | 117.16 | 13 | 3.1 | |
| 14 | 21 31 43.1 | 30.85 | 117.09 | 13 | 3.5 | |
| 15 | 16 18 54.9 | 30.87 | 117.13 | 19 | 3.1 | |
| 18 | 05 03 49.2 | 30.79 | 117.19 | 11 | 3.1 | |
| 22 | 19 53 49.4 | 30.84 | 117.08 | 23 | 3.4 | |
| 25 | 11 40 51.3 | 30.84 | 117.08 | 15 | 3.3 | |
| 27 | 01 58 51.0 | 30.80 | 117.17 | 5 | 3.0 | |
| Jul 16 | 23 50 35.3 | 30.75 | 117.19 | 3 | 3.1 | |
| Aug 06 | 17 13 08.8 | 30.80 | 117.13 | 15 | 2.9 | |
| 07 | 00 20 40.0 | 30.76 | 117.13 | (0) | 3.0 | |
| 23 | 21 36 49.2 | 30.76 | 117.07 | 19 | 3.0 | |
| 26 | 07 00 43.3 | 30.79 | 117.19 | 4 | 3.1 | |
| Sep 08 | 11 18 07.3 | 30.79 | 117.21 | 3 | 2.9 | |
| 10 | 09 01 07.4 | 30.72 | 117.21 | 13 | 3.3 | |
| 21 | 10 49 31.9 | 30.74 | 117.12 | 12 | 3.1 | |
| Oct 11 | 04 04 11.7 | 30.79 | 117.15 | 15 | 4.8 | Felt MMV |

TABLE 10. THE CADOUX EARTHQUAKE SWARM OF 1979-1980 (cont'd)

| *Date* | *Origin time (U.T.)* | *Lat.°S* | *Long.°E* | *Depth (km)* | $M_L$ | *Remarks* |
|---|---|---|---|---|---|---|
| Dec 11 | 02 50 57.1 | 30.97 | 117.19 | 12 | 3.1 | |
| 17 | 09 54 03.9 | 30.95 | 117.20 | 12 | 3.9 | |
| 20 | 19 47 42.7 | 30.82 | 117.19 | 12 | 3.3 | |
| 20 | 20 14 08.1 | 30.92 | 117.20 | 18 | 3.4 | |
| 26 | 18 41 15.4 | 30.74 | 117.16 | 3 | 3.0 | |
| *1980* | | | | | | |
| Jan 28 | 19 35 44.7 | 30.83 | 117.21 | 3 | 2.9 | |
| Feb 06 | 17 17 11.5 | 30.82 | 117.23 | 3 | 3.2 | |
| Apr 05 | 04 58 38.0 | 30.87 | 117.16 | 5 | 3.1 | |
| Jun 01 | 07 22 30.3 | 30.85 | 117.18 | 13 | 3.7 | Felt MMV |

TABLE 11. MINOR EARTHQUAKES IN THE CADOUX REGION, 1979-1980 ($M_L$ 1.9-2.9) (after Gregson, 1980)

| *Date* | *Origin time (U.T.)* | $M_L$ | *Date* | *Origin time (U.T.)* | $M_L$ |
|---|---|---|---|---|---|
| *1979* | | | | | |
| Mar 09 | 07 34 57.7 | 2.4 | Jun 02 | 19 47 34.1 | 2.3 |
| 13 | 08 28 48.6 | 2.2 | 02 | 19 48 48.7 | 2.2 |
| 15 | 03 14 55.1 | 2.3 | 02 | 21 35 25.9 | 2.9 |
| 15 | 05 57 48.0 | 2.1 | 02 | 22 10 12.9 | 2.5 |
| 16 | 09 38 27.0 | 2.2 | 02 | 22 15 12.9 | 2.6 |
| Apr 03 | 16 20 45.4 | 2.1 | 02 | 22 26 12.6 | 2.4 |
| Jun 01 | 22 06 02.2 | 2.1 | 02 | 22 26 32.6 | 2.7 |
| 01 | 22 11 42.6 | 2.2 | 02 | 23 22 23.2 | 2.2 |
| 01 | 22 16 07.9 | 2.3 | 03 | 00 01 57.5 | 2.4 |
| 01 | 22 22 09.4 | 2.7 | 03 | 01 19 44.0 | 2.3 |
| 01 | 22 38 38.4 | 2.4 | 03 | 03 01 23.0 | 2.4 |
| 02 | 00 27 34.0 | 2.0 | 03 | 03 07 29.3 | 2.5 |
| 02 | 00 27 47.2 | 2.7 | 03 | 03 20 42.6 | 2.4 |
| 02 | 00 50 50.4 | 2.7 | 03 | 03 36 16.8 | 2.3 |
| 02 | 01 46 50.4 | 2.6 | 03 | 03 57 25.8 | 2.4 |
| 02 | 07 19 58.1 | 2.3 | 03 | 09 54 40.7 | 2.9 |
| 02 | 12 11 22.0 | 2.2 | 03 | 11 11 09.9 | 2.8 |
| 02 | 12 20 15.5 | 2.5 | 03 | 11 12 54.4 | 2.3 |
| 02 | 12 31 42.9 | 2.6 | 03 | 15 20 58.0 | 2.4 |
| 02 | 12 38 11.7 | 2.5 | 03 | 16 34 08.9 | 2.2 |
| 02 | 12 59 50.1 | 2.4 | 03 | 17 13 57.9 | 2.8 |
| 02 | 13 00 26.3 | 2.6 | 03 | 19 17 39.3 | 2.8 |
| 02 | 14 18 21.8 | 2.3 | 04 | 02 26 02.2 | 2.9 |
| 02 | 14 51 43.5 | 2.4 | 04 | 02 46 42.7 | 2.7 |
| 02 | 15 48 20.0 | 2.4 | 04 | 03 52 39.7 | 2.8 |
| 02 | 16 11 33.1 | 2.4 | 04 | 06 24 17.7 | 2.6 |
| 02 | 17 19 46.8 | 2.8 | 04 | 09 22 14.8 | 2.1 |
| 02 | 17 47 26.9 | 2.5 | 04 | 12 58 38.4 | 2.5 |
| 02 | 18 10 23.0 | 2.3 | 04 | 13 31 51.8 | 2.7 |
| 02 | 18 12 00.9 | 2.4 | 04 | 14 14 03.9 | 2.7 |
| 02 | 18 53 50.7 | 2.5 | 04 | 14 16 13.8 | 2.8 |
| 02 | 19 21 34.6 | 2.2 | 04 | 19 39 30.5 | 2.0 |

TABLE 11. MINOR EARTHQUAKES IN THE CADOUX REGION, 1979-1980 (cont'd)

| *Date* | *Origin time (U.T.)* | $M_L$ | *Date* | *Origin time (U.T.)* | $M_L$ |
|---|---|---|---|---|---|
| Jun 05 | 01 26 18.0 | 2.6 | Jun 19 | 23 21 43.1 | 2.3 |
| 05 | 04 51 19.7 | 2.4 | 20 | 21 37 17.1 | 2.4 |
| 05 | 06 57 13.1 | 2.3 | 21 | 11 59 59.1 | 2.0 |
| 05 | 09 00 31.5 | 2.3 | 21 | 17 56 20.1 | 2.0 |
| 05 | 13 35 02.9 | 2.4 | 22 | 07 28 26.7 | 2.4 |
| 05 | 18 57 45.3 | 2.7 | 23 | 10 01 04.2 | 2.2 |
| 05 | 19 26 21.1 | 2.9 | 24 | 00 28 53.6 | 2.5 |
| 06 | 00 43 27.7 | 2.3 | 25 | 07 02 14.6 | 2.1 |
| 06 | 06 09 58.3 | 2.4 | 25 | 11 16 20.6 | 2.7 |
| 06 | 18 19 28.3 | 2.1 | 25 | 20 11 40.9 | 2.4 |
| 06 | 23 03 58.2 | 2.1 | 30 | 18 42 29.1 | 2.1 |
| 07 | 00 59 38.8 | 2.4 | Jul 03 | 00 32 54.3 | 2.0 |
| 07 | 07 03 13.3 | 2.4 | 04 | 01 44 22.5 | 2.1 |
| 07 | 07 47 40.9 | 2.4 | 05 | 11 01 34.5 | 2.4 |
| 07 | 14 41 49.6 | 2.4 | 08 | 03 09 20.7 | 2.1 |
| 07 | 16 59 23.2 | 2.6 | 12 | 19 25 57.5 | 2.7 |
| 07 | 23 18 13.1 | 2.5 | 17 | 18 27 52.3 | 2.5 |
| 07 | 23 38 10.8 | 2.4 | 19 | 02 06 25.2 | 2.3 |
| 08 | 00 28 33.3 | 2.7 | 22 | 15 14 58.9 | 2.7 |
| 08 | 09 48 02.3 | 2.5 | 26 | 07 55 48.6 | 2.9 |
| 08 | 13 08 40.4 | 2.5 | 26 | 12 27 08.9 | 2.5 |
| 08 | 16 44 49.5 | 2.0 | 28 | 05 34 42.0 | 2.1 |
| 10 | 01 20 53.6 | 2.4 | 28 | 12 07 21.8 | 2.1 |
| 11 | 11 56 48.8 | 2.3 | Aug 02 | 08 10 27.9 | 2.0 |
| 12 | 12 58 21.5 | 2.3 | 04 | 20 01 24.0 | 2.1 |
| 12 | 22 25 31.9 | 2.1 | 06 | 16 48 16.1 | 2.0 |
| 13 | 10 34 04.6 | 2.2 | 07 | 14 06 27.4 | 2.1 |
| 13 | 11 38 33.9 | 2.7 | 08 | 02 02 40.5 | 2.3 |
| 15 | 05 19 07.9 | 2.3 | 08 | 07 06 01.9 | 2.0 |
| 15 | 23 24 25.3 | 2.7 | 08 | 07 07 37.5 | 2.0 |
| 16 | 14 35 02.6 | 2.3 | 12 | 23 05 16.6 | 2.0 |
| 17 | 03 27 44.1 | 2.1 | 14 | 08 28 21.3 | 2.3 |
| 18 | 08 54 24.1 | 2.5 | 15 | 12 46 37.8 | 2.8 |
| 19 | 19 21 28.5 | 2.8 | 19 | 03 29 27.5 | 2.0 |

TABLE 11. MINOR EARTHQUAKES IN THE CADOUX REGION, 1979-1980 (cont'd)

| *Date* | *Origin time (U.T.)* | $M_L$ | *Date* | *Origin time (U.T.)* | $M_L$ |
|---|---|---|---|---|---|
| Aug 20 | 04 51 44.6 | 2.3 | Dec 26 | 16 09 03.5 | 2.6 |
| 28 | 07 16 56.6 | 2.5 | 29 | 17 13 27.0 | 2.3 |
| 29 | 21 11 37.5 | 2.0 | 31 | 17 35 37.5 | 2.5 |
| Sep 10 | 05 58 06.9 | 2.2 | *1980* | | |
| 13 | 17 47 52.6 | 2.3 | Jan 04 | 14 27 35.6 | 2.3 |
| 15 | 13 13 24.2 | 2.0 | 04 | 15 35 11.1 | 2.5 |
| 20 | 13 26 54.8 | 2.4 | 04 | 15 41 05.0 | 2.4 |
| Oct 02 | 02 22 42.6 | 2.0 | 10 | 12 57 17.9 | 2.3 |
| 06 | 11 22 54.3 | 2.3 | 21 | 20 09 34.5 | 2.3 |
| 17 | 09 38 33.2 | 2.1 | 22 | 05 29 37.2 | 2.3 |
| 23 | 06 30 14.3 | 2.4 | Feb 06 | 16 57 37.0 | 2.0 |
| 27 | 18 10 06.8 | 2.3 | 07 | 02 26 54.4 | 2.5 |
| Nov 02 | 11 23 07.6 | 2.1 | 11 | 06 29 23.3 | 2.4 |
| 03 | 16 58 23.5 | 2.0 | Mar 08 | 19 39 - | 2.0 |
| 10 | 15 33 55.2 | 2.0 | May 04 | 06 23 04.0 | 2.3 |
| 13 | 02 24 14.0 | 2.1 | 06 | 00 27 13.6 | 2.2 |
| 14 | 18 26 14.1 | 2.5 | 14 | 08 30 48.8 | 2.6 |
| 15 | 11 29 44.1 | 2.0 | 16 | 15 44 31.0 | 2.1 |
| 22 | 22 37 11.5 | 2.6 | 25 | 23 48 12.7 | 2.4 |
| Dec 10 | 07 31 22.3 | 2.5 | 28 | 21 03 37.6 | 2.3 |
| 11 | 04 44 07.1 | 2.5 | 30 | 16 49 29.9 | 2.1 |
| 11 | 05 02 33.1 | 2.1 | 31 | 10 30 10.4 | 2.5 |
| 12 | 06 37 52.2 | 2.1 | Jun 02 | 04 34 18.5 | 2.6 |
| 17 | 10 35 48.0 | 2.1 | 14 | 10 10 14.8 | 2.1 |
| 17 | 10 36 05.1 | 2.3 | 20 | 03 29 46.9 | 2.0 |
| 21 | 05 57 40.3 | 2.5 | 20 | 10 26 37.1 | 2.0 |
| 21 | 06 03 10.3 | 2.8 | 27 | 02 00 02.0 | 2.3 |

# APPENDIX II

## RELEVELLING OF BENCHMARKS IN THE CADOUX-KOORDA AREA

The relevelling of benchmarks along the main PWD water-supply pipeline in the vicinity of Cadoux was undertaken by the Australian Survey Office in July 1979. After encouraging results from this work the survey was extended in March 1980, with the assistance of the Western Australian Lands and Surveys Department. Absolute height determinations were made initially on the assumption that the benchmarks KD80 to KD73, which maintained the same relative heights as the original survey of 1963-4, had not been displaced. This was later supported by incorporating a new traverse between K8 and KD9 which showed that KD6 to KD9 had not been displaced.

In February 1981 the survey was extended south to Cunderdin by R. Payne and G. Lockhart of the Department of Surveying, Western Australian Institute of Technology, to give a complete traverse of the affected area from north to south.

The benchmarks surveyed by the Australian Survey Office are shown in Figure 54, and the complete levelling results in Tables 12 and 13.

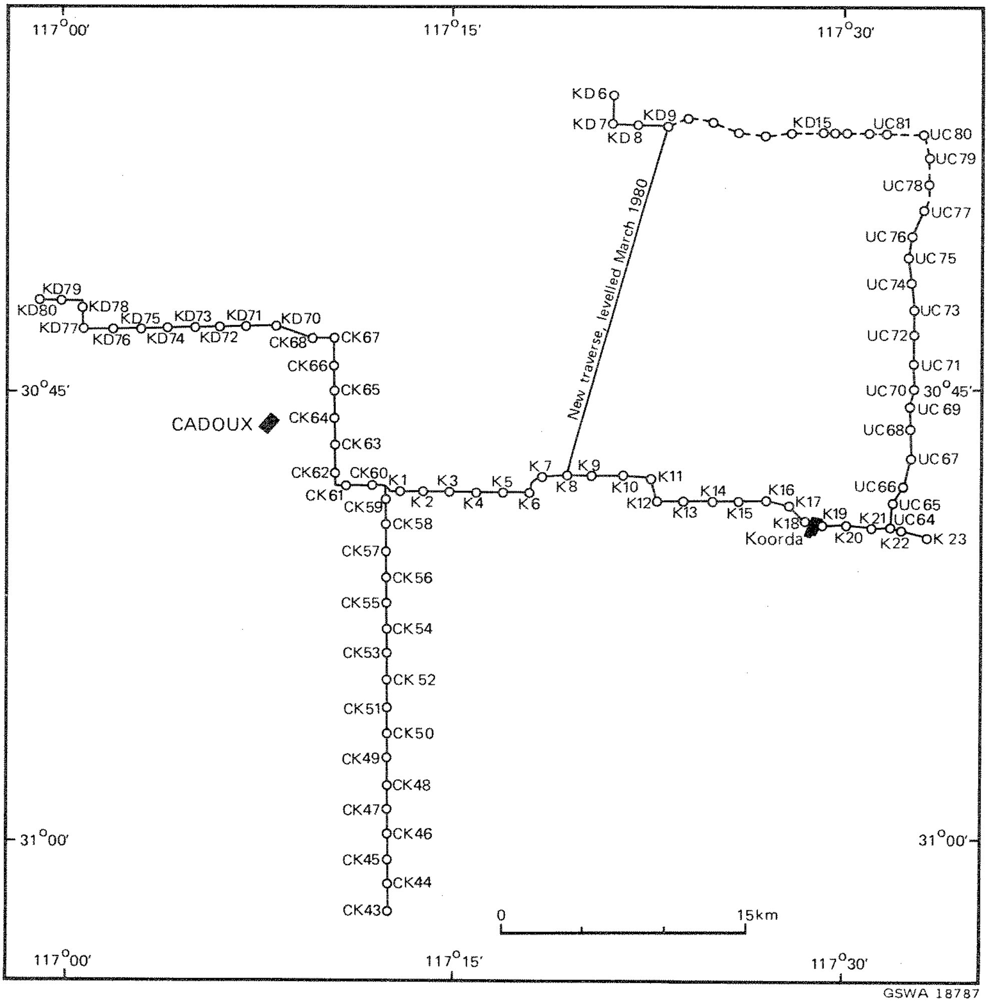


Figure 54. Benchmarks relevelled in the Cadoux-Koorda area, 1979-1980



15121—10

TABLE 12. RELEVELLING OF BENCHMARKS IN THE CADOUX-KOORDA AREA (JULY 1979 AND MARCH 1980)

| *Benchmark* | *Original level (1963) (m above MSL at Fremantle)* | *Adopted level (1980) (m)* | *Difference (m)* |
|---|---|---|---|
| KD80 | 310.586 | 310.586 | 0.000 |
| KD79 | 306.198 | 306.198 | 0.000 |
| KD78 | 304.716 | 304.716 | 0.000 |
| KD77 | 295.068 | 295.068 | 0.000 |
| KD76 | 297.407 | 297.407 | 0.000 |
| KD75 | 305.408 | 305.408 | 0.000 |
| KD74 | 312.836 | 312.836 | 0.000 |
| KD73 | 326.739 | 326.739 | 0.000 |
| KD72 | 337.618 | 337.618 | 0.000 |
| KD71 | 354.712 | 354.725 | +0.013 |
| KD70 | 386.984 | 387.087 | +0.103 |
| | Traverse intersected by the Tank Fault | | |
| CK68 | 388.372 | 388.958 | +0.586 |
| CK67 | 364.375 | 364.415 | +0.040 |
| CK66 | 360.060 | 360.152 | +0.092 |
| CK65 | 363.640 | 363.733 | +0.093 |
| CK64 | 359.131 | 359.243 | +0.112 |
| CK63 | 373.805 | 373.910 | +0.105 |
| CK62 | 379.598 | 379.725 | +0.127 |
| CK61 | 371.739 | 371.979 | +0.240 |
| CK60 | 364.247 | 364.438 | +0.191 |
| CK59 | 393.475 | 393.722 | +0.247 |
| CK58 | 373.690 | 373.862 | +0.172 |
| CK57 | 359.887 | 360.036 | +0.149 |
| CK56 | 337.689 | 337.840 | +0.151 |
| CK55 | 326.234 | 326.342 | +0.108 |
| CK54 | 324.104 | 324.206 | +0.102 |
| CK53 | 304.693 | 304.794 | +0.101 |
| CK52 | 308.234 | 308.367 | +0.133 |
| CK51 | 329.087 | 329.247 | +0.160 |
| CK50 | 326.104 | 326.245 | +0.141 |
| CK49 | 308.431 | 308.577 | +0.146 |

TABLE 12. RELEVELLING OF BENCHMARKS IN THE CADOUX-KOORDA AREA (cont'd)

| *Benchmark* | *Original level (1963) (m above MSL at Fremantle)* | *Adopted level (1980) (m)* | *Difference (m)* |
|---|---|---|---|
| CK49 | 308.431 | 308.577 | +0.146 |
| CK48 | 295.436 | 295.621 | +0.185 |
| CK47 | 289.159 | 289.331 | +0.172 |
| CK46 | 285.338 | 285.451 | +0.113 |
| CK45 | 306.340 | 306.529 | +0.189 |
| CK44 | 307.967 | 308.064 | +0.097 |
| CK43 | 309.773 | 309.867 | +0.094 |
| (For continuation of this line see Table 13) | | | |
| K1 | 365.794 | 366.043 | +0.249 |
| K2 | 343.611 | 343.883 | +0.272 |
| K3 | 320.586 | 320.875 | +0.289 |
| K4 | 313.341 | 313.612 | +0.271 |
| K5 | 303.880 | 304.185 | +0.305 |
| K6 | 302.356 | 302.691 | +0.335 |
| K7 | 300.031 | 300.386 | +0.355 |
| K8 | 305.667 | 306.018 | +0.351 |
| K9 | 316.204 | 316.543 | +0.339 |
| K10 | 346.358 | 346.618 | +0.260 |
| K11 | 364.182 | 364.444 | +0.262 |
| K12 | 357.601 | 357.886 | +0.285 |
| K13 | 337.109 | 337.416 | +0.307 |
| K14 | 318.212 | 318.548 | +0.336 |
| K15 | 300.844 | 301.190 | +0.346 |
| K16 | 297.391 | 297.724 | +0.333 |
| K17 | 314.469 | 314.752 | +0.283 |
| K18 | 300.027 | 300.314 | +0.287 |
| K19 | 316.139 | 316.383 | +0.244 |
| K20 | 330.065 | 330.279 | +0.214 |
| K21 | 352.596 | 352.754 | +0.158 |
| UC64 | 358.464 | 358.642 | +0.178 |
| K22 | 357.820 | 357.973 | +0.153 |
| K23 | 363.904 | 364.053 | +0.149 |

TABLE 12. RELEVELLING OF BENCHMARKS IN THE CADOUX-KOORDA AREA (cont'd)

| *Benchmark* | *Original level (1963) (m above MSL at Fremantle)* | *Adopted level (1980) (m)* | *Difference (m)* |
|---|---|---|---|
| UC64 | 358.464 | 358.642 | +0.178 |
| UC65 | 343.780 | 344.004 | +0.224 |
| UC66 | 325.473 | 325.688 | +0.215 |
| UC67 | 319.528 | 319.704 | +0.176 |
| UC68 | 324.483 | 324.667 | +0.184 |
| UC69 | 322.155 | 322.354 | +0.199 |
| UC70 | 351.513 | 351.693 | +0.180 |
| UC71 | 349.705 | 349.882 | +0.177 |
| UC72 | 327.831 | 328.030 | +0.199 |
| UC73 | 330.802 | 331.097 | +0.295 |
| UC74 | 336.546 | 336.745 | +0.199 |
| UC75 | 335.738 | 335.907 | +0.169 |
| UC76 | 358.114 | 358.284 | +0.170 |
| UC77 | 367.120 | 367.282 | +0.162 |
| UC78 | Not found | - | - |
| UC79 | 340.315 | 340.392 | +0.177 |
| UC80 | New B.M.,HV104 | 357.289 | - |
| UC81 | 368.851 | 369.001 | +0.150 |
| UC82-UC84 | Not found | - | - |
| KD15 | 396.166 | 396.166 | 0.000 |
| KD9 | 318.634 | 318.634 | 0.000 |
| KD8 | 326.395 | 326.395 | 0.000 |
| KD7 | 347.541 | 347.541 | 0.000 |
| KD6 | 339.122 | 339.122 | 0.000 |

TABLE 13. RELEVELLING OF BENCHMARKS, COWCOWING LAKES TO CUNDERDIN (FEBRUARY 1981)

| *Benchmark* | *Original level (1963) (m above MSL at Fremantle)* | *Adopted level (1981) (m)* | *Difference (m)* |
|---|---|---|---|
| CK42 | 337.203 | 337.276 | +0.073 |
| CK41 | 336.683 | 336.753 | +0.070 |
| CK40 | 332.369 | 332.432 | +0.063 |
| CK39 | 312.917 | 313.040 | +0.063 |
| CK38 | 301.830 | 301.897 | +0.067 |
| CK37 | 305.265 | 305.304 | +0.039 |
| CK36 | 314.271 | 314.334 | +0.063 |
| CK35 | 324.893 | 324.932 | +0.039 |
| CK34 | 341.629 | 341.659 | +0.030 |
| CK33 | 320.086 | 320.131 | +0.045 |
| CK32 | 329.771 | 329.806 | +0.035 |
| CK31 | B.M. displaced | - | - |
| CK30 | 304.578 | 304.637 | +0.059 |
| CK29 | 289.302 | 289.348 | +0.046 |
| CK28 | 268.108 | 268.158 | +0.050 |
| CK27 | 261.037 | 261.085 | +0.048 |
| CK26 | 255.070 | 255.113 | +0.043 |
| CK25 | 250.658 | 250.709 | +0.051 |
| CK24 | 246.328 | 246.390 | +0.062 |
| CK23 | 245.713 | 245.783 | +0.070 |
| CK22 | 254.919 | 254.973 | +0.054 |
| CK21 | not found | - | - |
| CK20 | 276.631 | 276.669 | +0.038 |
| CK19 | 297.385 | 297.404 | +0.019 |
| CK18 | 288.602 | 288.612 | +0.010 |
| CK17 | 295.065 | 295.048 | -0.017 |
| CK16 | not found | - | - |
| CK15 | 283.697 | 283.695 | -0.002 |
| CK14 | 275.126 | 275.118 | -0.008 |
| CK13 | 290.847 | 290.837 | -0.010 |
| CK12 | 305.887 | 305.876 | -0.011 |
| CK11 | 284.203 | 284.188 | -0.015 |

TABLE 13. RELEVELLING OF BENCHMARKS, COWCOWING LAKES TO CUNDERDIN (cont'd)

| *Benchmark* | *Original level (1963) (m above MSL at Fremantle)* | *Adopted level (1981) (m)* | *Difference (m)* |
|---|---|---|---|
| CK10 | 262.345 | 262.327 | -0.018 |
| CK9 | 255.360 | 255.343 | -0.017 |
| CK8 | 247.782 | 247.763 | -0.019 |
| CK7 | 251.248 | 251.232 | -0.016 |
| CK6 | not found | - | - |
| CK5 | 228.884 | 228.865 | -0.019 |
| CK4 | 215.525 | 215.508 | -0.019 |
| CK3 | 211.439 | 211.426 | -0.017 |
| CK2 | 211.499 | 211.488 | -0.013 |
| CK1 | not found | - | - |

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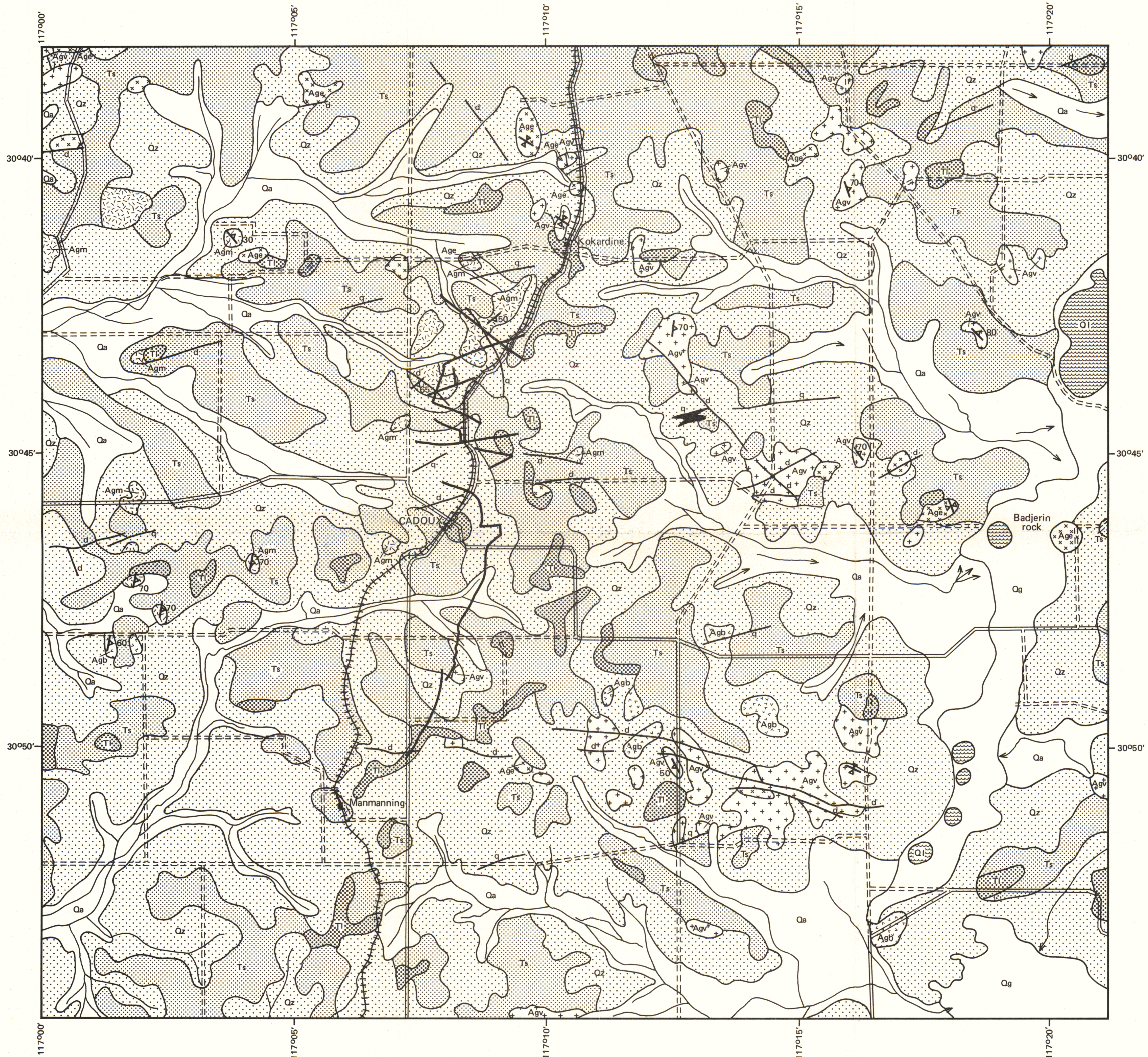


## GEOLOGICAL SURVEY OF WESTERN AUSTRALIA

# GEOLOGY OF THE CADOUX AREA

Mapped by J.A. Bunting, 1979

Scale 1:100 000

0 — 10km

### REFERENCE

- Ql — Lacustrine alluvium; clay, silt and sand in salt lakes
- Qg — Mixed lacustrine alluvium and eolian deposits; clay, silt and sand in small lakes and dunes adjacent to main salinas
- Qa — Alluvium; clay, silt and sand and gravel as valley fill
- Qz — Mixed sheetwash deposits, colluvium and alluvium; red-brown sandy and clayey loam on valley slopes
- Ts — Sand, yellow-white commonly containing limonite nodules. Remnant of tertiary sandplain
- Tl — Laterite and silcrete; grades upward into Ts and downward into weathered bedrock
- d / q — Dykes: d—dolerite, q—quartz
- Age — Biotite adamellite and granite; medium and fine-grained, equigranular, allotriomorphic
- Agv — Variable textured adamellite; medium and coarse-grained, commonly seriate due to continuous variation of microcline phenocrysts up to 6cms
- Agb — Biotite adamellite and granite; medium and coarse-grained, equigranular, allotriomorphic
- Agm — Mixed granitic rocks, not separable on map scale; includes pervasive pegmatites

- Geological boundary
- Fault
- 70 — Igneous foliation, inclined dip
- Igneous foliation, dip unknown
- Road
- Track
- Railway, narrow gauge
- Creek

GSWA 18792


GEOLOGICAL SURVEY OF WESTERN AUSTRALIA
THE CADOUX FAULT SYSTEM
Mapped by J.A. Bunting, N.A. Daetwyler and J.D. Lewis
Scale 1:25 000
0
2km
REFERENCE
Major fault
Fault, position uncertain
Tension fracture
Pressure ridge
Thrust fault, with dip of fault plane
Reverse fault, with dip of fault plane
Right-lateral fault, displacement in metres
Left-lateral fault
Heave of fault, in metres
Throw of fault, in metres, tick on downthrow side
Displacement of fence line, in metres
Calculated resultant displacement vector (see Table 3 for 1 - 6)
Vector scale:
0
1m
Railway reserve
Road
Track
Fence line
Water supply pipeline
Buildings
Major Buildings in Cadoux:-
1. C.B.H. Grain Storage
2. Recreation Complex
3. Cadoux Agency
4. Town Hall
5. Masonic Lodge
6. School
7. Church
8. Post Office and Store
9. Telephone Exchange
10. Golf Course
N
117°10'
To Kalannie
KALAJZIC FAULT
TANK SUBSIDIARY FAULT
TANK FAULT
Kokardine Tank
T.E.Kalajzic
CARTER MAIN THRUST
CARTER BACK THRUST
LINK FAULT
LONE TREE FAULT
C. Carter
CUMMING FAULT
E.W. Cumming
6 600000 mN
30°45'
To Wongan Hills
CADOUX
P. Hopkins
ROBB FAULT
A. Robb
6 595 000 mN
SHIRE OF WONGAN–BALLIDU
SHIRE OF DOWERIN
To Koorda
W.K. Shankland
6 590 000 mN
30°50'
To Dowerin