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GEOLOGY, GEOPHYSICS, AND HYDROCARBON POTENTIAL OF THE WAIGEN AREA, OFFICER BASIN WESTERN AUSTRALIA

by C. D'Ercole, F. Irimies, A. M. Lockwood, and R. M. Hocking

Geological Survey of Western Australia

GEOLOGICAL SURVEY OF WESTERN AUSTRALIA

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Cover photograph:
A breakaway surface of the Carboniferous–Permian Paterson Formation at Point Lilian Rock Hole on the LENNIS 1:250 000 sheet. The photo was taken by H. W. B. Talbot (negative 1500) during the first major geological expedition to the Musgrave Ranges in 1916 (GSWA Bulletin 75)

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Geology, geophysics, and hydrocarbon potential of the Waigen area, Officer Basin, Western Australia

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Abstract

The Waigen area of the western Officer Basin is centred on longitude 128°, latitude 28°, near the Western Australian – South Australian border. With only a single, deep petroleum stratigraphic well, a few shallow mineral exploration drillholes, regional potential-field data acquired in the early 1970s, and the semi-regional gravity data acquired in 1998, it is a poorly understood, underexplored region. The Waigen area contains a deep Neoproterozoic – Lower Cambrian depocentre, which shallows to the north and west towards the Musgrave Complex and Yilgarn Craton respectively, and is covered by a thin, younger Phanerozoic succession to the southeast and east. The northern margin is in thrusted contact with the rocks of the Musgrave Complex. The Waigen area appears to be continuous with the Birksgate Sub-basin in the eastern Officer Basin, South Australia.

The regional structural events that define the supersequence boundaries within the western Officer Basin are attributed to the Areyonga Movement, and the Petermann, Paterson, and Delamerian Orogenies. The Rodingan Movement and Alice Springs Orogeny also influenced the ultimate structural configuration of the basin. Supersequence 3 and 4 strata and the lower part of Supersequence 1 strata are present in the Waigen area, with the upper part of Supersequence 1 inferred at depth. In contrast with South Australian usage, Middle Cambrian volcanic rocks (Table Hill Volcanics) and later rocks that post-date or are synchronous with the Delamerian Orogeny are placed in a separate basin — the Gunbarrel Basin.

A new filtering technique based on the wavelet transform, referred to as the variably downward-continued method, was used to enhance the potential-field data over the Waigen area. This new technique provides a basis for revision of subdivisions of the Officer Basin and a new interpretation of the tectonic history of the area. The data show that the Albany–Fraser Orogen continues northeastward beneath the Waigen area, farther east from its previously inferred position, and extends towards the Musgrave Complex in the north. Deep crustal, circular magnetic features in the area are probably reverse remanently magnetized magma chambers that reflect underplating of the crust by a mantle plume. These intrusions are probably related to the c. 1075 Ma Warakurna magmatic event, or possibly the c. 510 Ma Kalkarinji magmatic event.

Source rocks, reservoirs, and seals are mapped consistently across the adjacent areas of the western and eastern Officer Basin, so they should be present within the Waigen area. The only geochemical data for the area are from Vines 1, which indicate that source rocks are late mature to overmature for oil generation. However, maturity data from adjacent areas suggest that the majority of the Neoproterozoic section is within the oil-generative window. New play possibilities within Supersequence 4 rocks, and equivalent Supersequence 2 and Supersequence 3 rocks if they extend into the study area, are promising within the Waigen area.

KEYWORDS: geophysical interpretation, filtering (geophysics), petroleum exploration, structural geology, petroleum potential, stratigraphy, gravity surveys, magnetic surveys, Waigen, Officer Basin, Albany–Fraser Orogen, Western Australia.

Introduction

The Officer Basin extends west to east from longitude 120°E in Western Australia to 132°30'E in South Australia, a distance of more than 1100 km (Fig. 1). From north to south, it extends from about latitude 22°S to 32°S, a distance of 550 km. The Officer Basin covers a total area of about 525 000 km^2, of which about 300 000 km^2 is in Western Australia. The Officer Basin is the southernmost and westernmost of a series of basins in central Australia (the Officer, Amadeus, Ngalia, and Georgina Basins; Fig. 1) that initially formed during the Neoproterozoic and which for much of their history shared a similar sedimentary evolution. This led to the proposal of the Centralian Superbasin (Walter et al., 1995). The concept is based on an extensional model for initial basin formation, followed by a series of compressional and extensional events in both the Neoproterozoic and

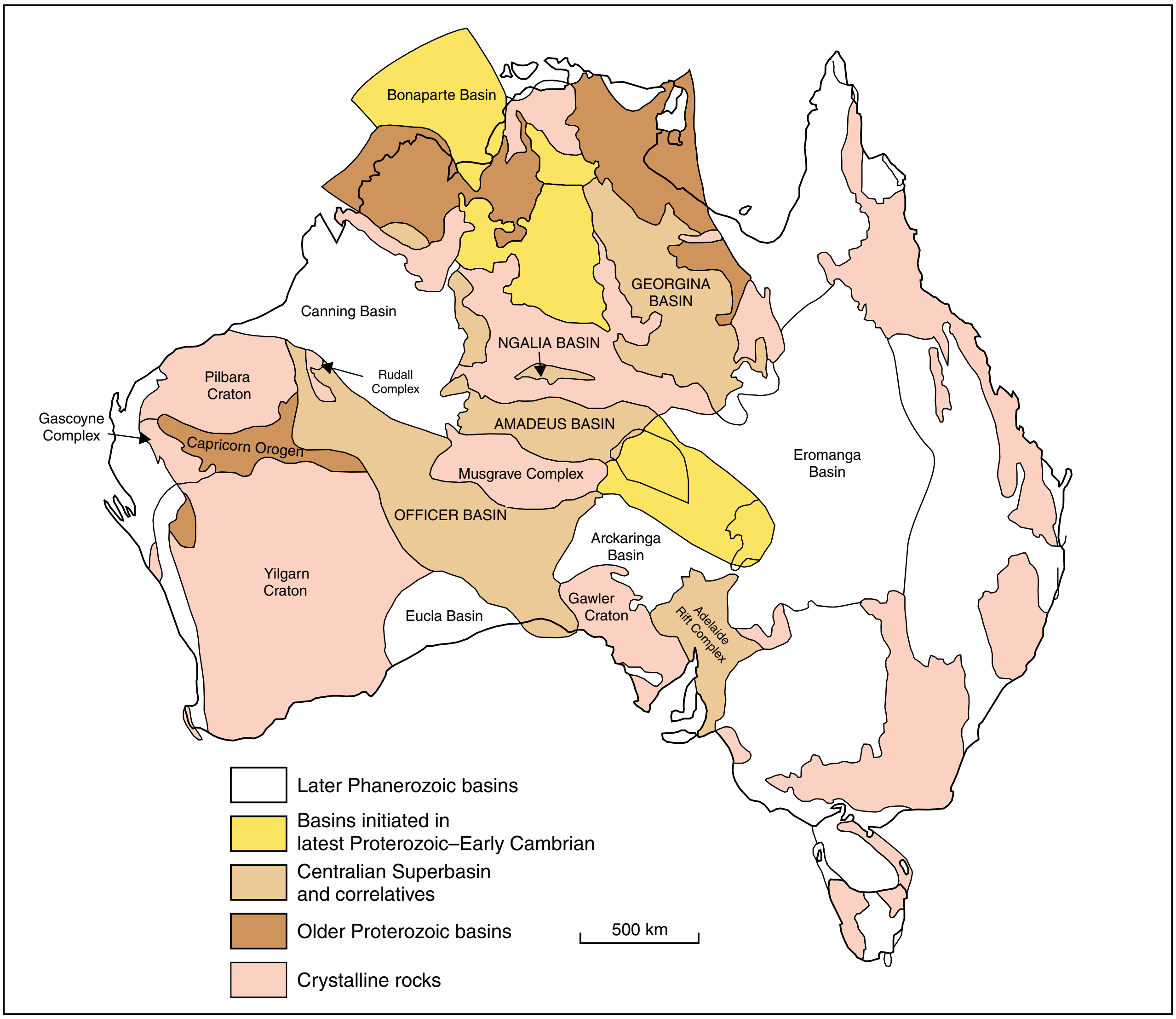

Figure 1. Component basins of the Centralian Superbasin (modified from Lindsay and Korsch, 1991)

Palaeozoic that deformed the superbasin and split it into the basins identified today. The present-day, largely east–west trending, intracratonic basins are remnants of this superbasin. Apak and Moors (2000a,b) interpreted the earliest stages of formation of the Officer Basin as a foreland style of basin, developed against an emergent Musgrave Complex, with the main tectonic movement during the Areyonga Movement (750 Ma).

The Neoproterozoic–Lower Cambrian sedimentary section in the western Officer Basin is commonly up to about 6 km thick, based on seismic data (Apak and Moors, 2000b; Simeonova and Iasky, 2005). The western Officer Basin combined with the overlying Gunbarrel Basin, and possibly an underlying Mesoproterozoic basin (penetrated by some drillholes such as WMC NJD 1, and imaged on deep seismic profiles; Apak and Tyler, 2002) reaches a thickness of up to 12 km, but this represents cumulative stratigraphic thickness rather than the real, deposited thickness. The Officer Basin strata are thickest in an arcuate string of asymmetric troughs that deepen towards the overthrust southern margin of the Musgrave Complex. The troughs are referred to as the Gibson, Yowalga, Lennis, and Waigen areas in Western Australia (Apak et al., 2002a; Apak and Carlsen, 2003; Fig. 2), and the Birksgate Sub-basin and Munyarai Trough in South Australia (Gravestock, 1997; Lindsay, 2002; Fig. 3).

For convenience, the Western Australian part of the basin (Fig. 2) is referred to as the western Officer Basin. This is bounded to the northeast by the Musgrave and Rudall Complexes (which together form the Paterson Orogen) and Warri Arch. In the western Officer Basin, the late Middle Cambrian Table Hill Volcanics and younger sedimentary rocks were excised from the Officer Basin by Hocking (1994) and assigned to a newly defined basin, the Gunbarrel Basin, which extends northwards into the Canning Basin. These conceal the Officer Basin succession except along the margin of the Musgrave Complex and in the northwest, north of the Palaeoproterozoic Earaheedy Basin (Fig. 2). The Gunbarrel Basin contains the entire Middle Cambrian to Cretaceous succession, unlike in

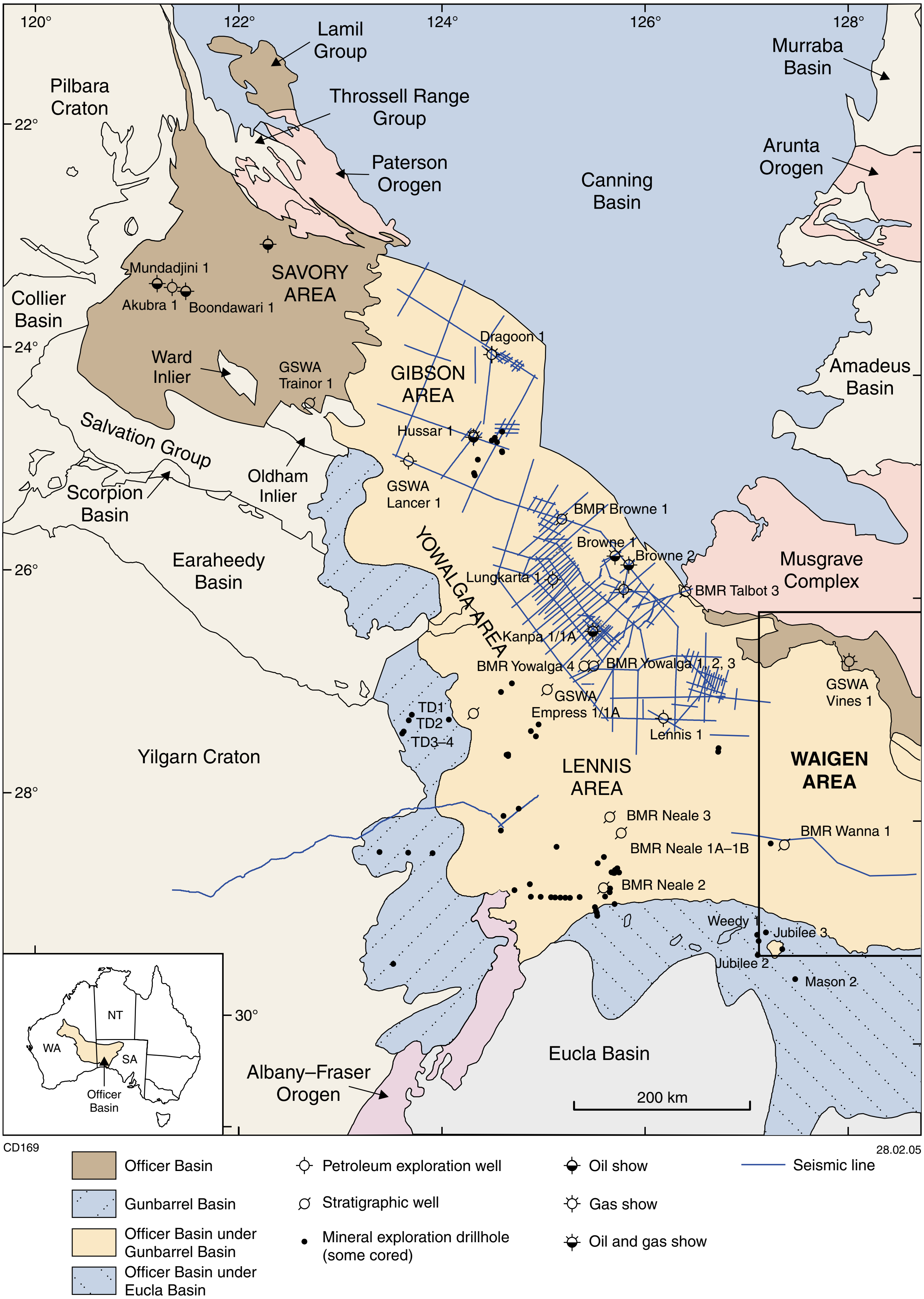

Figure 2. **Seismic coverage, petroleum exploration wells, and mineral exploration drillholes over the western Officer Basin showing the regional tectonic setting and area of interest**

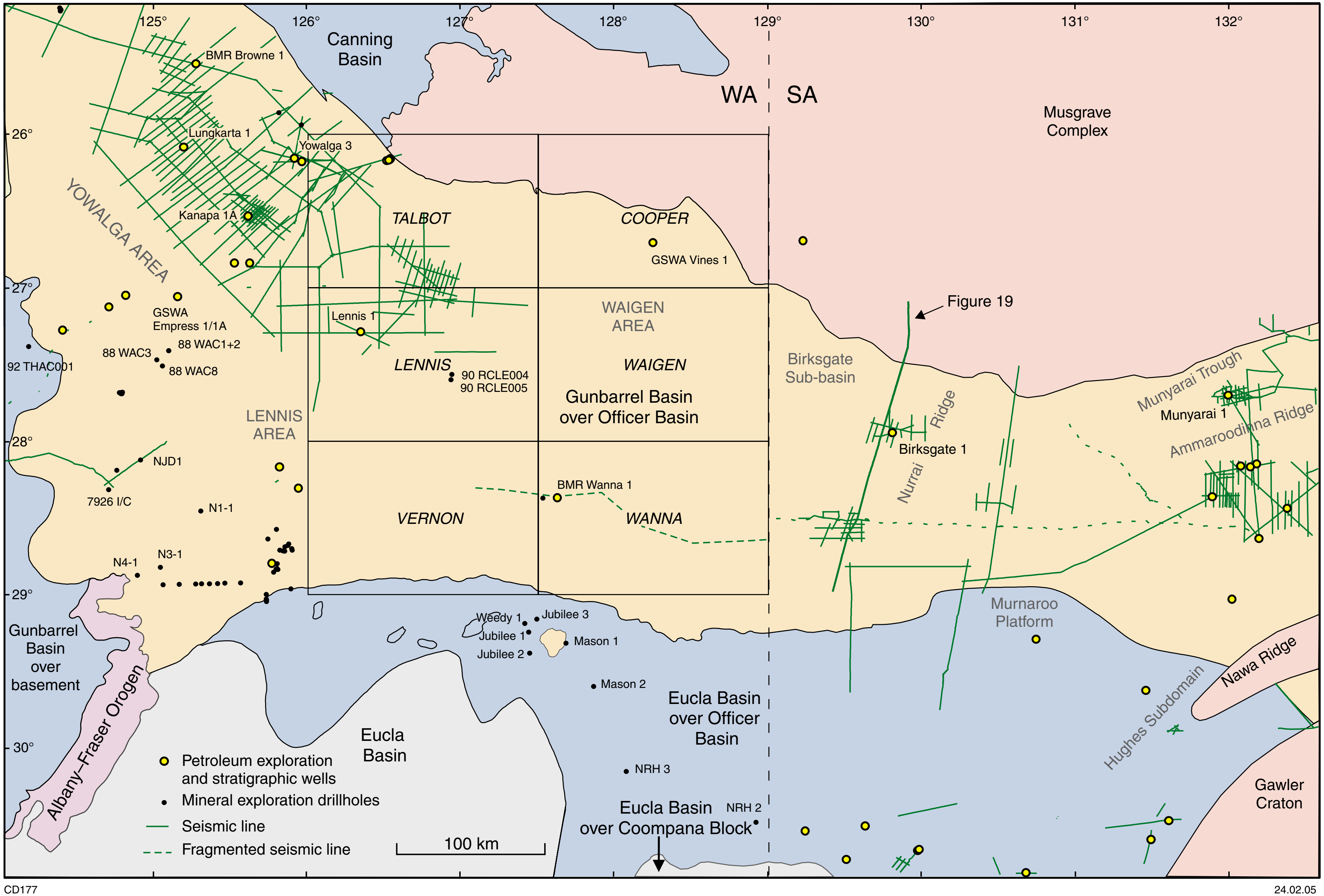

Figure 3. Location map of the Waigen area and adjacent eastern Officer Basin showing petroleum wells, mineral drillholes, and seismic coverage

South Australia where the Carboniferous–Permian and Mesozoic successions are placed in the Arckaringa and Eromanga Basins, respectively. The Eucla Basin onlaps the southern flank of the western Officer Basin. Within Western Australia, the Eucla Basin has traditionally included the entire Mesozoic–Cainozoic section (Lowry, 1970; Hocking, 1994), but in South Australia, only the Cainozoic section is assigned to the Eucla Basin (Benbow et al., 1995), and the Mesozoic section is called the Bight Basin (Hill, 1995). Bradshaw et al. (2003) reviewed the structural framework of the southern Australian margin in both South Australia and Western Australia, placing the Mesozoic succession in the Bight Basin and the Cainozoic in the Eucla Basin; this framework is to be introduced in Western Australia shortly. To the west, the basin is flanked by Archaean and Proterozoic rocks of the Albany–Fraser Orogen, Yilgarn Craton, and Capricorn Orogen.

The portion of the basin in South Australia, referred to as the eastern Officer Basin, is bounded to the north by the Musgrave Complex (referred to as the Musgrave Province in South Australia), and extends south under the Eucla Basin to the Coompana Block and east to the Gawler Craton, although the contact is obscured by the overlying Eromanga (Mesozoic) and Arckaringa (late Palaeozoic) Basins (Fig. 1). The Middle Cambrian to lower Carboniferous rocks assigned to the Gunbarrel Basin in Western Australia, beginning with the Table Hill Volcanics and equivalent Kulyong Formation in South Australia, are included in the Officer Basin in South Australia. The Lower–Middle Cambrian Marla Group or correlatives, if found in Western Australia, would be included in the western Officer Basin.

The Officer Basin is the third-largest onshore sedimentary basin in Australia, and is similar to the productive Amadeus Basin in the Northern Territory and to basins in the former USSR (Kontorovich et al., 1990; Kuznetsov, 1997) and Oman (Alsharan and Nairn, 1997), which contain giant oilfields and gasfields with proven oil reserves in the order of billions of barrels. Few exploration or stratigraphic wells have been drilled in the western Officer Basin, but hydrocarbons have been detected, mainly as gas, live oil, bitumen, fluorescence, and oil stains. The most recent record was a minor gas show at 1482 m in the Geological Survey of Western Australia's (GSWA) stratigraphic test, Vines 1 (Apak et al., 2002b). Based on the basin's size, contained sedimentary succession, and sparse exploration coverage, there is still potential for significant petroleum discoveries in the Officer Basin, which remains significantly underexplored.

The Geological Survey of Western Australia commenced a geological re-evaluation of the Officer Basin in 1994, which has included stratigraphic drilling, geophysical surveys, geochemical analyses, and limited field studies. After a comprehensive data review by Perincek (1998), reports were compiled on the Yowalga area of the central Officer Basin (Apak and Moors, 2000a), which contains the greatest amount of seismic data and well control, followed by the Lennis (Apak and Moors, 2000b) and Gibson (Moors and Apak, 2002) areas. This report deals with the Waigen area, one of the least explored areas of the Officer Basin, and covers the eastern part of the western Officer Basin. Because of the paucity of subsurface data in this area, the scope of the report extends eastwards into the Birksgate area in central-western South Australia (Fig. 3), where there is additional, although limited, drillhole and seismic data.

Previous work

Detailed accounts of the exploration history of the Officer Basin are given in Jackson and van de Graaff (1981) and Perincek (1998). The first major geological investigation of the area was in 1916, when Talbot and Clarke travelled through the Waigen area on the way to their main focus — the Musgrave Ranges. This geological reconnaissance for the Western Australian State Mines Department, following reports of auriferous country by earlier explorers, covered the region from Laverton to the South Australia border (Talbot and Clarke, 1917). Frome Broken Hill and Australasian Oil Exploration Ltd explored for petroleum in the 1950s, and a consortium consisting of the Hunt Oil Company, Hunt Petroleum Corporation, Placid Oil Company, and Exoil Company mounted a petroleum exploration program in the Officer Basin between 1961 and 1966. Five stratigraphic tests were drilled (Browne 1 and 2, Yowalga 1 and 2, and Lennis 1) and various potential-field and seismic surveys were conducted. In 1963, an airphoto interpretation by Hunt Oil Company and Geophoto Services Incorporated defined surface structures on the thickest interpreted sedimentary section in the Yowalga, Lennis, and Waigen areas. In the eastern Officer Basin, a major petroleum exploration program was initiated by Exoil in 1960 and continued by Continental Oil Company (Conoco) after 1966. Surface mapping (Shiels, 1961; Harrison, 1966), together with seismic data, indicated a thick sedimentary section in the South Australian part of the Officer Basin. Two deep stratigraphic wells were drilled: Birksgate 1 (Henderson and Tauer, 1967), located 70 km east of WAIGEN*, intersected mainly middle and upper parts of the Neoproterozoic succession; and Munyarai 1, 300 km east of WAIGEN, bottomed in late Neoproterozoic rocks at 2899 m.

The Bureau of Mineral Resources (BMR — now Geoscience Australia) and GSWA conducted a joint mapping operation in the late 1960s and early 1970s, which included surface mapping, shallow stratigraphic drilling, and the acquisition of gravity and seismic data. This work formed the basis of the bulletin by Jackson and van de Graaff (1981). Between 1980 and 1984, the Shell Company of Australia acquired 4682 line-km of seismic data and drilled three stratigraphic wells (Kanpa 1A, Lungkarta 1, and Yowalga 3). As a result of these investigations, the company divided the Officer Basin into sub-basins, updated the stratigraphy, and discussed basin evolution in relation to petroleum exploration (Townson, 1985). Eagle Corporation conducted an exploration and drilling program in the 1980s, north of the areas held by Shell, and drilled Dragoon 1 and Hussar 1.

* Capitalized names refer to standard 1:250 000 map sheets.

Geological setting

Seismic and well data, where available, indicate that there was remarkable lateral continuity of facies in the western Officer Basin, with relatively little change in deposited thickness other than thinning towards the western margin of the basin. Apak and Moors (2000a,b) considered that the basin does not contain individual depocentres, as previously deduced from potential-field data (Townson, 1985). Gravity lows that were previously thought to define structurally based sub-basins (Townson, 1985; Iasky, 1990) instead are mostly attributed to variations in thickness of the total sedimentary succession, which comprises an underlying Mesoproterozoic sedimentary–volcanic succession, the Officer Basin, and the overlying Gunbarrel Basin. For this reason, the previously named Waigen Sub-basin is now referred to as the Waigen area, pending revised terminology.

The Waigen area contains a sedimentary section that may be more than 10 km thick, comprising a Neoproterozoic – Lower Cambrian succession and an underlying Mesoproterozoic basin, covered by discontinuous Middle Cambrian volcanic rocks and a relatively thin post-Cambrian section to the southeast and east. The Waigen area is in thrusted contact with the Mesoproterozoic Musgrave Complex to the north, and is separated from the Lennis area to the west by a basement high (formerly named the Neale Arch; Fig. 4). Lower Buldya Group rocks are exposed near the Musgrave Complex, and probable Buldya Group rocks are found in the Ilma Inlier within the Eucla Basin, near the southeastern margin of the Officer Basin (Grey et al., 2005). The southern margin of the Waigen area is defined by the mineral drillholes Jubilee 1 and 2, Weedy 1, and Mason 1 and 2. The area may be continuous with the Birksgate Sub-basin in the eastern Officer Basin, although Blundell (1999) noted a gentle gravity ridge between them, possibly indicating some sedimentary thinning.

The only deep well in the Waigen area is Vines 1, a stratigraphic drillhole designed by GSWA to investigate and test the petroleum potential of the Neoproterozoic sequences. The nearest petroleum exploration wells are Lennis 1 (200 km west-southwest), Kanpa 1A (255 km west), Yowalga 3 (285 km west-northwest), and Birksgate 1 (206 km southeast in South Australia; Fig. 3). The nearest, usable seismic line is a line acquired by the Australian Geological Survey Organisation (AGSO) in 1993 in South Australia, which examined the relationship between the northern margin of the Birksgate Sub-basin and the Musgrave Complex. The structural interpretation of the Waigen area is therefore based largely on regional gravity and magnetic datasets together with the Waigen gravity survey, and inferences from reports and papers that deal with the adjacent areas.

Location and access

The Officer Basin occupies a remote, sparsely populated region of Western Australia. The Waigen area lies mainly on WANNA, WAIGEN, and COOPER in the eastern part of the western Officer Basin. Access is via Emu Road — a poorly maintained track that crosses the central part of the area from Laverton, 538 km to the west, to Emu Junction, 322 km to the east, and ultimately Coober Pedy. To the north, the Laverton–Warburton road is a well-maintained gravel road that carries substantial heavy transport during most of the year, and continues through to Mulga Park in South Australia and Yulara in the Northern Territory. There are scattered tracks within and across the basin, most of which are only suitable for 4WD vehicles. Airstrips cater only for light prop-planes. The nearest pipelines are the Goldfields Natural Gas Pipeline in Western Australia, and the Amadeus Basin pipeline system in the Northern Territory, each hundreds of kilometres distant. The Trans-Australian Railway and Eyre Highway give access to the southern part of the area.

Physiography, climate, and vegetation

The Waigen area ranges from about 275 to 500 m above mean sea level, and lies within the Great Victoria Desert. Physiography is largely controlled by an undulating duricrust peneplain, which formed during an earlier, wetter climate and is now covered by sand dunes or featureless sand plains. Relict drainage channels are recognizable over most of the Great Victoria Desert, and drain south into the Eucla Basin. Salt lakes, claypans, calcrete areas, and gypsiferous sand dunes are well developed in the palaeodrainages on WANNA and WAIGEN. Dune shape, lengths, and size vary considerably. Parallel longitudinal sand dunes are characteristic of the Great Victoria Desert, but irregularly shaped network dunes are also common, especially in palaeodrainage depressions (Jackson, 1978). The northern part of the Waigen area is part of an extensive belt of hills extending from Warburton Mission into South Australia. Two northwest-trending belts of quartzite are present in the northeastern corner of WAIGEN. They form prominent, steep-sided rocky ridges, which rise more than 30 m above the surrounding sand plains.

The climate is arid, with an irregular rainfall averaging 200 mm annually and an annual potential evaporation of 3300 mm. Daily temperatures in summer exceed 35°C, and winter is characterized by warm days and cold nights. There is no permanent surface water, but small quantities of groundwater have been obtained from shallow bores.

Vegetation is typically xerophytic, with drought-resistant perennial grasses, including spinifex, and clumps of mallee, mulga, and desert oak, which are common on the extensive laterite and sand plains. Saltbush (samphire) is present in salt lake areas.

Data coverage and previous investigations

Geological mapping

The surface geology in the Waigen area was reported by Jackson and van de Graaff (1981). Explanatory notes for COOPER, WAIGEN, WANNA, TALBOT, LENNIS, and VERNON are

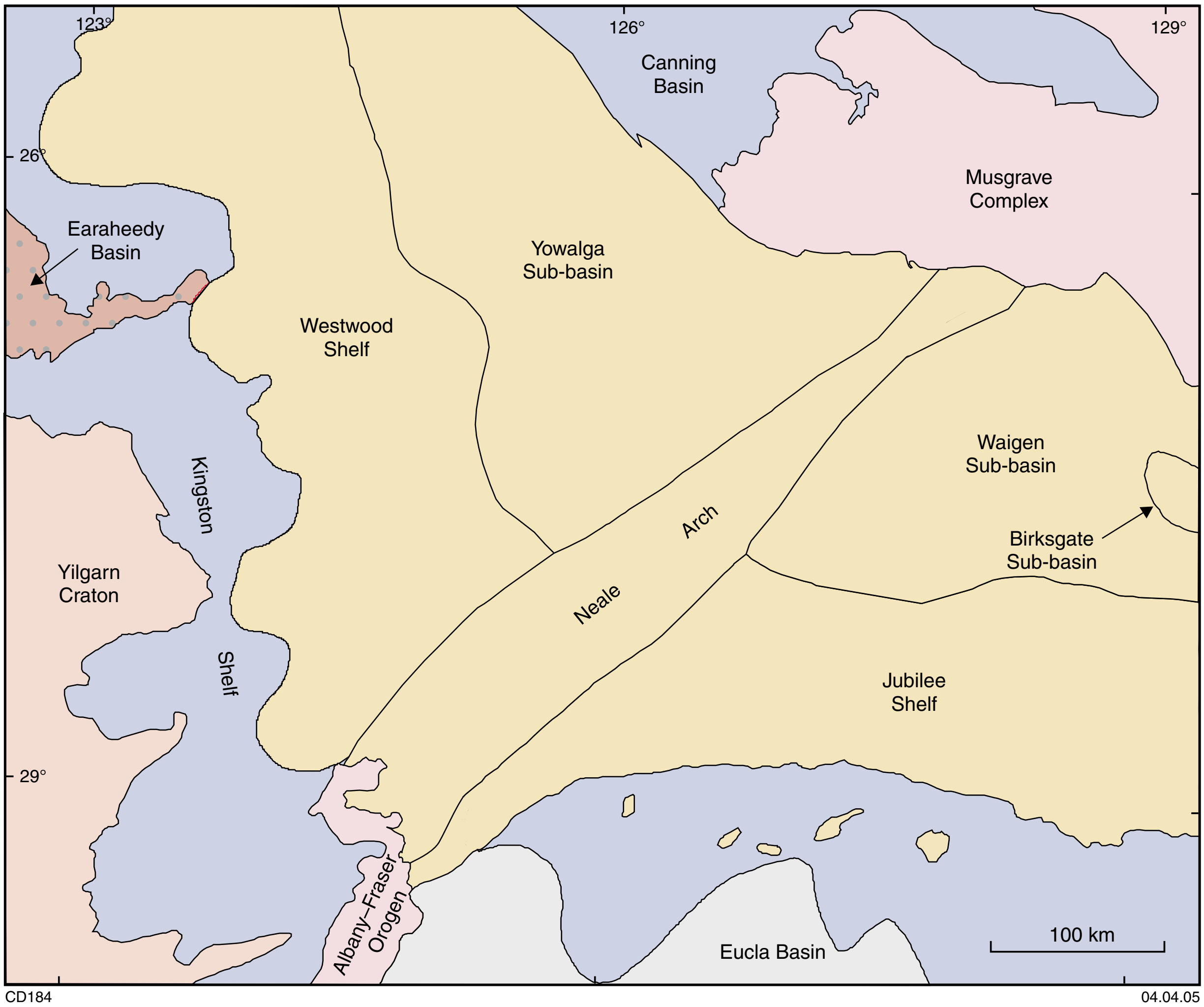

Figure 4. Former tectonic subdivisions of the western Officer Basin (after Iasky, 1990; Hocking, 1994)

by Daniels (1971a), Jackson (1978), Kennewell (1977), Daniels (1971b), Jackson (1977), and van de Graaff (1977) respectively. Cainozoic continental superficial units, up to 30 m thick, cover 95% of the Waigen area, and Permian rocks form flat-lying, low outcrops in the southwestern part of WAIGEN. The Table Hill Volcanics (late Middle Cambrian), Lennis Sandstone (?Ordovician), and Lennis Sandstone (?Devonian) of the Gunbarrel Basin are exposed discontinuously over the area.

The Townsend Quartzite and Lefroy Formation are exposed adjacent to the Musgrave Complex, in a linear outcrop belt centred on the Townsend Range. These were the subject of honours theses at the University of Western Australia by Grigson (1982) and Watts (1982). The majority of outcrops of non-metamorphic rocks on COOPER were mapped as Townsend Quartzite by Daniels (1971a), but the identity of many of these outcrops is doubtful (Grey et al., 2005). Exposures in the Livesay Range on southwest COOPER and outcrops from central COOPER west-southwest of South Hill were assigned to the Punkerri Sandstone by Jackson and van de Graaff (1981). Some of these outcrops consist of dolomite and interbedded sandstone, and contain poorly preserved specimens of the stromatolite *Basisphaera irregularis*, which is characteristic of the Browne Formation (Grey et al., 2005). Farther south, west of Pirrilyungka, sandstone and dolomite outcrops contain *Baicalia burra*, which is a stromatolite characteristic of the upper Buldya Group (Grey et al., 2005).

Drilling

In 1972, BMR drilled BMR Wanna 1 in the southern part of WANNA. At the total depth (TD) of 154.5 m, the drillhole was still in the Permian Paterson Formation. Vines 1 is the only deep drillhole in the Waigen area. It was drilled by GSWA in 1999 to test the stratigraphy and petroleum source potential of the Neoproterozoic rocks in this part of the Officer Basin, and was continuously cored from 44.5 to 2017.5 m (TD). Vines 1 was located by regional aeromagnetic data and a semi-detailed gravity survey (Blundell, 1999), as there are no seismic data within 120 km and the nearest petroleum exploration wells are more than 200 km away. Vines 1 intersected a thick conglomeratic succession, divisible into six units and collectively named the Vines Formation (Apak et al., 2002b; Stevens et al., 2002). No firm correlations can be established between this formation and existing lithostratigraphic units in the Officer Basin. Based on sparse reworked palynomorphs and some palaeomagnetic-pole data, the Vines Formation is of earliest Cambrian age (Apak et al., 2002b; Grey et al., 2005). A gas show was recorded at 1482.9 m, and was probably released from a fracture system noted in the drillcore between about 1425 and 1500 m (Apak et al., 2002b). Although Vines 1 lacks precise chronostratigraphic control and did not reach the major part of the Neoproterozoic succession, it is a key drillhole for understanding the lithostratigraphic development of the Waigen area, and documents the Petermann Orogeny.

Birksgate 1 is a partially cored hydrocarbon-exploration well in the Birksgate Sub-basin, in the eastern Officer Basin, South Australia, drilled by the Continental–Sun-Transoil consortium. The objectives were to resolve many uncertainties connected with the stratigraphic succession within the Officer Basin and to evaluate the hydrocarbon potential of the area. The well was sited on a small, seismically defined anticline, and reached a TD of 1878 m (Henderson and Tauer, 1967). Henderson and Tauer (1967) originally recognized Cainozoic–Cretaceous rocks above 340 m, overlying ?Permian red beds to a depth of 500.7 m, and then four Proterozoic units ('A', 'B', 'C', and 'D'), with tops at 500.7 m, 662.3 m, 952.5 m, and 1121 m, respectively. Lindsay and Reine (1995) reinterpreted the well-log data, assigning the first 962 m to the Lower and Middle Cambrian 'Wirrildar beds' and Trainor Hill Sandstone (middle to upper Marla Group), and the remainder of the drillhole to the lower Ungoolya Group (Supersequence 3, correlative with the Wahlgu Formation). However, Lindsay (1995) subsequently reassigned the entire succession above 962 m to the 'Wirrildar beds'. Grey (1999) reassessed Birksgate 1 and considered that the drillhole probably bottomed in the Alinya Formation (Supersequence 1), beneath the Murnaroo Formation. She tentatively assigned the middle part of the drillhole to the Dey Dey Mudstone, Karlaya Limestone, and Tanana Formation (middle Supersequence 3). This interpretation is tentative due to the lack of productive palynological samples (Grey, 1999). Birksgate 1 is significant in that it probably penetrates a large proportion of the Ungoolya Group, which has considerable potential as a source rock.

Lennis 1, together with Browne 1 and 2, and Yowalga 1, were drilled in 1965 to obtain shallow stratigraphic information. The wells were located along seismic lines where the section was considered at least 600 m thick. Lennis 1, the deepest well, was drilled to 614.5 m and bottomed in Table Hill Volcanics. It penetrated 425 m of Lennis Sandstone, 47 m of Paterson Formation, and 140 m of Lower Cretaceous Samuel Formation.

CRA Exploration Pty Ltd (CRAE) drilled eight mineral exploration boreholes in 1981 — Jubilee 1, 2, and 3, Mason 1 and 2, and NRH 1, 2, and 3; and three in 1982 — 90 RCLE 004, 90 RCLE 005, and Weedy 1 (Fig. 3; NRH 1 lies to the south of the figure). Most boreholes were geophysically logged by Geoscience Associates Pty Ltd in Adelaide. These boreholes intersected the Eucla Basin succession and part of the Officer Basin succession. Neoproterozoic sedimentary rocks were intersected in Jubilee 1, 2, and 3, Mason 1 and 2, NRH 3, and possibly Weedy 1. In this part of the Officer Basin, the Neoproterozoic sedimentary succession is about 1200 m thick and assumed to be typically flat lying. Three lithological units were recognized: a lower unit, correlated with the Ilma Formation; a middle unit, named the Mason Conglomerate; and an upper unit that was initially correlated with the McFadden Formation equivalent, but is now considered to be an older Neoproterozoic unit within the Buldya Group (Grey et al., 2005). The Mason Conglomerate conformably overlies the Ilma Formation in Jubilee 1 and Mason 1, whereas Mason 2 bottomed in the formation. In Mason 1 and 2, the Mason Conglomerate is conformably overlain by a unit that is probably undivided Buldya Group.

Lennis Sandstone was intersected in Jubilee 3, Mason 1 and 2, and Weedy 1. The maximum intersected thickness of this unit is 150 m in Jubilee 3. The formation is overlain by the Wanna Formation in Jubilee 3 and Mason 1. There is limited age constraint for these two formations — in outcrop they overlie the late Middle Cambrian Table Hill Volcanics, and they pre-date the Carboniferous–Permian Paterson Formation. By comparison with other successions in central and western Australia, there were widespread sandy depositional phases in the Middle Ordovician and Devonian, so the Lennis Sandstone and Wanna Formation are tentatively given Ordovician and Devonian ages respectively. Permian strata intersected in these mineral holes were assigned to the Paterson Formation (Lowry et al., 1972), and in Jubilee 1 they were tested for kerogen content.

Cretaceous strata intersected in NRH 1, 2, and 3 consist of the Loongana Sandstone and Madura Formation. The Loongana Sandstone unconformably overlies Permian strata in NRH 2, Neoproterozoic strata in NRH 3, and Proterozoic granite in NRH 1. The Madura Formation was considered a potential oil-shale target, but appeared barren in terms of carbonaceous or kerogenous material. Cainozoic strata, including the Eocene Hampton Sandstone and Wilson Bluff Limestone, and the Miocene Nullarbor Limestone and Colville Formation, were intersected in NRH 1, 2, and 3 and Weedy 1.

Previous geophysical investigations

Gravity data

Complete reconnaissance gravity coverage of the Officer Basin was acquired by BMR in three helicopter surveys: in the Gibson Desert in 1962 (Lonsdale and Flavelle, 1968); in Western Australia in 1970–71, using an 11-km grid spacing (Fraser, 1973); and in South Australia in 1970, using a 7-km grid spacing (Pettifer and Fraser, 1974). To the northwest of the Waigen area, Hunt Oil Company conducted two semi-detailed gravity surveys, the Lennis and Breaden surveys, in the central Officer Basin in 1963–65 (Bazhaw and Jackson, 1965). These consisted of 35 265 gravity stations spaced at 800-m intervals on 6.4 × 6.4 km (2 × 2 mile) and 3.2 × 9.7 km (2 × 6 mile) grids, and covered the major part of the Yowalga and Lennis areas.

In 1998, GSWA conducted the Waigen gravity survey, which consisted of 1365 stations observed on a 3 × 2 km grid (Blundell, 1999). The survey covers part of the thickest sedimentary succession in the Waigen area, the shelf formed by the Neale Arch, and the southern margin of the Musgrave Complex. The Waigen gravity survey shows the structure in far more detail than the previous regional datasets.

Magnetic data

Four aeromagnetic surveys have been flown within the western Officer Basin. The first, consisting of three lines, was conducted by BMR in 1960 west of the Musgrave Complex. The survey showed a large area of low magnetic response, which was equated with a thick sedimentary sequence (Goodeve, 1961). In 1965, an aeromagnetic survey was flown over the Gibson Desert for Union Oil, covering MADLEY, WARRI, COBB, and HERBERT (Tucker, 1974).

Aeromagnetic surveys were flown by BMR between 1975 and 1976 with a nominal ground clearance of 150 m. The flight-line spacing for surveys flown over BROWNE, LENNIS, ROBERT, THROSSELL, WAIGEN, WESTWOOD, and YOWALGA was 3000 m, and 1500 m over BENTLEY, COOPER, SCOTT, and TALBOT. The sample interval along flight lines was 60 m for all the surveys.

Seismic data

The Waigen area has minimal seismic coverage. Because of this, some seismic data (mainly the 1993 AGSO data and seismic lines from the Lennis area) have been used to assist in structural interpretation and basement modelling of the Waigen area. Within the Waigen area, a single regional seismic traverse links the Western Australian and Southern Australian parts of the Officer Basin, along the Emu Road — Line B of the Mabel Creek Seismic Survey (S.S.), shot for Exoil Pty Ltd in 1962 by Namco International Incorporated. The data from this traverse are poor, and correlation of the seismic reflectors is difficult. Namco International concluded that the thickening of sediments ranged from 5000 feet (~1500 m) in the eastern part of the basin to a maximum of 10 000 feet (~3000 m) in the west. Shotpoints 226–369 were reprocessed by Geophysical Service Inc. (GSI) in Perth in September 1982 on behalf of CRAE. Although the quality of the data was very poor, a slight updoming of sediments was interpreted near a basement high that was previously illustrated by gravity and magnetic data.

A number of relatively small-scale seismic surveys were carried out in the eastern Officer Basin, beginning in 1966. The closest to the study area is the Serpentine Lakes S.S., which is an early Vibroseis survey conducted by Conoco. This survey led to the siting of Birksgate 1.

In 1993, as part of the National Geoscience Mapping Accord, AGSO recorded five regional seismic lines in the central part of the Officer Basin, South Australia. Line 93AGS-01, which is located north of the unnamed conservation park (Dobrzinski, 1997), investigated the nature of the northern margin of the Officer Basin and its relationship with the Musgrave Complex. It was tied to Birksgate 1 for stratigraphic control. Lines 93AGS-03, 93AGS-04, 93AGS-05, and 93AGS-06 provide a regional seismic network south and east of the conservation park.

In the Lennis area, Hunt Oil Company carried out the 270-km Lennis North S.S. between 1965 and 1966 as operator for a group of companies comprising Hunt Oil Company, Hunt Petroleum Corporation, Placid Oil Company, and Exoil Pty Ltd. The quality of the survey was poor, with lateral continuity shown only by the Table Hill Volcanics reflector. Shell Company of Australia conducted seismic surveys in the Lennis Area from 1980 to 1982 (Townson, 1985; Perincek, 1998). GSWA recently reprocessed over 4000 line-kms of seismic data in the western Officer Basin (Simeonova, 2003), some of which was in the Lennis area.

Stratigraphy

Outcrops in the Officer Basin are scattered and of limited extent, which has led to many synonymous names, and shortcomings in understanding the lithostratigraphic framework of the basin. The wells and drillholes in the basin are widely spaced and commonly shallow. Much of the stratigraphic section is unknown in outcrop and has only been documented in exploration wells, and some parts of the stratigraphic section mapped from seismic data remain untested. Grey et al. (2005) provided a comprehensive re-evaluation of the lithostratigraphic framework of the western Officer Basin (Fig. 5), which assessed and integrated earlier reviews and work by Jackson and van de Graaff (1981), Townson (1985), Phillips et al. (1985), Iasky (1990), Williams (1992, 1994), Perincek (1997), Carlsen et al. (1999), Apak and Moors (2000a,b, 2001), and Moors and Apak (2002). The stratigraphic framework for the western Officer Basin is different from that of the eastern Officer Basin, in part because the basin spans an area remote from both Perth and Adelaide, but also because the basin has been defined in different ways in the two states. A notable difference is that the Table Hill Volcanics (Kulyong Volcanics in South Australia) and younger rocks are included in the Officer Basin succession in South Australia, but were excised and placed in the Gunbarrel Basin in Western Australia by Hocking (1994). Grey et al. (2005) compared the two frameworks and possible correlations across the border (Fig. 6).

The Officer Basin is included in the Centralian Superbasin of Walter and Gorter (1994) and Walter et al. (1995), who proposed a single depositional system comprising the Amadeus, Ngalia, Georgina, and Officer Basins (Fig. 1). Other Neoproterozoic basins have since been included (Walter, 2000). Combined biostratigraphy, lithostratigraphy, isotope stratigraphy, and sequence analysis enabled the division of the Centralian Superbasin into four supersequences (Walter et al., 1995): Supersequence 1 (early Cryogenian: Willouran,

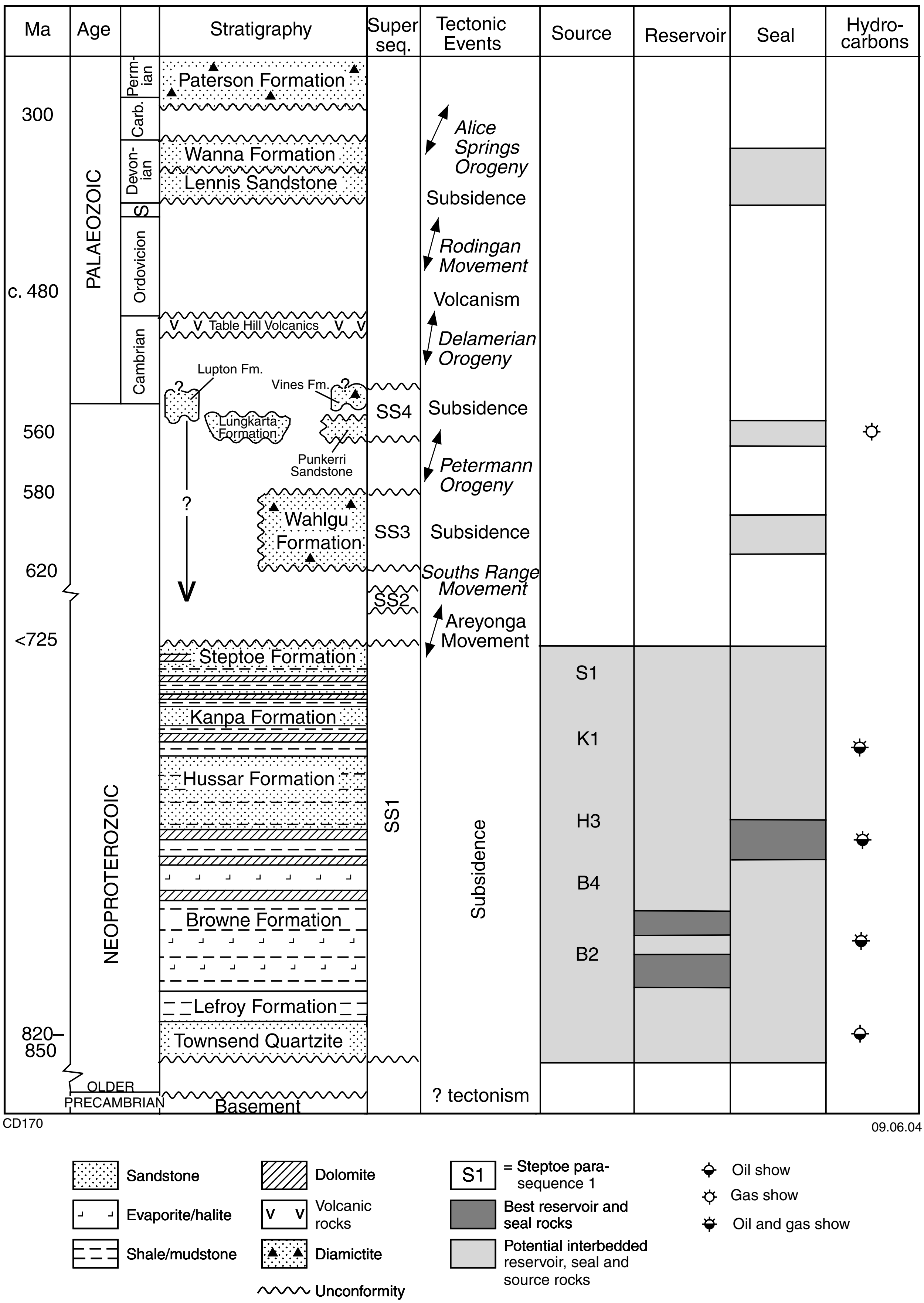

Figure 5. Summary of current stratigraphy, major tectonic events, and hydrocarbon-prospectivity indicators of the western Officer Basin (modified from Apak and Moors, 2000b, 2001; Carlsen et al., 2003)

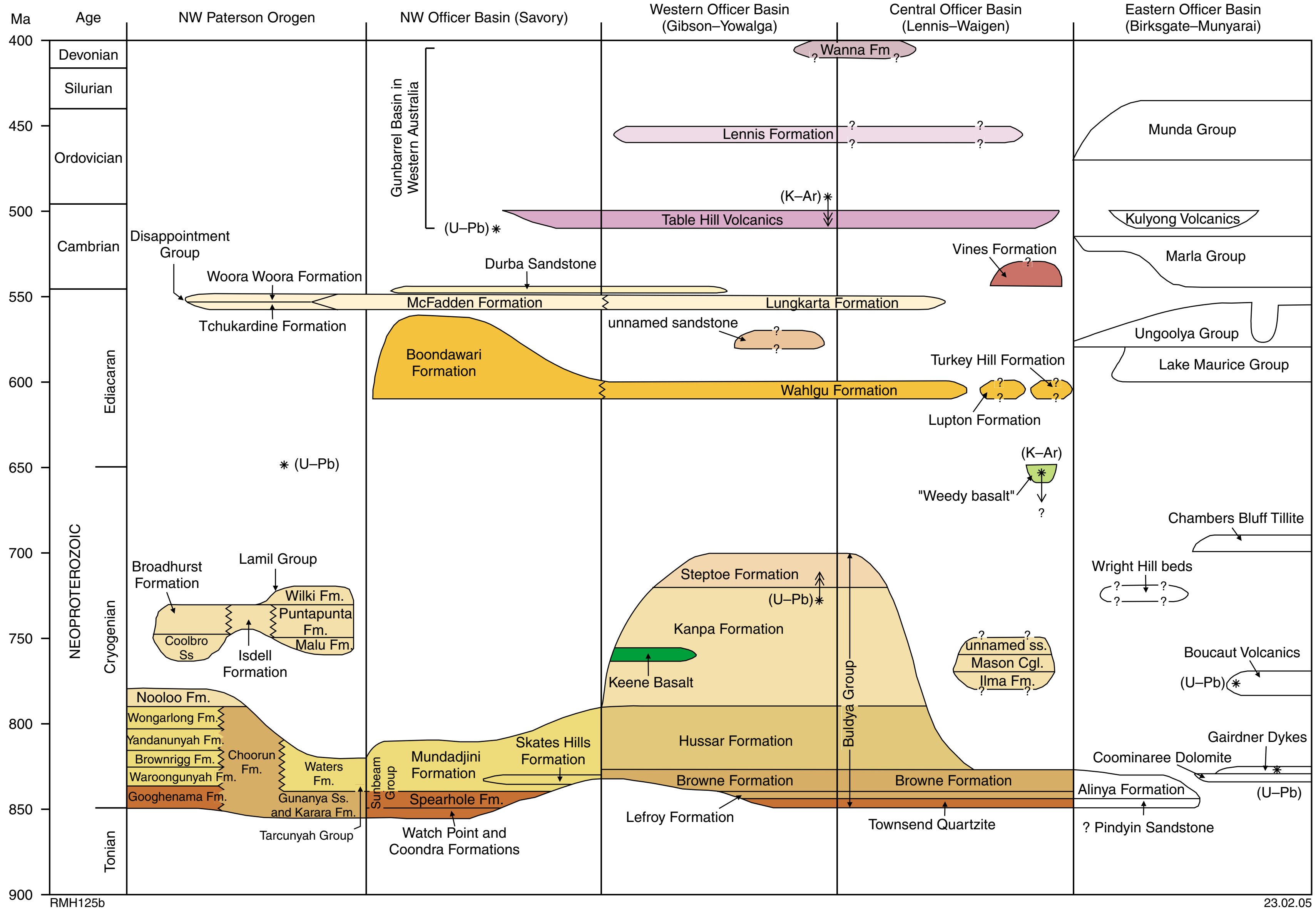

Figure 6. Generalized stratigraphy for the eastern and western Officer Basin (after Grey et al., 2005)

Torrensian, and early Sturtian*), Supersequence 2 (middle–late Cryogenian: mid-Sturtian – early Marinoan), Supersequence 3 (late Cryogenian: early–mid-Marinoan), and Supersequence 4 (Ediacaran).

Supersequence 1 consists of the Buldya Group (Grey et al., 2005) in the western Officer Basin, of which the Townsend Quartzite and Lefroy Formation outcrop adjacent to the Musgrave Complex, and the Callana Group in the eastern Officer Basin (Morton, 1997). In other parts of the Centralian Superbasin, commonly only the lower part of Supersequence 1 appears to be preserved. Part of Supersequence 2 is probably present in the eastern Officer Basin, but has not been positively identified in Western Australia (Grey et al., 1999, 2005), although Bagas (2003) considered that it could be present in the northwest Paterson Orogen based on the similarity of detrital zircon populations in that area to known Supersequence 2 populations in the Amadeus Basin. In the Waigen area, the Lupton Formation outcrops and may be part of Supersequence 3. The Punkerri Formation is part of Supersequence 4, but the Vines Formation may be marginally younger. Other parts of the Officer Basin succession are undoubtedly present in the Waigen area, but do not outcrop and have not been intersected. In much of the area, they will be at considerable depth, given the presence of a thick latest Neoproterozoic and early Cambrian succession. The Table Hill Volcanics and younger Palaeozoic rocks of the Gunbarrel Basin unconformably overlie the western Officer Basin.

With very limited outcrop, no significant well control (Vines 1 intersected only Early Cambrian rocks, and did not reach the Neoproterozoic section), and one line of poor-quality seismic data, the following summary of the stratigraphy is based mainly on observations from the Yowalga and Lennis areas of the western Officer Basin and Birksgate Sub-basin of the eastern Officer Basin.

Pre-Officer Basin

The Waigen area is flanked by four main areas of crystalline basement: the Mesoproterozoic Musgrave Complex, the Archaean Yilgarn Craton (west of the marginal shelves of the Officer Basin), and the Mesoproterozoic Albany–Fraser Orogen in Western Australia, together with the Archaean–Mesoproterozoic Coompana Block to the south in South Australia.

The Musgrave Complex consists of igneous rocks (volcanic rocks, granites, and layered mafic–ultramafic intrusions) emplaced into granulite- and amphibolite-facies Mesoproterozoic orthogneisses and paragneisses, which may be migmatitic (Myers, 1990b; Major and Conor, 1993; Glikson et al., 1996; Gravestock, 1997). These rocks are overlain by late Mesoproterozoic volcanic and sedimentary sequences of the Cassidy and Mission Groups. The complex was extensively deformed prior to development of the Officer Basin, and again during the Petermann and Alice Springs Orogenies.

The Mesoproterozoic Albany–Fraser Orogen comprises stacked thrust sheets of mainly metasedimentary rocks, orthogneiss, and granite, and includes mafic–ultramafic intrusions and remnants of basaltic dykes (Myers, 1990a; Condie and Myers, 1999; Fitzsimons, 2003). The orogen is longitudinally divided into the Biranup and Nornalup Complexes, with the former being strongly deformed (Myers, 1990a). The rocks have been metamorphosed to granulite facies. The orogen may have developed as a result of continental collision between the West Australian Craton and the Mawson Craton at c. 1300 Ma (South Australian – East Antarctic continent; Myers, 1990a; Myers, 1993; Condie and Myers, 1999), or on the site of an older orogen (Myers, 1990a).

The Coompana Block is a poorly known province that sits west of the Gawler Craton in South Australia and straddles the boundary between Western Australia and South Australia. It comprises Archaean to Mesoproterozoic gneiss and granite intruded by dolerite–gabbro plugs and dykes (Flint and Daly, 1993; Gravestock, 1997). The block is concealed beneath Phanerozoic sediments, and its margins were interpreted from aeromagnetic data. The rocks were deformed during the Musgravian Orogeny (1180–1160 Ma; Flint and Daly, 1993; Gravestock, 1997). Granite and gneiss intersected in drillholes along the Transcontinental Railway (Lowry, 1970) presumably belong to the Coompana Block. The block is overlain by the Neoproterozoic – Lower Cambrian Officer Basin, Carboniferous–Permian Denman Basin, Cretaceous Bight Basin, and Cainozoic Eucla Basin.

Officer Basin

Supersequence 1

Buldya Group

The constituent formations of the Buldya Group are the Townsend Quartzite, the Lefroy, Browne, Hussar, Kanpa, and Steptoe Formations, and probably the Ilma Formation and Mason Conglomerate. The group is exposed on BENTLEY, COOPER, MADLEY, NEALE, ROBERT, TALBOT, THROSSELL, and WARRI, and possibly as minor outcrops on MINIGWAL, RASON, WESTWOOD, WAIGEN, YOWALGA, and MASON. It is best known from drillholes, and was intersected in Browne 1 and 2, Dragoon 1, Hussar 1, Kanpa 1A, GSWA Lancer 1, Lungkarta 1, Yowalga 2 and 3, Madley 1, BMR Talbot 1, 3, and 4, BMR Throssell 1, Warri 20, GSWA Empress 1 and 1A, and deep mineral drillholes Kennecott N1-1, WMC NJD 1, and 92 THAC 001 (Perincek, 1998; Grey et al., 2005). The Buldya Group has an estimated thickness of about 4500 m, but may have been much thicker in deeper parts of the basin prior to erosion and salt movement. The group is a mixed succession of sandstone, siltstone, mudstone, dolomite, halite, and other evaporites.

Townsend Quartzite

Outcrops of the Townsend Quartzite are restricted mainly to the western and southern margins of the Musgrave Complex on BENTLEY, TALBOT, WAIGEN, and COOPER (Daniels, 1971a,b; Jackson, 1978; Jackson and

* Names in parentheses refer to IUGS chronometric divisions and Adelaide Rift Complex chronostratigraphic subdivisions respectively.

van de Graaff, 1981; Grigson, 1982; Watts, 1982). The only intersections of the Townsend Quartzite are in BMR Talbot 1 and possibly in Kanpa 1A, although the latter is disputed (Grey et al., 2005). In South Australia (on BIRKSGATE and LINDSAY), an equivalent of the Townsend Quartzite outcrops along the southern margin of the Musgrave Complex and is termed the Pindyin Sandstone (Major, 1973; Krieg, 1973; Zang, 1995a; Morton, 1997). Based on similarities in stratigraphic sequences, biostratigraphy, and isotope correlation of the overlying formations, the Townsend Quartzite is considered to be laterally equivalent to the lower sandstone part of the Pindyin Sandstone (Fig. 6; Preiss, 1993; Zang, 1995a,b; Morton, 1997; Grey et al., 2005). The Pindyin Sandstone consists of fine- to coarse-grained quartzose sandstone, with a basal pebble conglomerate at the type section (Pindyin Hills).

In outcrop, the Townsend Quartzite consists of up to 370 m of fluvial to shallow-marine silicified sandstone (Townson, 1985). The upper part of the unit can be seen immediately below the only outcrop of the Lefroy Formation, in the Browne Range, where it is conformably overlain by sandstone, siltstone, and shale of the Lefroy Formation.

The main lithologies identified are cross-bedded, well-sorted, medium- to coarse-grained sandstone and very coarse grained, pebbly sandstone ranging in composition from quartz arenite to feldspathic arenite. The composition and texture indicate slow deposition, with reworking of the sand in a high-energy environment and some channel fill deposits. The finer grained top of the upper part of the Townsend Quartzite indicates a deepening-upward succession, from fluvial to shallow marine (Jackson and van de Graaff, 1981; Grigson, 1982; Watts, 1982).

Lefroy Formation

The Lefroy Formation is exposed along the southern margin of the Musgrave Complex. The formation is 250 m thick at its type section, near Ainslie Gorge on TALBOT (Jackson and van de Graaff, 1981). On COOPER and WAIGEN, the formation has not been differentiated from the Townsend Quartzite. In South Australia on BIRKSGATE, the upper part of the Pindyin Sandstone ('Pindyin Beds' of Major, 1973) and the lower part of the Alinya Formation (Zang, 1995a) may be lateral equivalents of the Lefroy Formation (Fig. 6).

The Lefroy Formation consists of shaly, evenly and continuously bedded siltstone and mudstone with intercalations of quartz sandstone. The lower boundary of the formation is transitional with the Townsend Quartzite and the upper boundary is commonly eroded. Near Ainslie Gorge, Jackson and van de Graaff (1981) considered the formation to be transitional into overlying glacigene Lupton Formation, but Grey et al. (2005) considered the upper boundary to be 10 m lower and unconformable. The sediments were deposited in a low-energy, offshore-marine environment, below wavebase. Apak and Moors (2000b) suggested that the Lefroy Formation is a deeper water facies of the Townsend Quartzite. Based on relative stratigraphic position and palynomorphs in the correlative Alinya Formation, the inferred age of the Lefroy Formation is between 825 and 800 Ma (Zang, 1995a).

Browne Formation

The Browne Formation consists of red shale and siltstone, with interbedded halite, anhydrite, and fine-grained dolomite or dolomitic limestone. Thick halite deposits were intersected in the lower Browne Formation in BMR Madley 1, BMR Warri 20, Kanpa 1A, Yowalga 3 (the thickest section), Dragoon 1, GSWA Empress 1A, GSWA Lancer 1, Browne 1 and 2, and Hussar 1. The Browne Formation rests conformably on the Lefroy Formation, or unconformably on older rocks, as in Empress 1A, NJD 1, and Lancer 1, and is conformably overlain by the Hussar Formation.

The *Acaciella australica* Stromatolite Assemblage was identified in Yowalga 3, Empress 1A, and Lancer 1, and *B. irregularis* was found in Empress 1A. Both are characteristic of the Browne Formation. Scattered outcrops of dolomite and interbedded sandstone in central COOPER, 27 km west-southwest of South Hill, contain poorly preserved specimens of *B. irregularis*, indicating that they are probably part of the Browne Formation (Grey et al., 2005). These are the only known outcrops apart from diapir cores on MADLEY and WARRI. The Browne Formation may correlate to the Alinya Formation in South Australia based on its stratigraphic position (Zang, 1995a), although the Alinya Formation is very poorly constrained (Preiss, W. V., 2004, written comm.). The Browne Formation was deposited in shallow-marine (commonly restricted circulation), sabkha, and playa-lake settings, under strong oxidizing conditions (Townson, 1985, Apak and Moors, 2000a).

Hussar Formation

On COOPER, outcrops of sandstone overlain by stromatolitic dolomite containing *B. burra* could be Hussar or Kanpa Formation (Grey et al., 2005), the thickest of which was designated as the type section (Iasky, 1990; Grey et al., 2005). The Hussar Formation is composed of sandstone interbedded with dolomite, mudstone, minor conglomerate, and scattered evaporites, with a maximum known thickness of 897 m in Yowalga 3. The formation is potentially the best reservoir in the Officer Basin. In well intersections, the lower boundary of the Hussar Formation is placed at the base of a thick mudstone that overlies interbedded halite, mudstone, sandstone, and dolomite of the Browne Formation, and the upper contact at the base of a mudstone unit defined as the basal Kanpa Formation. The Hussar Formation contains repeated upward-coarsening progradational sedimentary cycles from shelf through shoreline to tidal flat and locally fluvial deposits (Apak and Moors, 2000a,b).

Kanpa Formation

The Kanpa Formation is conformable between the Hussar and Steptoe Formations, and has been intersected in most wells to the west and northwest of the Waigen area (Grey et al., 2005). The contact with the overlying Steptoe Formation has only been intersected in Empress 1A and Kanpa 1A. On COOPER (Skirmish Hill, Livesay Range, and 4 km west of Pirrilyungka) and BIRKSGATE (Patricia Johnson Hills), outcrops of sandstone and dolomite, previously mapped as Townsend Quartzite and Pindyin

Sandstone respectively, contain *B. burra*, which is characteristic of the upper Buldya Group (Browne, Hussar, Kanpa, and Steptoe Formations) rather than the Townsend Quartzite (Grey et al., 2005).

The Kanpa Formation consists of interbedded stromatolitic dolomite, shale, siltstone, and sandstone with minor evaporite and chert. Townson (1985) divided the formation into four units, whereas Apak and Moors (2000a,b) recognized two conformable parasequences from core studies in Empress 1A and Kanpa 1A, both of mudstone grading upward into dolomite and sandstone. The formation was deposited in a shallow-marine to tidal-flat environment, similar to the Hussar Formation. The interbedded shales of the Kanpa Formation are potential seals for the porous sandstones of the Kanpa and Hussar Formations (Phillips et al., 1985).

Steptoe Formation

The Steptoe Formation is known only from drillholes Kanpa 1A, Empress 1A, and possibly NJD 1 (Hocking, 2002). The type section is in Kanpa 1A (829–1301 m). The Steptoe Formation is conformable on the Kanpa Formation. The upper boundary is an eroded unconformity with the Lungkarta Formation in Kanpa 1A and the Wahlgu Formation in Empress 1A. Townson (1985) recognized four units within the formation: a basal massive sandstone with an interbedded dolomite unit; a massive, grey dolomite unit with minor shale and siltstone; fine- to coarse-grained white sandstone grading up into red-brown siltstone and shale; and at the top, coarse-grained, poorly consolidated sandstone with minor siltstone and dolomite. Apak and Moors (2000a,b) identified two parasequences similar to those in the underlying Kanpa Formation. Deposition took place in a similar setting to the Kanpa Formation.

Ilma Formation

The Ilma Formation is poorly exposed in the northwest of MASON and was intersected in Jubilee 1, 2, and 3, and Mason 1. The basal contact has not been penetrated in these drillholes, as all four terminated in the formation. The Ilma Formation is a folded sequence of sandy oolitic dolomite with minor limestone, chert, and sandstone. Grey et al. (2005) inferred that the formation rests unconformably on crystalline basement as it does in drillholes farther south. In Jubilee 1 and 2, the unit is unconformably overlain by the Paterson Formation, and in Jubilee 3 and Mason 1 it is apparently transitional upward into the Mason Conglomerate. The Ilma Formation was deposited in a shallow-marine to hypersaline-lagoon, partly intertidal environment. There is no unequivocal palaeontological control for the Ilma Formation, but lithologically it resembles the Buldya Group. Therefore, the Ilma Formation and Mason Conglomerate were tentatively assigned to the group by Grey et al. (2005), although correlations at formation level are unknown.

Mason Conglomerate

In Mason 1 and Jubilee 3, the Ilma Formation is overlain by the Mason Conglomerate, with the contact apparently transitional over several coarsening-upward cycles (Grey et al., 2005). There are no known outcrops, and the type section is in Mason 1 from 240 to 246 m. The conglomerate is dominated by angular to subrounded siltstone and limestone clasts in a silty matrix. This unit was also recorded at the base of Mason 2 and appears to extend laterally over a distance of at least 60 km (Ellis, 1981). In Mason 1 and 2, the unit grades upward from conglomerate into a sandstone that was assigned to the 'Babbagoola Beds' (now Lungkarta Formation) by Ellis (1981) and Perincek (1998), but is now considered as an unnamed sandstone within the Buldya Group (see **Ilma Formation**, and Grey et al., 2005). The sandstone could be at the level of the Lancer Member of the Browne Formation in Lancer 1 (Haines et al., 2004), or higher in the group. Two facies are present in the sandstone in Mason 1 and 2: a lower unit comprising grey calcareous sandstone with evaporite structures and local interbeds of thin siltstone; and an upper unit comprising reddish brown, fine-grained sandstone (Ellis, 1981). Both appear lithologically similar to the upper Buldya Group.

Supersequence 3

Wahlgu Formation

The Wahlgu Formation is a diamictite-dominated unit with some mudstone and sandstone. The formation was defined because the age and stratigraphic relationships of the Lupton Formation in its type area are ambiguous. The identity of intersections of 'Lupton Formation' away from the type area is uncertain, so the Wahlgu Formation was proposed. The Wahlgu Formation is mostly a glaciomarine deposit that developed in shallow conditions beneath a floating ice shelf, although some sandstone in Empress 1A may be fluvial to fluvio-glacial. The Wahlgu Formation was deposited during the Marinoan glaciation (Supersequence 3), and correlates with similar units of this age in the eastern Officer Basin, Amadeus Basin, and Adelaide Rift Complex, and the Boondawari Formation in the northwestern Officer Basin (Grey et al., 2005). The Wahlgu Formation is thicker in the Lennis area than it is in the Yowalga area (300 m) — around 500 m thick towards the salt walls (Apak and Moors, 2001).

Lupton Formation

The Lupton Formation is very poorly exposed along the southern margin of the Musgrave Complex on TALBOT and COOPER, and was recognized in BMR Talbot 1. The diamictite interval in Empress 1 and 1A, initially assigned to the ?Lupton Formation (Stevens and Apak, 1999; Apak and Moors, 2000a,b), is now assigned to the Wahlgu Formation (Apak and Moors, 2001; Grey et al., 2005) because it is uncertain whether the Lupton Formation seen in outcrop is the same unit found in the subsurface elsewhere in the basin. The type section is at Lupton Hills on central COOPER and is 69 m thick (Grey et al., 1999). The formation consists of massive conglomerate and interbedded siltstone, sandstone, and diamictite. Jackson and van de Graaff (1981) described the contact with the underlying Lefroy Formation as conformable in the Ainslie Gorge area, but re-examination of this locality suggests the contact was placed 10 m too high and that it is unconformable (Grey et al. 2005). This is far more likely given the stratigraphic succession found elsewhere in the basin. The upper contact is eroded throughout the basin. Grey et al. (2005) suggested that the Lupton Formation could be laterally equivalent to either the Wahlgu or Boondawari Formations if a glacial origin is assumed, or to the Vines Formation based on lithology and proximity.

Supersequence 4

Lungkarta Formation

The Lungkarta Formation has not been identified in outcrop, but is widely recognized on seismic sections and was intersected in Hussar 1, Kanpa 1A, Lancer 1, Lungkarta 1, 90 RCHE 003, and (tentatively) in BMR Westwood 1 and 2 and NRH 3. Intersections now assigned to the Lungkarta Formation were originally placed in the 'Babbagoola Formation' (Jackson, 1966; name abandoned by Grey et al., 2005), or the 'McFadden Formation equivalent' (Apak and Moors, 2000a,b, 2001; Moors and Apak, 2002). The section in Lancer 1 is very similar to exposed McFadden Formation in the northwest Officer Basin. Based on seismic data, the unit reaches a maximum thickness of 1200 m in the Lennis area near salt walls, and is characterized by three seismic horizons: a basal unconformity, an intraformation marker, and an upper unconformity with the overlying Table Hill Volcanics (Apak and Moors, 2001). The section below the intraformational marker has not been intersected in any drillhole, so its identity and relationship to the rest of the Lungkarta Formation are uncertain; it may instead be related to the upper Boondawari Formation (Grey et al., 2005). The upper unconformity is locally angular (Apak and Moors, 2001; Moors and Apak, 2002; Simeonova and Iasky, 2005), indicating a significant hiatus before extrusion of the Table Hill Volcanics, and Williams and Bagas (2000) inferred that the correlative McFadden Formation had been weakly deformed late in the Paterson Orogeny.

The Lungkarta Formation is a sand-rich sequence with small amounts of siltstone, mudstone, and minor evaporites. There is no conclusive evidence for the age of the Lungkarta Formation other than its relative stratigraphic position. This constrains the age to between c. 600 and 510 Ma. The Lungkarta Formation, like the McFadden Formation, is thought to be a product of the Petermann and Paterson Orogenies (Apak and Moors, 2001; Grey et al., 2005). If so, its age is c. 550 Ma (Bagas and Smithies, 1998; Bagas et al., 2000; Bagas, 2003).

Punkerri Sandstone

The Punkerri Sandstone outcrops in the northeastern corner of WAIGEN, parts of COOPER, and the central part of TALBOT in Western Australia, and on BIRKSGATE and LINDSAY in South Australia. The type section lies across the southern flank of the Punkerri Hills on BIRKSGATE, where a minimum of 1200 m of sandstone is exposed. In the Waigen area, the Punkerri Sandstone outcrops in the Patricia Johnson Hills, where two major units are present: a lower unit (about 200 m thick) that contains parallel-bedded, reddish brown sandstone; and an upper unit (400 m thick) of fine- to medium-grained, moderately to well sorted quartz arenite with interbeds of fine-grained sandstone and siltstone near the middle of the succession (Jackson and van de Graaff, 1981; Grey et al., 2005). The upper and lower boundaries are not exposed but are inferred to be regional unconformities. In South Australia, the Punkerri Sandstone disconformably overlies the Wright Hill Formation and is overlain by the Wirrildar beds, which are units not recognized in Western Australia. In South Australia, the Punkerri Sandstone also contains Ediacara-type fauna considered to be latest Neoproterozoic in age (c. 565 Ma), and indicates a shallow-marine depositional environment.

Vines Formation

The Vines Formation, named after GSWA Vines 1, is only known from this hole, where it extends from 4.0 to 2017.5 m (TD). The lithology comprises sandstone, diamictite, siltstone, shale, mudstone, and conglomerate, with rare carbonate and evaporitic rocks, all within a single conformable succession (Apak et al., 2002b; Stevens et al., 2002). Six informal units were recognized in Vines 1, based primarily on changes in lithology observed in the core and, to a lesser extent, on wireline-log character (Apak et al., 2002b; Stevens et al., 2002). Within the Officer Basin, the Vines Formation could correlate with the Lupton Formation (based on lithological similarity alone), the upper parts of the Lungkarta or McFadden Formations (based on all three units being generated by the Petermann or Paterson Orogenies), or with one of several synorogenic formations in South Australia that formed during the Petermann Orogeny. The most likely correlative in both age and rock type from the Amadeus Basin is the Mount Currie Conglomerate (Grey et al., 2005). The type section of the Lupton Formation is located 31 km northwest of Vines 1, and comprises 69 m of lithologies similar to Units 2, 3, and 4 of the Vines Formation.

Palynomorphs recovered from Vines 1 are reworked and of mid-Neoproterozoic to earliest Cambrian age, which indicates that the succession possibly has a maximum age of earliest Cambrian (Grey et al., 2005). Palaeomagnetic results from oriented drillcore indicate a late Neoproterozoic or Cambrian age (Pisarevsky, 2002). Dolomite containing the *Baicalia burra* and *A. australica* Stromatolite Assemblages outcrops about 35 km east of the Lupton Formation type section and about 22 km northeast of Vines 1, which suggests that these rocks underlie both the Lupton and Vines Formations, providing a maximum age constraint for both formations. The Cambrian Table Hill Volcanics outcrop 33 km south-southeast of the Lupton Formation type section and 17 km southwest of Vines 1, providing a minimum age constraint for the Lupton and Vines Formations.

The Vines Formation was deposited during a regressive phase, with turbiditic, deep-marine to unstable slope deposits at the base, followed by diamictite-dominated mass flows on an unstable slope, and finally grading up to sandstone-dominated submarine mass flows, which is consistent with tectonic instability along the southern margin of the Musgrave Complex (Stevens et al., 2002).

Post-Officer Basin (Gunbarrel Basin)

Palaeozoic

Table Hill Volcanics

The base of the Table Hill Volcanics marks the base of the Gunbarrel Basin (Hocking, 1994). The volcanic rocks, which outcrop on the southwestern and northeastern margin of the western Officer Basin on TALBOT, WAIGEN, and COOPER, can be correlated seismically over a large portion of the basin (Apak and Moors, 2000b, 2001), and appear to correlate with the Kulyong Volcanics in South Australia. They were intersected in Yowalga 3, Kanpa 1A, Lungkarta 1, and Empress 1 and 1A. In outcrops west of the Musgrave Complex, the Table Hill Volcanics consist of multiple basaltic flows separated by sandstone and siltstone. Moussavi-Harami and Gravestock (1995) suggested a Middle to Late Cambrian age for the Kulyong Volcanics based on stratigraphic correlation, which is compatible with robust radiometric ages of 500 to 510 Ma for the Antrim Plateau Volcanics (Hanley and Wingate, 2000). K–Ar radiometric dating from Empress 1A gives an Early Ordovician age of 484 ± 4 Ma for the Table Hill Volcanics (Stevens and Apak, 1999), but this is probably an alteration age. The Table Hill Volcanics are approximately coeval with the Antrim Plateau Volcanics, and could possibly be part of the same thermal event (Grey et al., 2005).

Lennis Sandstone and Wanna Formation

The Lennis Sandstone and Wanna Formation are sandstone-dominated units, which van de Graaff (1972), Jackson and Muir (1981), and Jackson and van de Graaff (1981) interpreted as shallow-marine deposits. They unconformably overlie the Table Hill Volcanics, and are overlain by the Paterson Formation, thus constraining their age to between Cambrian and Carboniferous. Jackson and van de Graaff (1981) correlated the formations with the Cambrian–Ordovician Munda Group (Mount Chandler Sandstone, Indulkana Shale, Blue Hills Sandstone) of South Australia, whereas Green and Gleadow (1984) suggested a Devonian–Carboniferous age based on fission track analysis. Myers and Hocking (1988) showed the two units as Devonian, but later inferred an Ordovician or Devonian age (Myers and Hocking, 1998). The Lennis Sandstone outcrops in the eastern and northeastern parts of the western Officer Basin, and the Wanna Formation outcrops in the southeastern part of the basin. On WANNA, WAIGEN, COOPER, and LENNIS the inferred distribution of the two units suggests that the Lennis Sandstone is disconformably overlain by the Wanna Formation. This raises the possibility that the Lennis Sandstone may be mid-Ordovician and the Wanna Formation mid-Devonian, based on major phases of sandy deposition elsewhere in central and South Australia.

Paterson Formation

The Upper Carboniferous – Lower Permian Paterson Formation outcrops extensively, and was intersected in most of the wells drilled in the western Officer Basin. The unit consists of diamictite, cross-bedded, coarse-grained pebbly sandstone, and well-bedded claystone, siltstone, and fine-grained sandstone. The Paterson Formation was deposited in subglacial, glaciolacustrine, and fluvioglacial environments, with some possible marine influence (Jackson and van de Graaff, 1981). In the northern part of the Eucla Basin, the formation is disconformably overlain by Cretaceous and Cainozoic marine carbonate rocks and marginal-marine to continental siliciclastic rocks. Based on lithological similarities and sparse palynological information, the Paterson Formation probably correlates with the Buck Formation in central Australia (Wells et al., 1970) and the Reeves Formation and possibly Grant Group of the Canning Basin (Crowe and Towner, 1976; Stevens and Apak, 1999).

Post-Paterson Formation sedimentary rocks

The Loongana Sandstone unconformably overlies Permian, Lower Cambrian, or Precambrian units of the Officer Basin and forms the basal part of the Eucla Basin succession as defined by Lowry (1970) and used by Hocking (1990, 1994). The Mesozoic part of this succession was recently excised from the Eucla Basin and placed in the Bight Basin by Bradshaw et al. (2003) following South Australian usage. The Loongana Sandstone consists of medium- to coarse-grained, poorly sorted fluviatile sandstone and conglomerate. The formation is conformably overlain by the Madura Formation, which consists of glauconitic sandstone, carbonaceous sandstone, siltstone, claystone, and shale. The Aptian–Albian age of the Madura Formation suggests a correlation with part or all of the Samuel Formation and Bejah Claystone, which lie in other areas of the Gunbarrel Basin. Lowry (1970) concluded that most of the formation was deposited in a marine environment.

A thin sedimentary succession, consisting of the Eocene Hampton Sandstone and Wilson Bluff Limestone, and Miocene Nullarbor Limestone, was deposited during the Cainozoic and is overlain by a superficial cover of Quaternary sediments including eolian sand dunes, clay, silt, gypsiferous sand, salt lakes, and silcrete. The Hampton Sandstone is composed of granule-size quartz grains in a peaty matrix and is a chronostratigraphic equivalent of the Pidinga Formation (Ellis, 1981; Clarke et al., 2003) of the Eucla Basin in South Australia. The Wilson Bluff Limestone is characterized by grey, moderately soft limestone, and is conformably overlain by Nullarbor Limestone, which consists of light-grey, hard, recrystallized limestone. The Nullarbor Limestone forms a cover to the Eucla Basin. The stratigraphy and terminology of the basin was re-evaluated by Clarke et al. (2003).

Structure

The western Officer Basin is an asymmetrical basin that is fault-bounded against rocks of the Musgrave Complex and has a ramp platform hinge margin to the south-southwest. Based on potential-field data, the deepest area of the basin appears to be adjacent to the Musgrave Complex in the Waigen area (Fig. 7) and Birksgate Sub-basin. The Townsend Quartzite is adjacent to the complex, but is not observed near the western margin, where the Browne Formation rests on basement (Grey et al., 2005), which indicates that this asymmetry developed early in the depositional history of the basin. Crustal loading to the northeast following the Petermann Orogeny also affected the basin's asymmetry (Carlsen et al., 1999; Apak et al., 2002a).

The Officer Basin is characterized by low-frequency Bouguer gravity anomalies (Fig. 7). It is flanked to the northeast by a gravity high (Musgrave Complex), to the west and east by a region of complex patterns associated with shield areas (Yilgarn and Gawler Cratons), and to the south by an arc-shaped anomaly associated with basement underlying the Eucla Basin (Coompana Block).

Carlsen et al. (2003), following Japan National Oil Company (1997), identified five structural zones in the western Officer Basin based on seismic data: a Marginal Overthrust Zone, a Salt-ruptured Zone, a Thrusted Zone, a Western Platform, and a salt-dominated Minibasins Zone (Fig. 8). These were defined within the central part of the western Officer Basin and are indicative of the orogenic processes within each area, the associated salt mobilization, and the style of the halokinetic structures produced. Simeonova and Iasky (2005) refined this into four zones, eliminating the Minibasins Zone, as there is no clear seismic evidence confirming its presence. These zones may extend into the Waigen area, but cannot be mapped due to inadequate seismic coverage.

Waigen area

Techniques: potential-field data

Gravity observations acquired from the Geoscience Australia database and a semi-detailed survey conducted by GSWA (Blundell, 1999) were gridded to produce the image shown in Figure 7. An isostatic correction (Simpson et al., 1983) was applied to these data to remove the effect of mantle topography from the gravitational field (Fig. 9). The mantle topography is predicted from the surface topography under the assumption of isostatic equilibrium. However, there is some doubt that the region has settled into a state of isostatic equilibrium (Haddad et al., 2001), and the topography is very subdued, making it difficult to estimate the crustal thickness precisely. The difference between the Bouguer anomaly and the isostatic residual anomaly is very small in this region, due to the large crustal depths and the low topographic relief.

The total magnetic intensity (TMI) image (Fig. 10) clearly shows the effect of the thick, non-magnetic sedimentary section of the Officer Basin. Shallow magnetic basement of the Musgrave Complex dominates the northwestern part of the TMI image and is in sharp contrast to the magnetic response of basement beneath the Officer Basin, which is subdued by the intervening non-magnetic sedimentary rocks. Conventional TMI image-processing techniques (e.g. first vertical derivative of reduced-to-pole image) are useful for enhancing magnetic anomalies associated with shallow structures, but only offer limited improvement when dealing with deeper structures such as those within the Waigen area (Fig. 11). A new filtering technique, called variable downward continuation, which varies the level of enhancement of the aeromagnetic data over the basin according to the sediment thickness modelled from the isostatic residual gravity data, was developed to define the basement structure below the Officer Basin.

A gravity model of the depth to crystalline basement (Fig. 12) was determined from the isostatic residual anomaly using the method of Pilkington and Crossley (1986), as implemented by Lockwood (2004). The depth-to-basement model was constrained to agree with published seismic interpretations and known basement intersections from drillholes in the basin. Density logs from drillholes were also used to determine the appropriate density contrast at the base of the sedimentary section. As potential-field data can be represented by a plane of sources at any level below the survey, additional constraints need to be defined in order to select the most reasonable basement model. This algorithm calculates the smoothest basement topography defining a known density contrast that fits the observations within the noise limits, at an average depth constrained by borehole data. This process is the same as a downward-continuation filter with a smoothing constraint to limit the amount of high-amplitude features in the model (Pilkington and Crossley, 1986).

Fourier-transform-based image processing tools, such as the downward-continuation filter, apply the same filter to all areas of a dataset. This is effective only for regions covered by a relatively constant thickness of non-magnetic sedimentary rocks. In the Waigen area, the complex, highly magnetic rocks of the Musgrave Complex outcrop in the northern part of the dataset (Figs 9 and 10), and any attempt to downward continue the data using Fourier-based methods will be highly unstable over these areas of shallow basement. The wavelet transform is an alternative to the Fourier transform for potential-field data processing, as it can be made to vary spatially (Ridsdill-Smith and Dentith, 2000). Instead of decomposing the geophysical signal into the sum of sine waves with varying amplitudes and relative phase shifts, the wavelet transform is essentially the correlation of the signal with a discrete wavelet function as its amplitude and position are varied. As well as providing computational advantages, the wavelet transform preserves the localization of information in the transform space. This makes it possible to create a downward-continuation filter where the depth of continuation is the basement depth as modelled from the gravity data.

Ridsdill-Smith and Dentith (2000) described the application of the wavelet transform to drape-correction of aeromagnetic data. The method is used here to continue the data to the level of basement as determined by the gravity inversion over the Waigen area (Fig. 12), yielding an optimal downward-continuation distance for each datum in the TMI image. Noise in the data is amplified by the downward-continuation process, so an adaptive exponential smoothing filter is applied in parallel with the downward-continuation filter to maintain a decaying power spectrum of the filtered data. The smoothing is necessary to stabilize the process, but suppresses high-

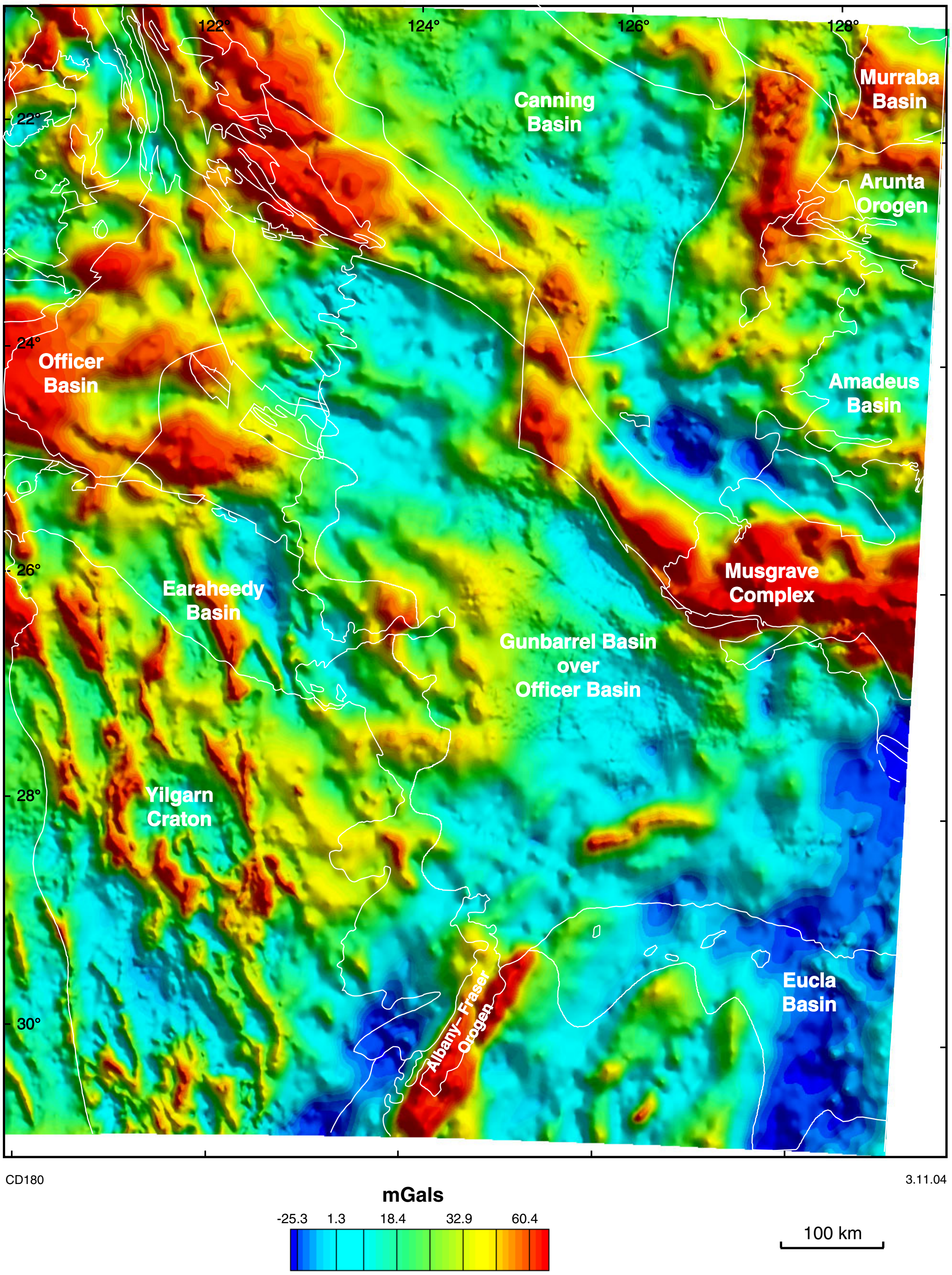

Figure 7. Isostatic residual, Bouguer-corrected gravity field over the western Officer Basin

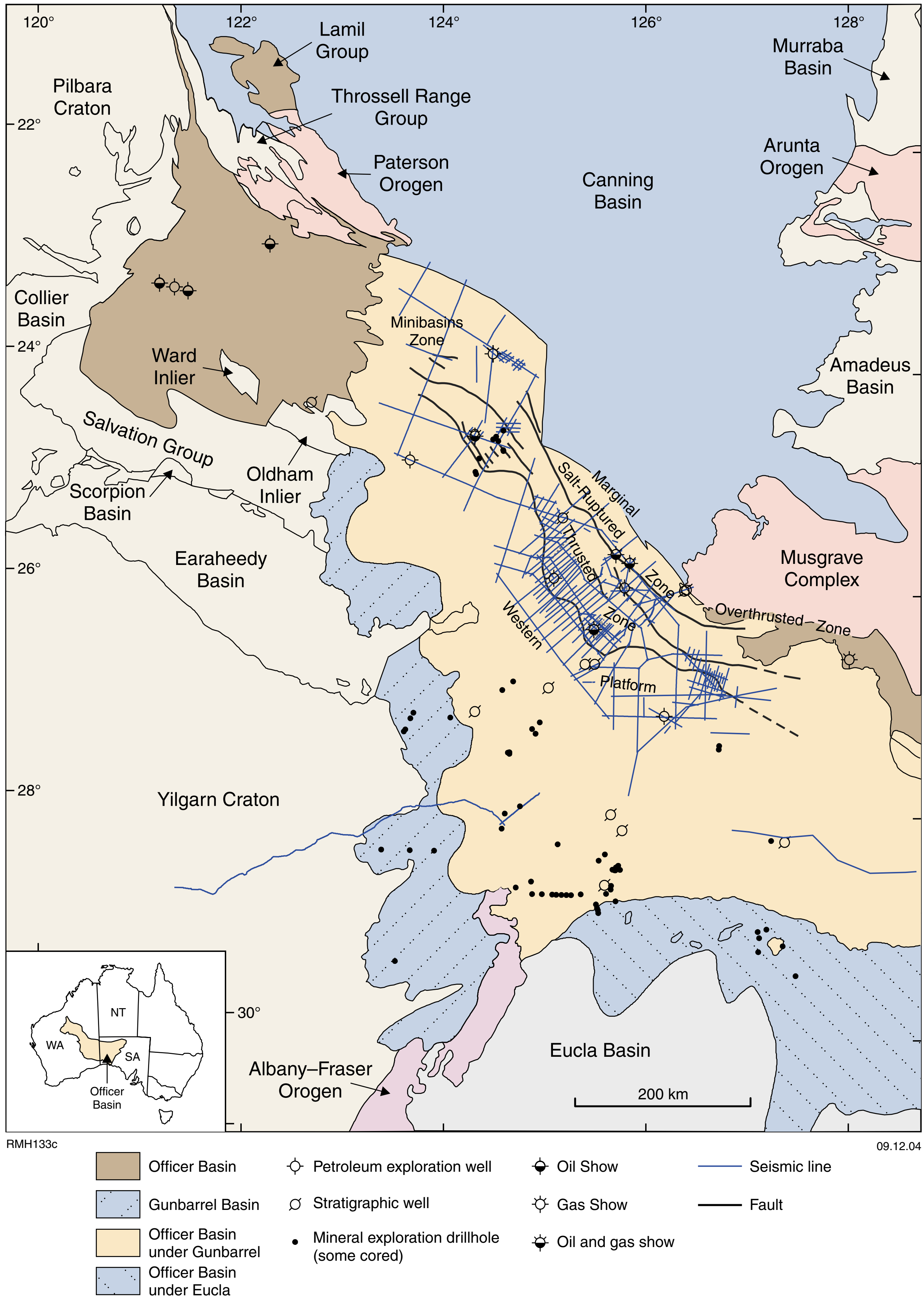

Figure 8. Structural subdivision of the central western Officer Basin based on seismic data (after Carlsen et al., 2003). A figure of the refined subdivison of this area is shown in Simeonova and Iasky (2005)

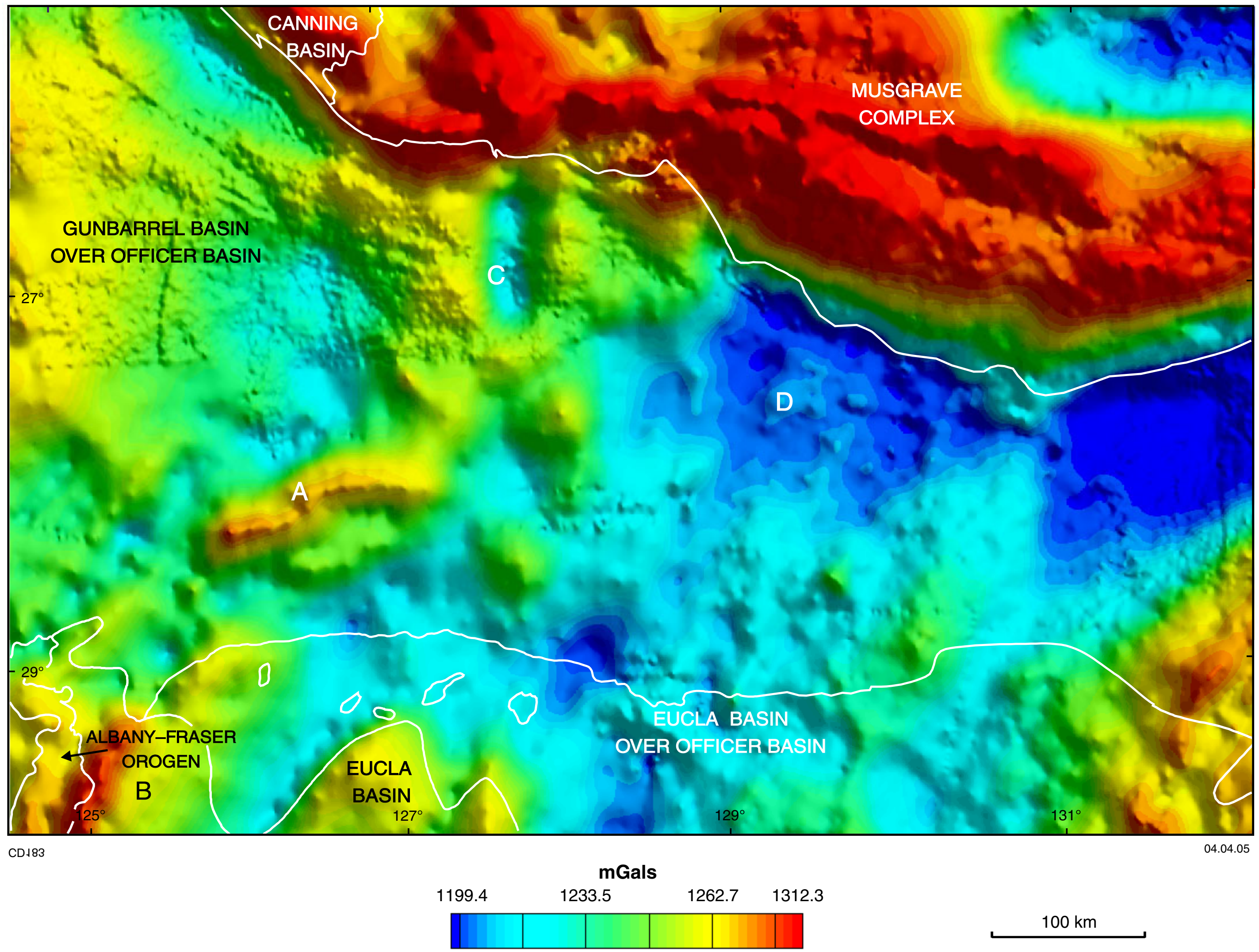

Figure 9. Isostatic residual, Bouguer-corrected gravity field over the Waigen area and surrounds: A = prominent ridge representing Albany–Fraser Orogen at depth; B = outcropping Albany–Fraser Orogen; C = Cooper Graben; and D = Birksgate Sub-basin

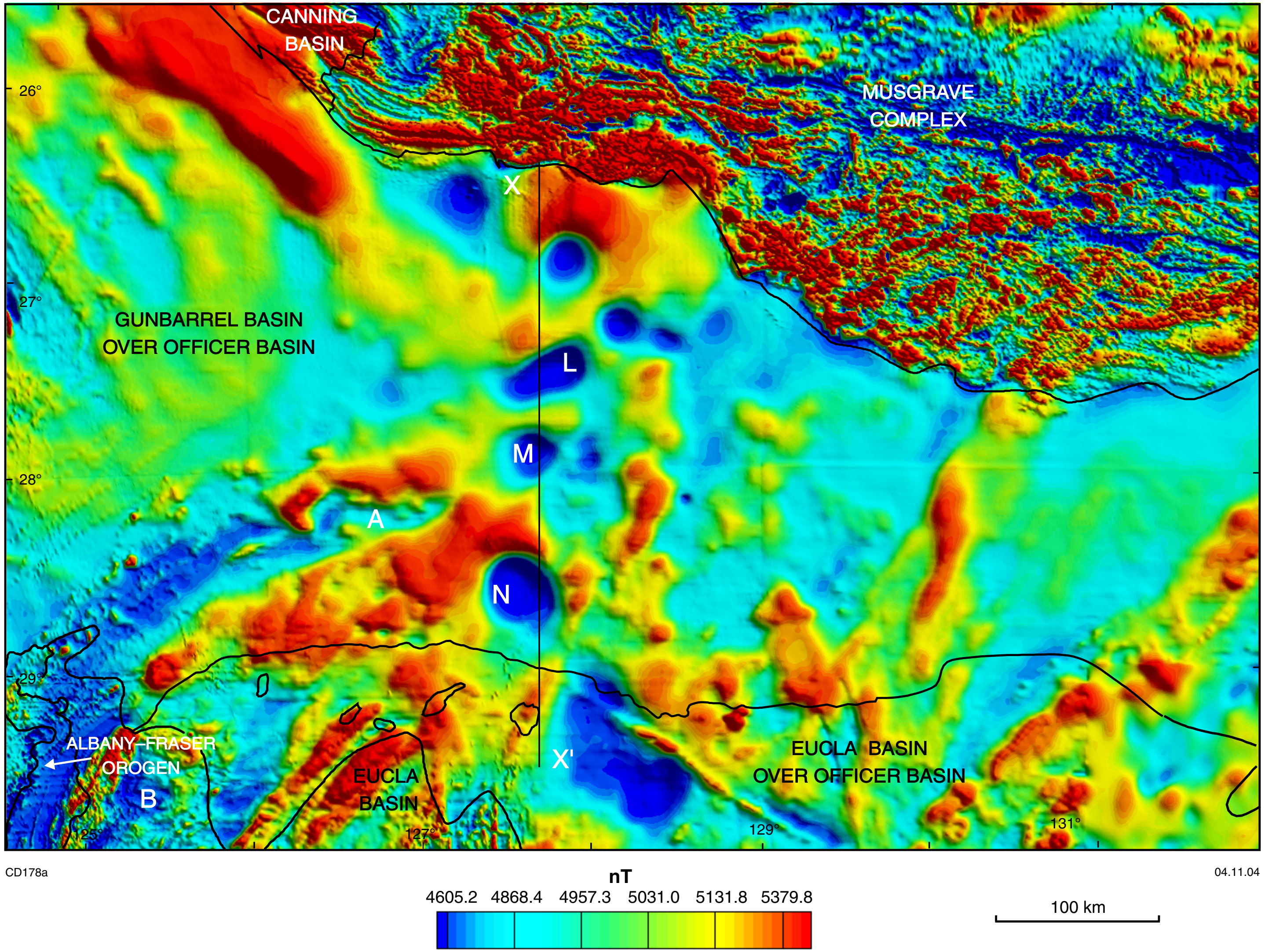

Figure 10. Total magnetic intensity, reduced to pole, of the Waigen area and surrounds: A = magnetic low corresponding to a gravity ridge on Figure 9; and L–N = modelled circular lows representing possible plutons. Cross section X–X' is shown in Figure 16

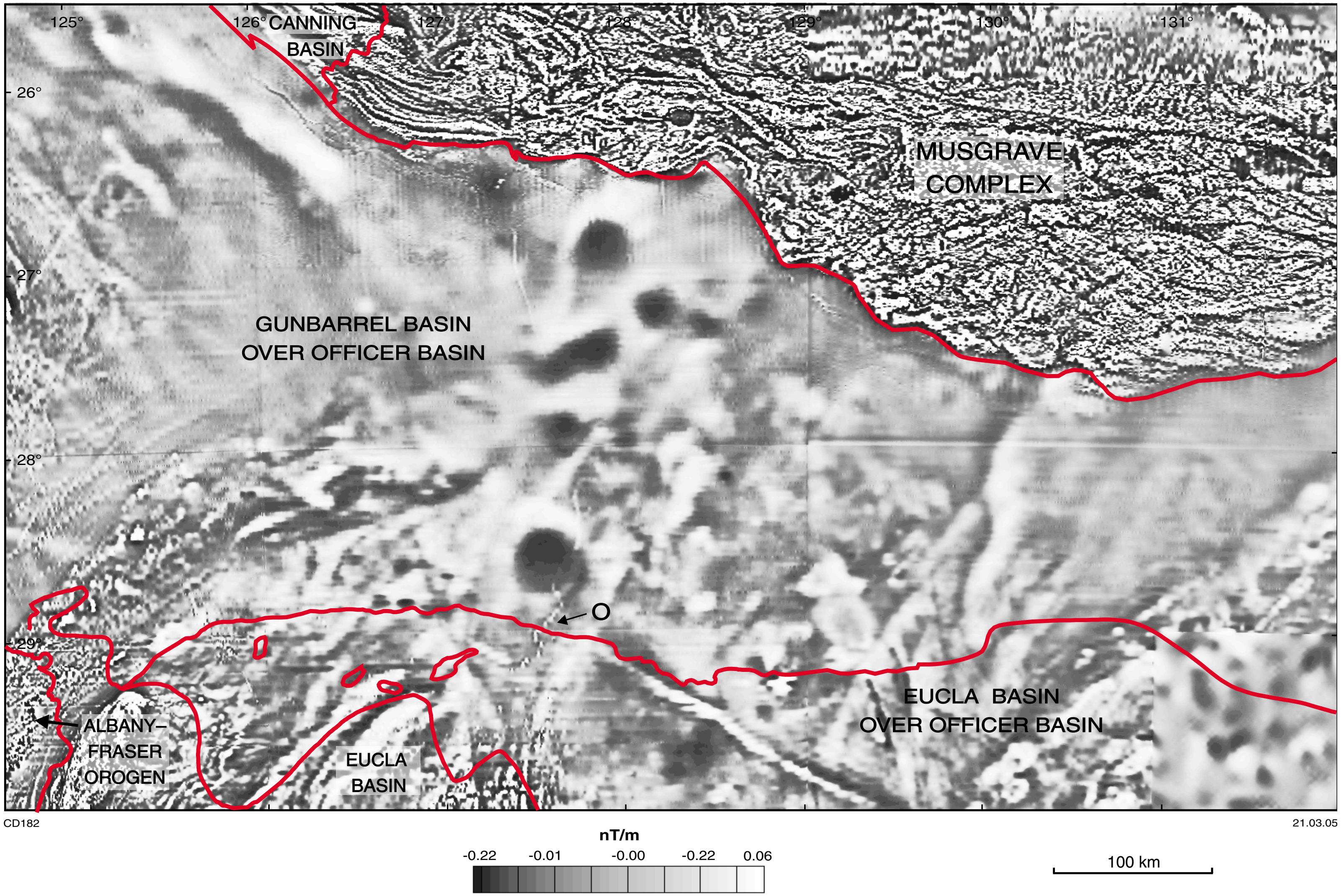

Figure 11. First vertical derivative of the total magnetic intensity for the Waigen area and surrounds: O = sinuous body

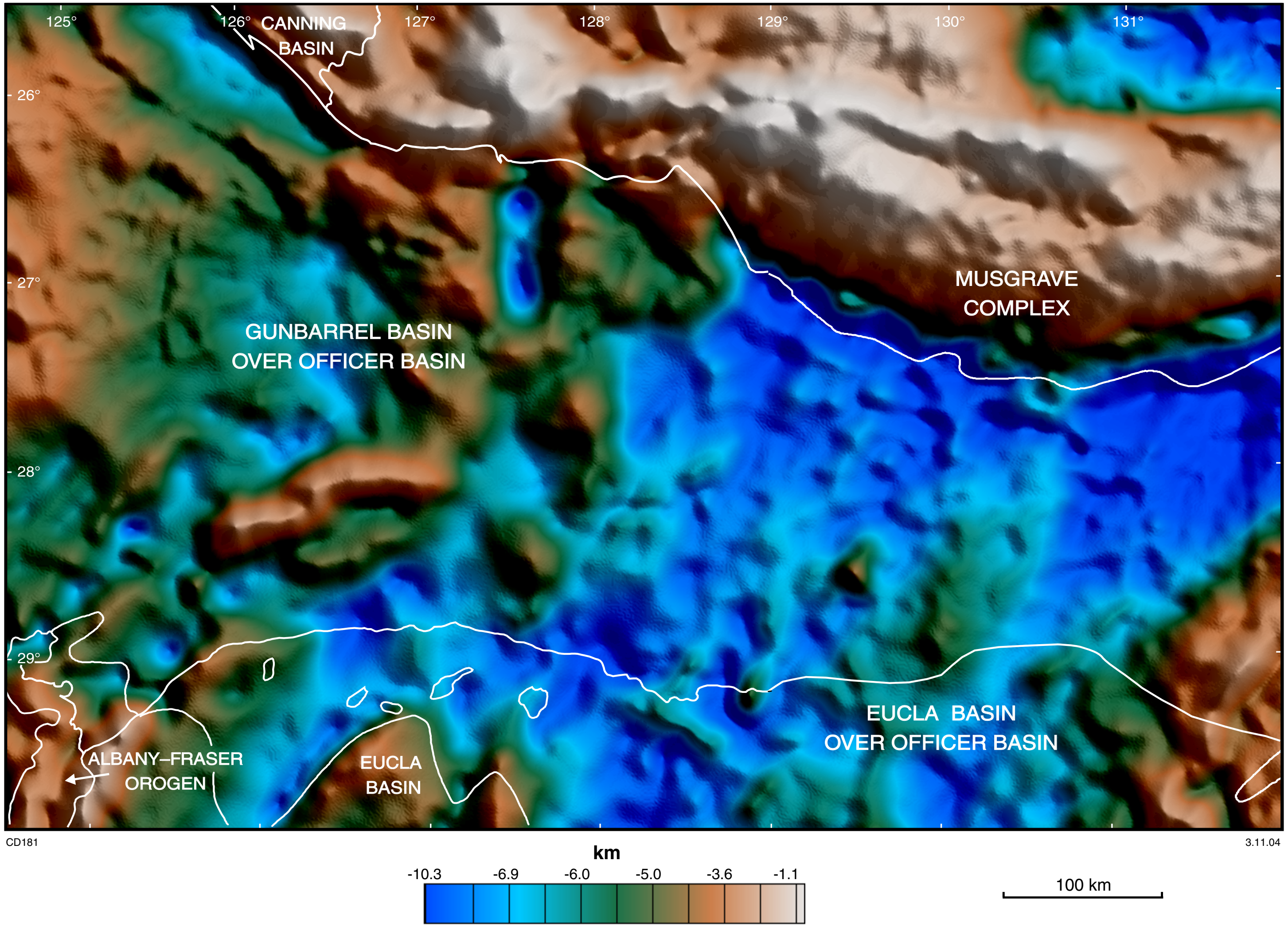

Figure 12. Depth to basement, modelled from gravity data, for the Waigen area and surrounds

frequency content so that the downward-continued data will appear smoother than it should, especially in regions where the depth of continuation is of the order of 10 km. Despite this, the improvement in the resolution of the basement is considerable over the deeper parts of the sedimentary section (Fig. 13) when compared to the TMI image (Fig. 10).

Interpretation

The gravity and magnetic patterns highlight complex basement structures beneath the sedimentary section of the Waigen area (Figs 9, 10, and 13). These basement structures will ultimately determine what features may be present in the overlying sedimentary basin. The gravity and magnetic images show that the previously recognized subdivisions in the western Officer Basin (Iasky, 1990; Hocking, 1994), particularly in the Waigen area, need revision. The following refined subdivision of the area is based on the potential-field data combined with the eastern Officer Basin subdivisions of Morton and Drexel (1997) and Rankin (2003).

The largest negative gravity anomaly lies along the southern margin of the Musgrave Complex, on the edge of the Waigen area, and extends into the Birksgate Sub-basin (D on Fig. 9). This anomaly represents the thickest section of preserved sedimentary strata within the western Officer Basin, where estimated depths are up to about 11 km (Fig. 12). The depth-to-basement image broadly shows that the basement is shallower in the western part of the Waigen area, with the exception of the Cooper Graben — a northerly trending trough in the north, near the margin of the Musgrave Complex (C on Fig. 9), with an estimated depth of about 10 km.

The Waigen area has a smooth magnetic signature that indicates deep basement sources (Figs 10, 11, and 13). The TMI image (Fig. 10) shows that the constituents of the basement are dominantly magnetic with minor non-magnetic areas probably related to metasedimentary rocks.

The Waigen area and its surrounds have been subdivided into nine domains representing areas of common magnetic character (Figs 14 and 15). The variably downward-continued image (Fig. 13) highlights subtle features not seen in the TMI image (Fig. 10), particularly over the Officer Basin, and, together with the first vertical derivative (Fig. 11) image, was used to refine the tectonic subdivisions and interpret the tectonic history of the Waigen area. Domain 1 is the Musgrave Complex. Domains 2 and 3 fall mostly within the Yowalga and Lennis areas, with the southeasternmost corners impinging on the Waigen area. Domain 4 is almost entirely within the Waigen area. Domain 5 is within the southern part of the Lennis area. Domains 6 and 7 cover parts of the Officer Basin in both Western Australia and South Australia. Domain 6 encompasses most of the Birksgate Sub-basin, the easternmost part of the Waigen area, the Nurrai Ridge, and the western part of the Murnaroo Platform. Domain 7 falls within the northern part of the Coompana Block. Domains 8 and 9 are restricted to the eastern Officer Basin in South Australia. Domain 8 covers the eastern part of the Birksgate Sub-basin, the Munyarai Trough, and the eastern part of the Murnaroo Platform, and domain 9 includes subcropping Gawler Craton and the Hughes Subdomain (Fig. 3).

A similar tectonic framework of this area was included in an Australia-wide, crustal-scale study by Shaw et al. (1996). Their work was a useful compilation of regional-scale gravity and magnetic interpretations by Fraser et al. (1977) and Wellman (1978, 1988) within this area, but does not consider the tectonic evolution.

Domain 1

Domain 1 consists of complex, mainly west-northwesterly to northwesterly trending structures (thrust faults) and narrow, well-defined, high-amplitude anomalies related to outcropping rocks (granites, gneisses, and gabbros). The sharp, southern boundary of domain 1 is marked by a northerly dipping thrust fault at the edge of the Officer Basin (Figs 9, 10, and 13). The complicated pattern of anomalies is a consequence of intense deformation within the Musgrave Complex. The coincident gravity high reflects exposed basement adjacent to a thick, less dense sedimentary section. The high-grade metamorphic rocks are typically denser than granitic basement material, which further strengthens the gravity high.

Domain 2

Domain 2 consists of basement, possibly Musgrave Complex or Palaeoproterozoic Rudall or Gascoyne Complex, below a relatively thin cover of Officer Basin strata (Supersequence 1, 3, and 4 strata). The anomalies are broader than those corresponding to outcropping rocks of the Musgrave Complex in domain 1 (Fig. 13). This domain contains a series of similar northwesterly trending lineaments, from both gravity and magnetic data, which parallel those seen in the adjacent Musgrave Complex. The basement features deepen to the southeast of the domain.

Salt-related features, such as diapirs and salt walls, have been noted in this domain from drillholes (Browne 1 and 2, Yowalga 3) and seismic data (Japan National Oil Corporation, 1997; Apak and Moors, 2000a,b, 2001). The Browne diapir, in the Yowalga area, is a northwesterly trending salt wall (Apak and Moors, 2000b, fig. 13) that corresponds to a magnetic low (A on Fig. 13) flanked by magnetic highs. The salt is responsible for the reduced magnetic signature. The salt wall appears to coincide with a northwesterly trending structural feature in the basement (although it may not directly overlie it), which has presumably served as a focus for salt movement. Other linear, magnetic lows within the domain (e.g. B on Fig. 13) also appear to correlate with either salt walls or salt-related features noted in the western Officer Basin by Japan National Oil Corporation (1997) and Apak and Moors (2000a,b, 2001).

In the adjacent Lennis area, linear salt walls with lengths in excess of 120 km (C, D, and E on Fig. 13) were mapped by Durrant and Associates (1998) and Apak and Moors (2001, plate 1). These salt walls do not appear to

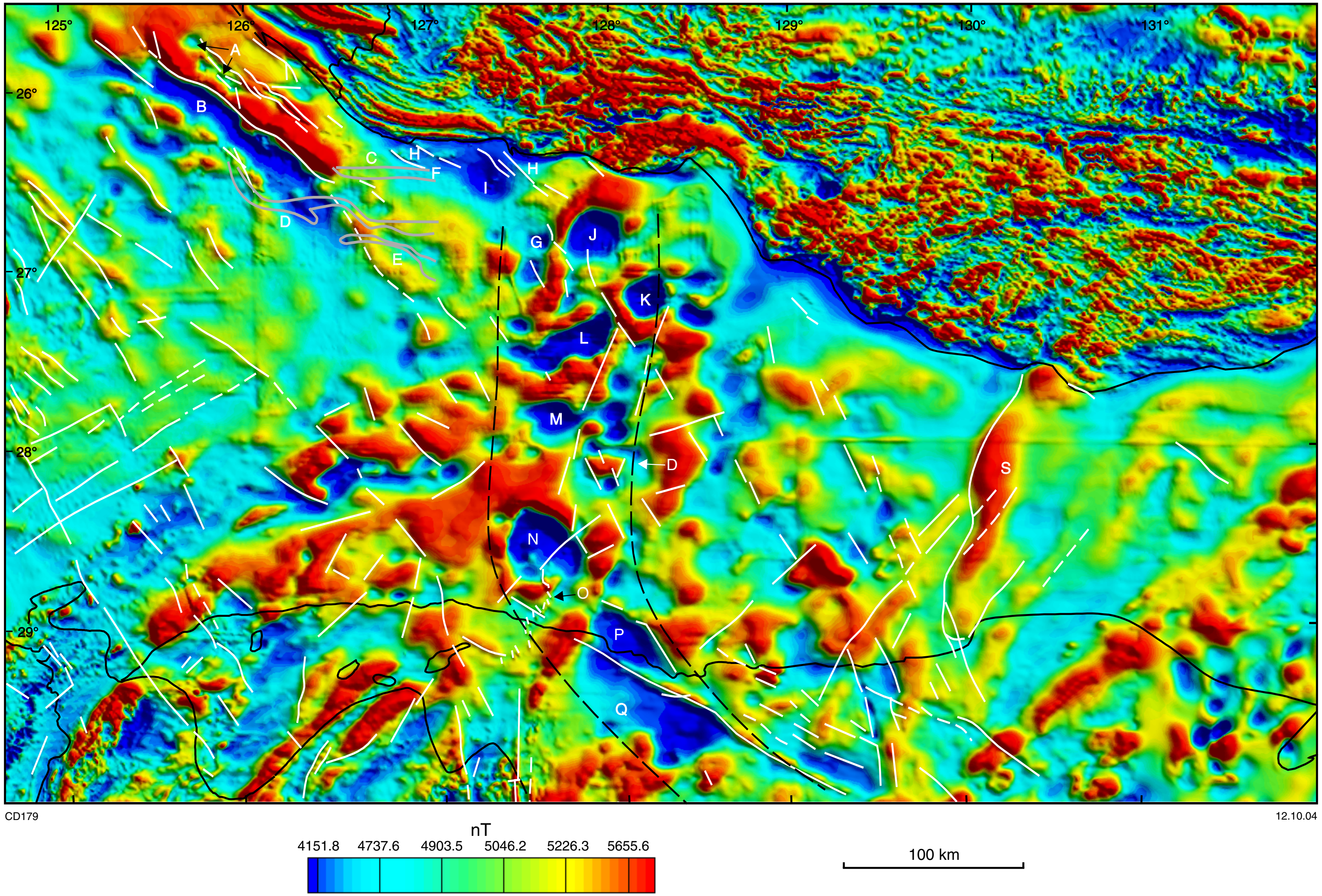

Figure 13. Variably downward-continued image of the total magnetic intensity: A = Browne diapir (low related to salt wall); B = low related to salt; C–E (shown by grey outlines) = salt walls from Durrant and Associates (1998); F = triangular zone of low response; G = Cooper Graben from aeromagnetic data; H = area of fault-controlled Musgrave Complex under thin Officer Basin; I = intrusive body in triangular zone; J–N = circular intrusive bodies; O = sinuous body; P–Q = circular intrusive bodies in the south; R = broad trend of circular anomalies (shown by black dashed lines); and S = Nurrai Ridge

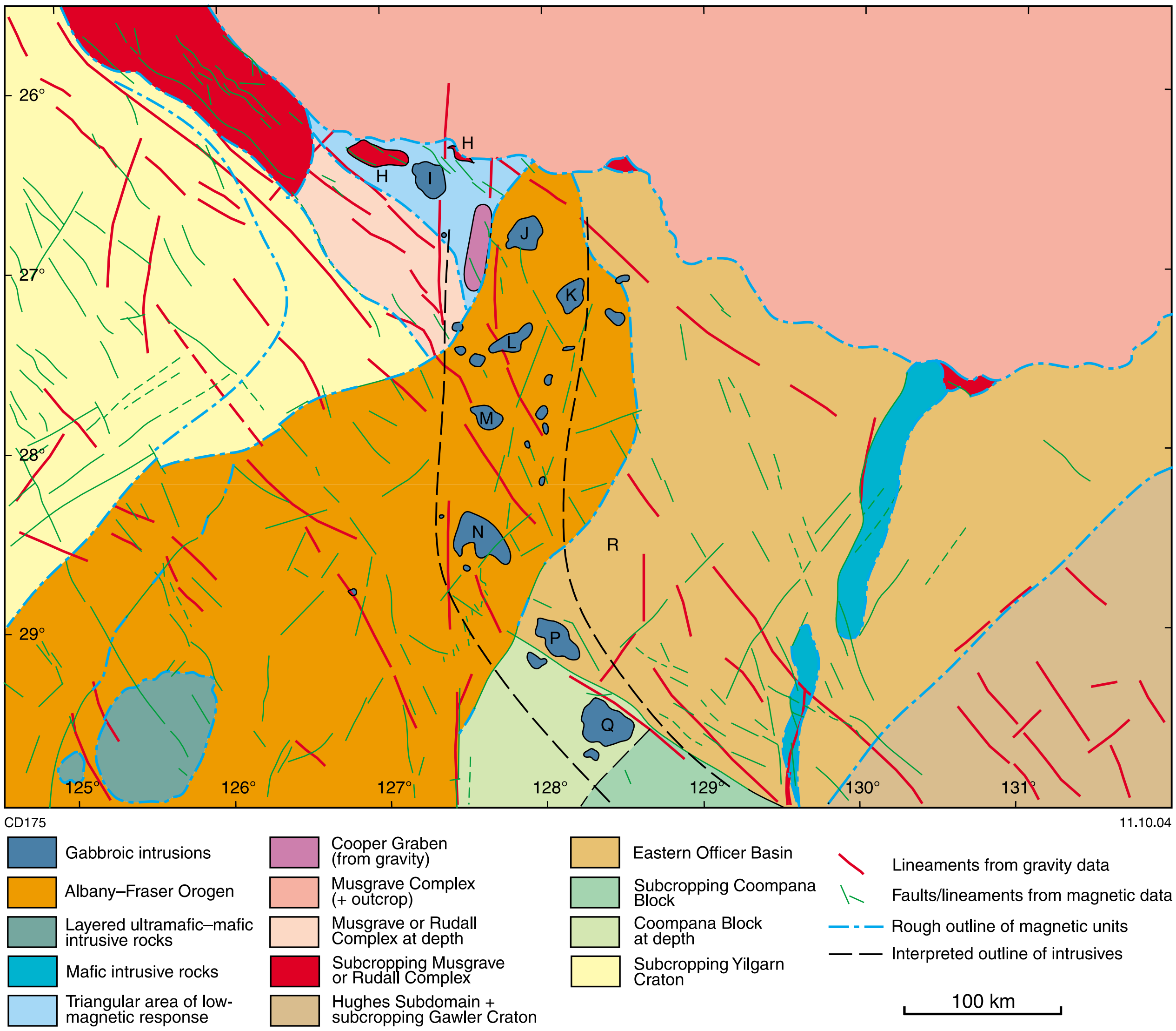

Figure 14. Structural framework of the Waigen area and surrounds interpreted from geophysical (magnetic and gravity) and drillhole data. See Figure 13 for explanation of features labelled H–R

coincide with any magnetic or gravity lineaments, but on a broad scale the northwesterly trending tips of these walls do correspond with northwesterly trending lineaments, and are parallel with structures bounding the Musgrave Complex. Simeonova and Iasky (2005) provided a detailed description of salt features within this area and their correlation to potential-field data.

A small, triangular zone of low magnetic response lies between domains 1, 2, and 4 (F on Fig. 13 and light blue area on Fig. 14). This zone includes the Cooper Graben (G on Fig. 13; Figs 14 and 15), which contains a sedimentary section up to 10 km thick and has a corresponding gravity low. Other magnetic features within this zone include areas of shallow, fault-controlled Musgrave Complex basement in the northeastern and northwestern corner (H on Figs 13 and 14), as well as a deep, circular intrusive body (I on Figs 13 and 14). This zone is perhaps a result of the rotation of the Musgrave Complex and Albany–Fraser Orogen, causing localized extension (see **Synthesis of geophysical and geological data**).

Domain 3

Domain 3 is subcropping Yilgarn Craton, with the eastern corner covering the junction between the Yilgarn Craton, Musgrave Complex, and Albany–Fraser Orogen. The domain is dominated by subdued, narrow, northwesterly trending anomalies truncated or displaced by minor northeasterly trending lineaments (Figs 13 and 14). Apak and Moors (2000b, 2001) noted northwesterly trending salt-related features in the northwestern portion of the area, near the boundary between domains 2 and 3, which may coincide with some of these anomalies. Depth to basement is very shallow west of this area (38–109 m from mineral drillholes TD1–4, 7926 1/C, and 92THAC001; Figs 2 and 3), but increases to the east (about 2–5 km from seismic and gravity data; Fig. 12), consistent with the thickening of the Officer Basin (Apak and Moors, 2000b) and a ?Mesoproterozoic basin (Apak and Tyler, 2002) towards the Musgrave Complex. The underlying ?Mesoproterozoic section could be an extension of the Earaheedy Basin; however, ?Mesoproterozoic rocks

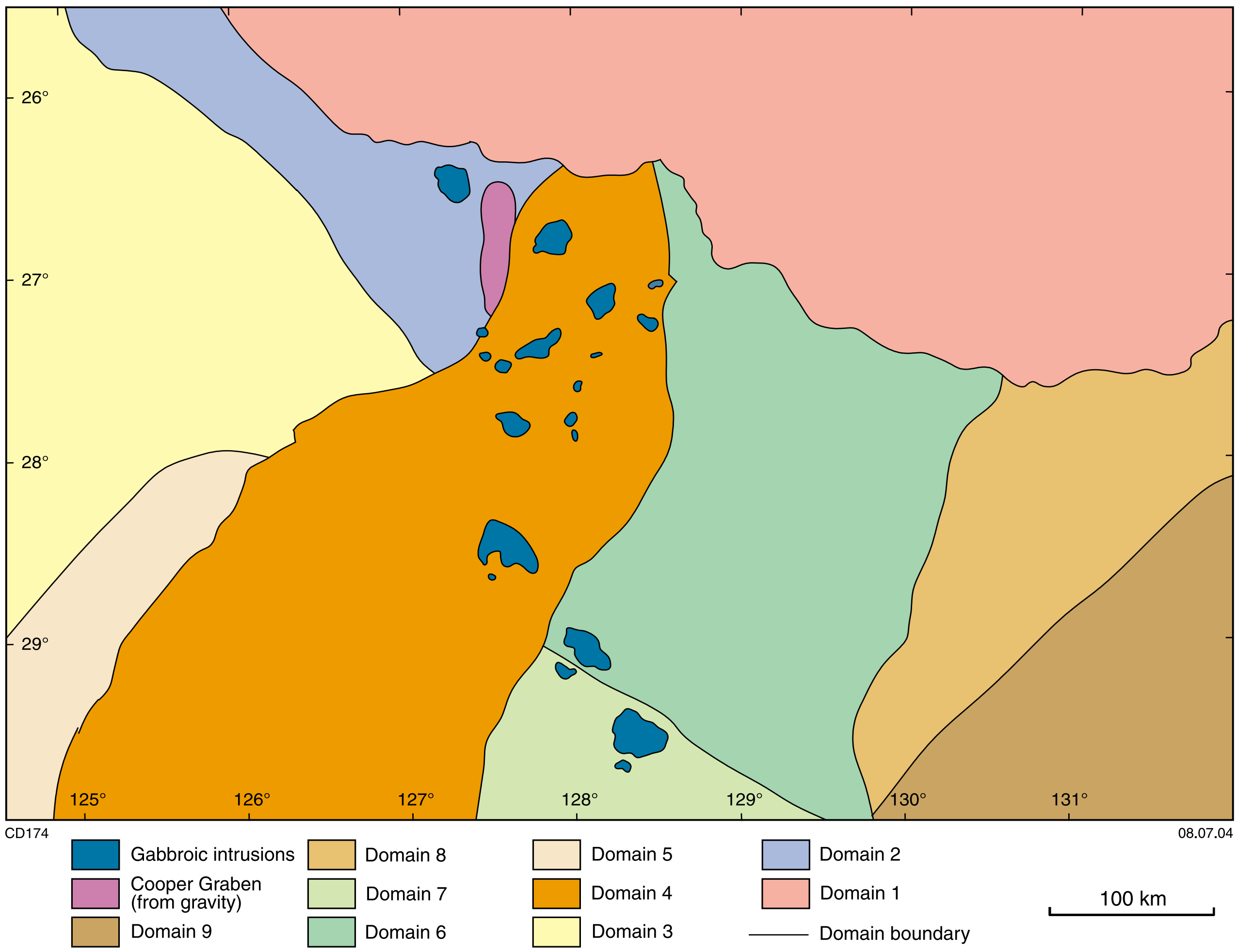

Figure 15. Synthesis domain map of the Waigen area and surrounds

intersected at the bases of GSWA Empress 1/1A and NJD 1 could be correlatives of the upper or lower Bangemall Supergroup (Hocking, 2002) or Musgrave Complex cover sequence (i.e. Mission and Cassidy Groups). Magnetic features in this domain may represent structures in crystalline basement of the Yilgarn Craton, although some of the magnetic highs could be due to magnetite and haematite within the flat lying Table Hill Volcanics. This unit was intersected in mineral drillholes 88 WAC1, 2, 3, and 8 (Fig. 3) and shown to have magnetic susceptibility values from 60 to 1500 × 10^{-5} SI units (Manini and Aravanis, 1988, appendix 4).

Domain 4

Domain 4 has the most complex magnetic pattern within the region and contains deep, broad, high-amplitude anomalies and low-amplitude circular features ranging from 2 to 21 km in diameter with sharp, curvilinear, discordant contact zones (e.g. J–N on Figs 13 and 14). These features are caused by reverse remanently magnetized intrusive bodies at depth, or by salt. Salt is probably present in the Neoproterozoic succession in this region, as it is recorded on either side of the Waigen area in the western and eastern Officer Basin; however, intrusive bodies are more likely for reasons outlined below.

Magnetic modelling suggests depths of between 8 and 19 km for some of the circular magnetic sources (e.g. L, M, N on Fig. 10), implying that they are either mid-crustal or deeper features (Fig. 16). Thus, they are more likely to be features intruding basement, and not salt diapirs within the sedimentary section, although this does not rule out a halotectonic origin in other areas where minor magnetic lows are present. Typically large intrusive bodies within the crust are expected to influence sedimentary thickness estimates derived from gravity data, due to a density contrast between crystalline basement and the deep intrusive bodies (Lockwood and D’Ercole, 2003). However, the depth-to-basement model shows no strong perturbations above the modelled location of the sources of these anomalies, suggesting little or no density contrast between the lower crust and these intrusions. Consequently, magnetic models of the intrusions require a negative magnetic susceptibility contrast with crystalline basement to fit the observations (S = 0.02 for basement versus S = 0 for intrusives; Fig. 16). This modelling suggests that the intrusions are reverse remanently magnetized, with the induced field cancelled by the remanent field (Konigsberger ratio of about 1), and are interpreted as magma chambers, possibly of mafic–ultramafic composition. These intrusions all possess the same polarity, indicating virtually simultaneous

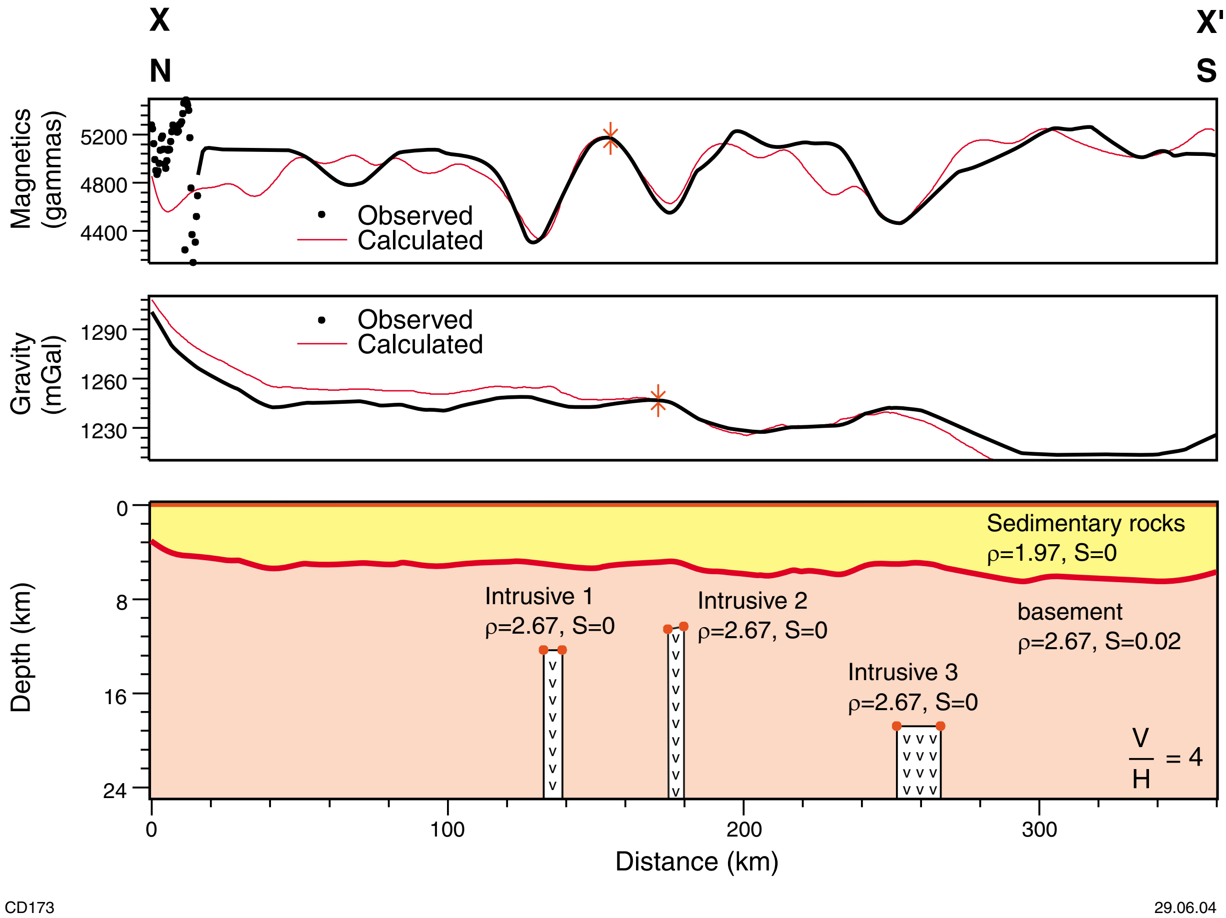

Figure 16. 2D magnetic-field model of deep crustal features along a north–south section of the Waigen area. Line of section is shown in Figure 10 (ρ = density in g/cm^3; S = magnetic susceptibility in SI units)

emplacement and rapid crystallization during a period when the Earth's magnetic field was reversed relative to the present field.

A sinuous body near the southern limit of one of the circular features (O on Figs 11 and 13) was interpreted as a channel that has been infilled by multiple lava flows, and was later confirmed by the intersection of basalt in Weedy 1 (Nelson, 2002; Grey et al., 2005). This feature can be traced for about 140 km and traverses one of the circular features, but is not related to it.

The circular intrusions loosely correspond to gravity highs (Figs 9 and 13), except in the south (P and Q on Fig. 14) where they coincide with gravity lows. The bodies cannot be located precisely on the magnetic images because significant remanence is present in the anomalous field. These circular anomalies form a broad, northerly trending feature (R on Figs 13 and 14) within the central part of domain 4, which seems to coincide with a set of northerly trending lineaments observed in both the gravity and magnetic data (Figs 9, 10, and 13). These lineaments collectively form part of a regional crustal-scale feature termed the Lasseter Shear Zone (Braun et al., 1991) or lineament G12 (Elliot, 1994), the southern extension of which may correlate with the shallow Mundrabilla Fault (Myers and Hocking, 1998) in the Eucla Basin. The Lasseter Shear Zone appears to transect Western Australia from the eastern margin of the Bonaparte Basin in the north, along the western edge of the central Australian basins (i.e. through the Arunta Orogen, Amadeus Basin, and Musgrave Complex), and finally through basement beneath the western Officer and Eucla Basins (Braun et al., 1991, fig. 5; Elliot, 1994, fig. 4). At the southern end of the domain, this feature (Figs 13 and 14) bends around to the southeast and appears to line up with similar anomalies in the Coompana Block, South Australia, that are sourced from shallower mafic intrusives (Flint and Daly, 1993; see **Domain 7**).

Based on regional potential-field contour maps, Iasky (1990) identified a broad basement high separating the Waigen area from depocentres to the west and named it the Neale Ridge (renamed the Neale Arch by Hocking, 1994). A reinterpretation of the gravity and magnetic data shows a prominent ridge in the southwestern part of the Waigen area (A on Fig. 9) that straddles the boundaries of the Neale Arch and Jubilee Shelf. The magnetic data clearly show that this ridge lies farther east than previously mapped, and aligns with outcropping Albany–Fraser Orogen to the south. This suggests that the basement ridge is an extension of the Albany–Fraser Orogen, and the name 'Neale Arch' has therefore been abandoned. Our interpretation partly concurs with that of Perincek (1996), in that the Albany–Fraser Orogen swings around to the northeast beneath the Waigen area. However, the interpretation of the variably downward-continued aeromagnetic image (Fig. 13) indicates that it does not extend towards the Gawler Craton, as suggested by Perincek (1996), but is truncated by lineaments that relate to the Lasseter Shear Zone on its eastern side, and continues northwards to the Musgrave Complex (Figs 13 and 14). Some earlier interpretations suggested the presence of a basement high in the region of the former Neale Arch, and this was attributed to an extension of the Albany–Fraser Orogen (Robertson et al., 1980; Townson, 1985), but based on the recent interpretation of the potential-field data there are no magnetic or gravity signatures within this region that correspond to the orogen.

The majority of magnetic highs within domain 4 probably correspond to mafic–ultramafic rocks and mafic granulites of the Fraser Complex (part of the Mesoproterozoic Biranup Complex within the Albany–Fraser Orogen). The metagabbro and mafic granulites are expected to be the sources of the anomalous magnetic fields. Outcropping Fraser Complex rocks southeast of domain 4 (Figs 13 and 14) appear to be continuous with gravity and magnetic anomalies farther northwest.

Apart from the few northerly trending major crustal lineaments, there is no dominant structural trend within the area. The lineaments range in orientation from northwest to northeast (Figs 13 and 14). Two possible layered intrusions have been noted in the southwestern corner of domain 4 (Fig. 14). Based on aeromagnetic data, signatures in the southwestern corner of domain 4 resemble concealed layered mafic–ultramafic intrusives. Layered mafic intrusives are exposed farther north on PLUMRIDGE (van de Graaff and Bunting, 1977).

There is no direct evidence for the nature, size, and distribution of folds in the sedimentary section in the Waigen area, but their existence is inferred from regional observations and analogies with the nearby areas. Fold patterns have been recognized within the Albany–Fraser Orogen from the magnetic data (Fig. 17). Based on gravity modelling, sediment thickness within domain 4 ranges up to about 8 km (Fig. 12).

Domain 5

Domain 5 has a more subdued magnetic signature than that of domain 4 (Figs 10 and 13), although the frequency content of the observed field is characteristic of shallower sources than those in domain 4. Domain 5 corresponds to the northwestern edge of known outcropping and subcropping granitic rocks, gneisses, and minor sedimentary rocks of the Mesoproterozoic Biranup Complex within the Albany–Fraser Orogen. Such lithologies would explain the low magnetic relief in this domain, compared with the adjacent mafic–ultramafic rocks of the Fraser Complex within domain 4. The change in magnetic character defines the boundary between domains 4 and 5. An arcuate belt of high magnetic anomalies on the northwestern edge of domain 5 forms the boundary with domain 3 (Fig. 13). Mineral exploration holes (N4-1, N3-1, and N1-1; Figs 3 and 13) drilled on these anomalies intersected metagabbros and norites at depths of between 24 and 612 m.

Domain 6

Domain 6 is characterized by smooth magnetic anomalies, indicating deep sources (Fig. 13). The sedimentary section in this domain deepens to the north, ranging from about 5 to 11 km thick (Fig. 12), and onlaps the Coompana Block to the south and Gawler Craton to the east (Preiss, 1993; Rankin, 2003). Northwesterly to north-northwesterly trending magnetic and gravity lineaments dominate the structural expression of this area (Figs 13 and 14).

North-northeasterly trending magnetic highs, such as the Nurrai Ridge (Figs 13 and 14), mark the boundary between domains 6 and 8 (Fig. 15). Ranking (2003) interpreted these ridges as folded belts of mafic intrusives. The thrusted contact with the Musgrave Complex marks the boundary with domain 1.

Domain 7

The northwesterly trending mafic dykes in this domain are part of a dyke swarm within the Coompana Block. Although most of the dykes possess normal remanent magnetization, some are reverse remanently magnetized. Both the gravity and aeromagnetic data show that the Coompana Block is shallow near the Western Australian border and deepens to the north (Figs 12 and 13). This is supported by drillhole data from the Coompana Block south of domain 7, which show that basement is at about 300 m near the border, but deepens to the east (547 to 1341 m) and north (Flint and Daly, 1993). The western boundary of domain 7 corresponds to the Albany–Fraser Orogen.

Magnetically low, circular to elliptical features in domain 7 (P and Q on Fig. 14; Figs 13 and 15) are similar to those within domain 4 and farther south in the Coompana Block (Rankin, 2003, fig. 11). In the Coompana Block, these circular anomalies correspond to mafic–ultramafic intrusions up to about 50 km in diameter (Flint and Daly, 1993); several mineral exploration holes targeting these anomalies intersected gabbro and dolerite between depths of 280 and 340 m (Flint and Daly, 1993). The intrusive bodies within the Albany–Fraser Orogen in domain 4 may be compositionally similar and part of the same suite of intrusions, but are at considerably greater depths (8–19 km from magnetic modelling in domain 4).

Domain 8

Domain 8 is magnetically ‘quiet’ with only minor anomalies, which are probably caused by deep intrusive bodies. This domain contains the most intense and largest gravity low within the region (Fig. 9), representing the thickest part of the Officer Basin. The thickness of the sedimentary section increases dramatically towards the northeast (6–11 km; Fig. 12) into the Munyarai Trough. The boundary between domains 8 and 9 is marked by a major northeasterly trending magnetic feature, which

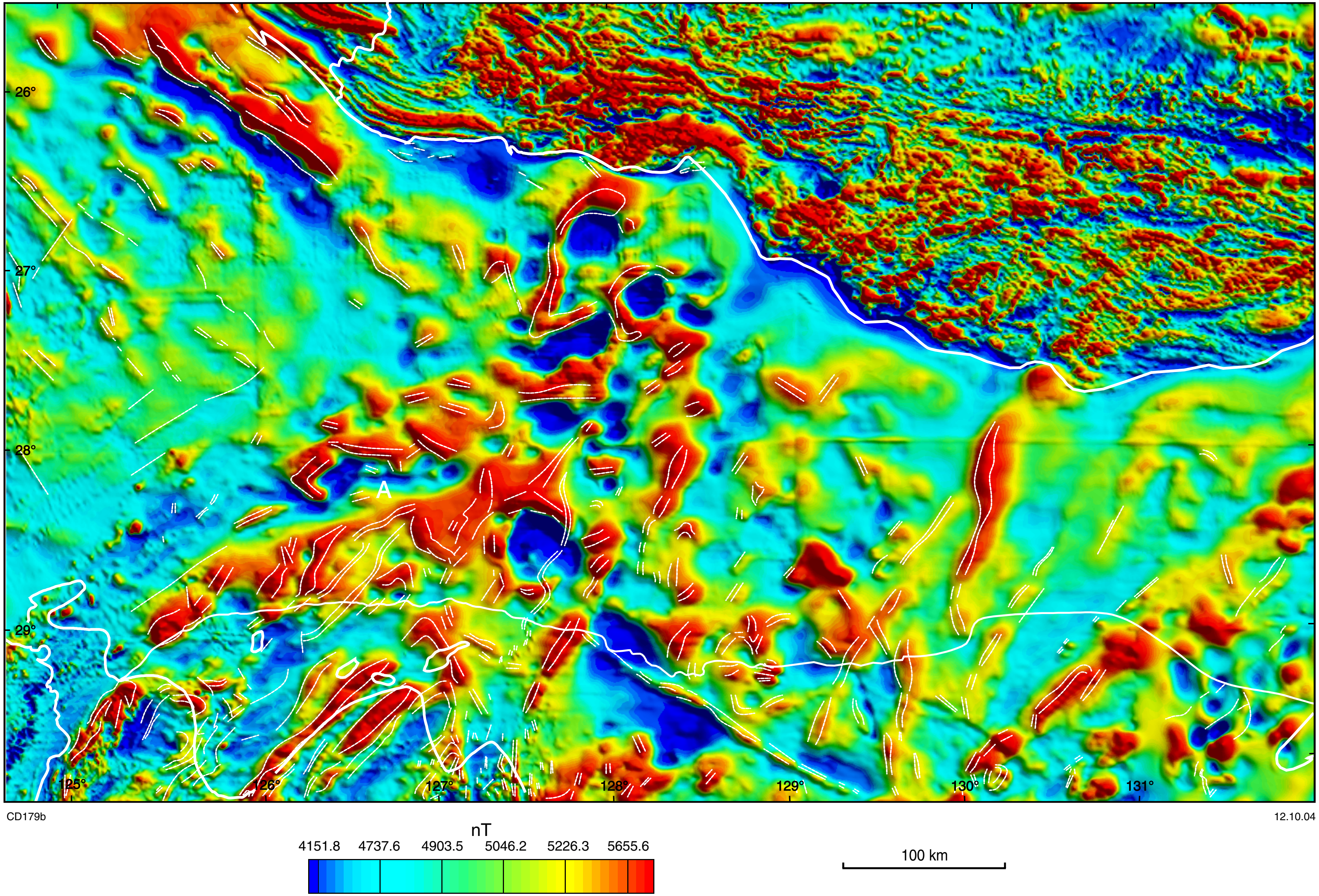

Figure 17. 'Observation layer' from magnetic data highlighting causative magnetic bodies

could be a major thrust fault (Fig. 13). The extension of this feature to the northeast roughly lines up with the Ammaroodinna Ridge, which is a basement inlier (schist, gneiss, and granite) within a major thrust fault complex (Krieg, 1973; Gravestock, 1997).

Domain 9

Domain 9 contains high-amplitude, elliptical magnetic anomalies (Fig. 13) that correlate with granitoids of the Hughes Subdomain (Rankin, 2003) and Gawler Craton in South Australia. Rankin (2003) interpreted these granitoids as being closely related to the Kulgeran Suite granitoids of the Musgrave Complex. The edge of domain 9 is delineated by a northeasterly trending zone of magnetic highs. As with the Musgrave Complex, the coincident gravity high within this domain reflects higher density lithologies than in the surrounding domains. This domain is covered by a veneer of sedimentary rocks from the eastern Officer Basin.

Synthesis of geophysical and geological data

The Waigen area contains complex geophysical signatures that reflect the underlying basement, the interpretation of which has allowed new inferences about the tectonic history of the region. The basement beneath the Officer Basin in the area is dominated by the northeastern extension of the Albany–Fraser Orogen, which is commonly attributed to the continental collision between the West Australian Craton and Mawson Craton (South Australian – East Antarctic continent) at c. 1300 Ma (Myers, 1990a, 1993; Myers et al., 1996). The orogen is interpreted as a northeasterly trending Mesoproterozoic suture along which oceanic crust was consumed as fragments of continental crust were assembled into the Rodinia supercontinent (Condie and Myers, 1999; Fitzsimons, 2003).

There are two theories concerning the tectonic history of the Albany–Fraser Orogen. Clarke et al. (2000) suggested two thermo-tectonic stages for the Albany–Fraser Orogen. Stage I (c. 1345–1260 Ma) involved the collision of continental masses, resulting in the emplacement of the orogen, high-grade deformation and metamorphism, and synorogenic felsic plutonism. Stage II (c. 1214–1140 Ma) involved renewed intracratonic reactivation of the orogen initiating a second episode of metamorphism, deformation, crustal thickening, and intrusion of syn- to late-orogenic felsic granitoids. Alternatively, Dawson et al. (2003) suggested three stages: Stage I (equivalent to Stage I of Clarke et al., 2000); Stage II (c. 1215–1180 Ma), involving an anorogenic environment related to a craton-scale thermal anomaly (equivalent to early Stage II of Clarke et al., 2000); and Stage III (c. 1180–1140 Ma), involving the reactivation of the orogen due to renewed compression (equivalent to late Stage II of Clarke et al., 2000).

Originally, the Albany–Fraser Orogen may have extended straight towards the central part of Australia (Fig. 18a), where it is truncated by the northwesterly trending Musgrave Complex, but was deformed and rotated during uplift and thrusting of the Musgrave Complex during the Neoproterozoic. As the Musgrave Complex was thrust to the southwest over the Officer Basin, it was indented by the Albany–Fraser Orogen (Fig. 18b). Our interpretation is that the Albany–Fraser Orogen behaved as a rigid body during thrusting and uplift of the Musgrave Complex. From the shape of domain 4, the orogen appears to have rotated around the shallow basement in domain 2 (possibly pre-Gascoyne or Rudall Complex — GRC on Fig. 18a) during sinistral transpression, explaining the irregular contact seen where the two meet. This created a zone of local extension between the basement elements underlying the Officer Basin (Fig. 18c). This zone of extension is marked by the small, triangular area of low magnetic response between domain 2, the Musgrave Complex, and the Albany–Fraser Orogen (F on Fig. 13; Fig. 14), and by the deep Cooper Graben (G on Fig. 13; Fig. 14) on the edge of the Albany–Fraser Orogen. The c. 550 Ma Petermann Orogeny is interpreted as a dextral transpressive event (Camacho and McDougall, 2000), but the sinistral event recognized here may represent the earlier c. 750 Ma Areyonga Movement, thereby restricting the formation of the Cooper Graben and low magnetic zone to the Neoproterozoic.

The deep, circular to elliptical magnetic features in domains 4 and 7 are interpreted as either mantle material emplaced during rift-related crustal thinning prior to Phanerozoic events, or as deep mafic–ultramafic magma chambers that originated from an underplating event prior to rift initiation. Similar features noted around the world have been linked to mantle plumes (Pirajno, 2000). Within continental Australia, four possible documented mantle plume events and associated volcanism are relevant to the Waigen area: c. 1075 (Wingate et al., 2004), c. 800 (Zhao et al., 1994), c. 755 (Wingate and Giddings, 2000), and c. 510 Ma (Hanley and Wingate, 2000). The timing of the episodes at c. 800 and c. 755 Ma are only constrained by tentative correlations to large dyke swarms. Dyke swarms are typically oriented in a radial pattern above a mantle plume (Ernst et al., 1995a,b; Ernst and Buchan, 2001) or can follow pre-existing lithospheric breaks. The c. 800 Ma magmatic event is associated with the c. 800 Ma Amata Suite, 827 ± 6 Ma Gairdner Dyke Swarm, and 827 ± 9 Ma Little Broken Hill Gabbro in South Australia (Zhao et al., 1994; Wingate et al., 1998). The dyke swarm in the Coompana Block may also be related to this same event (Flint and Daly, 1993; Rankin, 2003), although there are no data to support this hypothesis. The only dates available from the Coompana Block are from granites (1185–1159 Ma; Webb et al., 1982; Flint and Daly, 1993) and these correlate with Stage II of Clarke et al. (2000) and Dawson et al. (2003). These dates represent the minimum age of the gneissosity and indicate a Musgravian Orogeny overprint (Flint and Daly, 1993). This implies that the Coompana Block was emergent at about 1200 Ma (Rankin, 2003). The c. 755 Ma magmatic event is associated only with the Mundine Well dyke swarm in the Pilbara Craton and Capricorn Orogen (Wingate and Giddings, 2000). Based on the minimum data available, it is unlikely that either of these magmatic events is related to the magnetic features in the study area.

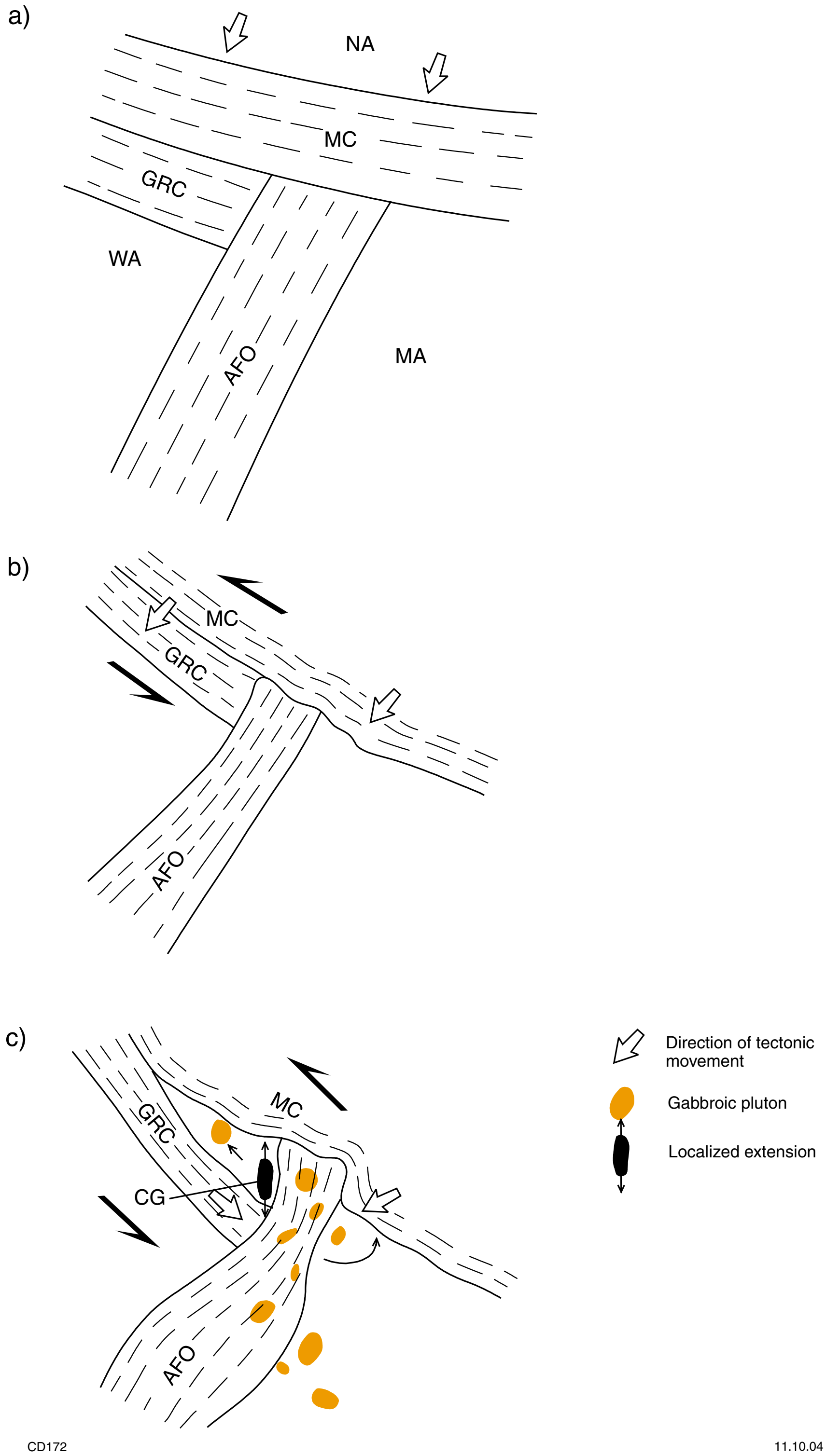

Figure 18. Schematic diagram of the Neoproterozoic tectonic history of the Waigen area: a) formation of the Albany–Fraser Orogen (AFO) and Musgrave Complex (MC) resulting from the collisions of the West Australian Craton (WA), Mawson Craton (MA; South Australian – East Antarctic continents), and North Australian Craton (NA). The AFO extends towards the central part of Australia. Initiation of thrusting of MC and rotation around pre-existing Gascoyne or Rudall Complex (GRC); b) continuation of uplift and thrusting of MC and initiation of rotation of AFO and sinistral transpression of GRC; and c) completion of thrusting of MC and rotation of AFO, initiation of local extension (Cooper Graben; CG). Impact of mantle plume (c. 1075 or 510 Ma) and emplacement of gabbroic plutons

The magnetic features within the Waigen area are more likely to be related to the Warakurna large igneous province (LIP) proposed by Wingate et al. (2004) within central western Australia. These authors suggested that a large mantle plume existed beneath central Australia at c. 1075 Ma based on palaeocurrents, radiating dyke swarms, and high-Mg parental melts, which together imply proximity to the hot centre of a plume head. They also inferred a link between the Warakurna LIP event and plate-boundary forces along the Australian–Antarctic continental margin, which may explain the overall arcuate shape of magnetic features between domains 6 and 7 and the northeastern end of domain 4 near the Albany–Fraser Orogen, which is a major lithospheric break. If a plume were present, the magma would have followed this zone of weakness, intruding the Albany–Fraser Orogen. Such intrusions would then pre-date the Neoproterozoic deformation events affecting the western Officer Basin.

Alternatively, the magnetic features may be related to the c. 510 Ma Kalkarinji LIP, which includes the Antrim Plateau Volcanics of northern Australia (Hanley and Wingate, 2000; Glass, 2002) and the Table Hill Volcanics, meaning that the intrusions would post-date the deformation events, but more evidence is required to confirm this. If the Table Hill and Antrim Plateau Volcanics belong to the same LIP, they extend for some 1700 km in a northerly direction and at least 1300 km in an easterly direction, with a possible aggregate areal extent of about 2.2×10^6 km^2 (Grey et al., 2005).

Gunbarrel Basin

The Gunbarrel Basin is separated from the Officer Basin by the regional uplift and erosion that occurred during the Delamerian Orogeny. The structures in the Gunbarrel Basin are both syndepositional and post-depositional, consisting of tectonic folding, halokinetic uplift, and faulting (e.g. Westwood Fault). The structural subdivision of the Gunbarrel Basin comprises three flat-lying formations that unconformably overlie the Proterozoic sequence and extend eastwards into South Australia, where the Gunbarrel Basin has not been differentiated from the Officer Basin. The Table Hill Volcanics form the base of the sequence and are a lithologically distinctive unit identifiable in seismic sections. Using outcrop distribution and seismic interpretation, Jackson and van de Graaff (1981) produced an accurate structural configuration for the base of this sequence, which shows that the Gunbarrel Basin is regionally folded into gentle northwest-elongated synclines and anticlines in the Yowalga area, and elsewhere is very gently dipping.

Tectonic evolution

Several structural models have been proposed for the initiation and development of the Officer Basin (Lambeck, 1984; Walter and Gorter, 1994; Zhao et al., 1994; Walter et al., 1995; Carlsen et al., 1999; Apak and Moors, 2000a,b, 2001). The simplest model, proposed by Walter and Gorter (1994) and Walter et al. (1995), groups the Officer, Amadeus, Ngalia, Savory (now included in the Officer Basin), and Georgina Basins into a single Centralian Superbasin that developed during crustal extension at the time of the Gairdner Dyke Swarm, and continued as a single depositional entity until major uplift and emergence of the Musgrave Complex, possibly as late as the Petermann Orogeny. However, Grey et al. (2005) disputed the concept of a single basal sand sheet deposited synchronously across the Centralian Superbasin, as the basal sand unit (Townsend Quartzite and equivalents) is absent in the western Officer Basin except near tectonically active margins with some hinterland relief. Camacho et al. (2002) recently demonstrated that the Musgrave Complex was emergent and contributing sediment to the southern Amadeus Basin from at least 700 Ma, which suggests that there was always a series of related basins rather than a single entity (Grey et al., 2005). Haddad et al. (2001), using gravity modelling, also confirmed the evolution of a series of separate, but related basins, which were initially connected in a broad continental sag. They also supported the proposal of Apak and Moors (2000a,b) of an early foreland basin evolution for the western Officer Basin and its exclusion from the Centralian Superbasin.

Apak and Moors (2000a,b) considered that the earliest stages of basin formation were initiated by intermittent loading of a thrusted northern margin (the Musgrave Complex) with significant tectonic movement deforming Supersequence 1 during the Areyonga Movement, prior to deposition of Supersequence 2. An interpretation of seismic line 93AGS-01 (Fig. 19) in the Birksgate Sub-basin in South Australia by Leven and Lindsay (1995) and Lindsay and Leven (1996) indicates thrusting from the Musgrave Complex (northerly dipping structures within basement). Thrust structures at the southern end of the line terminate at the base of Supersequence 1 strata (Fig. 19) and do not disrupt the basal sedimentary rocks (Pindyin Sandstone and Alinya Formation in South Australia and Townsend Quartzite and Lefroy Formation in Western Australia). This suggests that the structures were truncated by an erosional event that peneplaned basement before deposition of these basal units (Leven and Lindsay, 1995). At the northern end of the line, the thrust structures truncate lower Supersequence 1 strata (Fig. 19).

Apak and Moors (2000b) suggested that this movement occurred during or after deposition of Supersequence 1 and could have provided some of the loading mechanism for basin subsidence. The thrusted margin with synchronous loading originally suggested for the Birksgate Sub-basin, and adopted by Apak and Moors (2000b) for the Yowalga area in Western Australia, is also pertinent for the Waigen area. Although a foreland basin model appears applicable for deformation of Supersequence 1, it is uncertain whether the depositional style shown in Supersequence 1 fits this model; that is, basal sands deposited near margins with hinterland relief, but not on low-relief margins, followed by very uniform facies belts in a continuing marginal-marine setting over virtually the entire basin (and very similar in all other component basins of the Centralian Superbasin). The sequence clearly thickens towards the Musgrave Complex, but it is uncertain to what extent this reflects rapid subsidence of the basin floor (utilizing basin-bounding faults against the complex) versus active overthrusting of the complex over the Officer

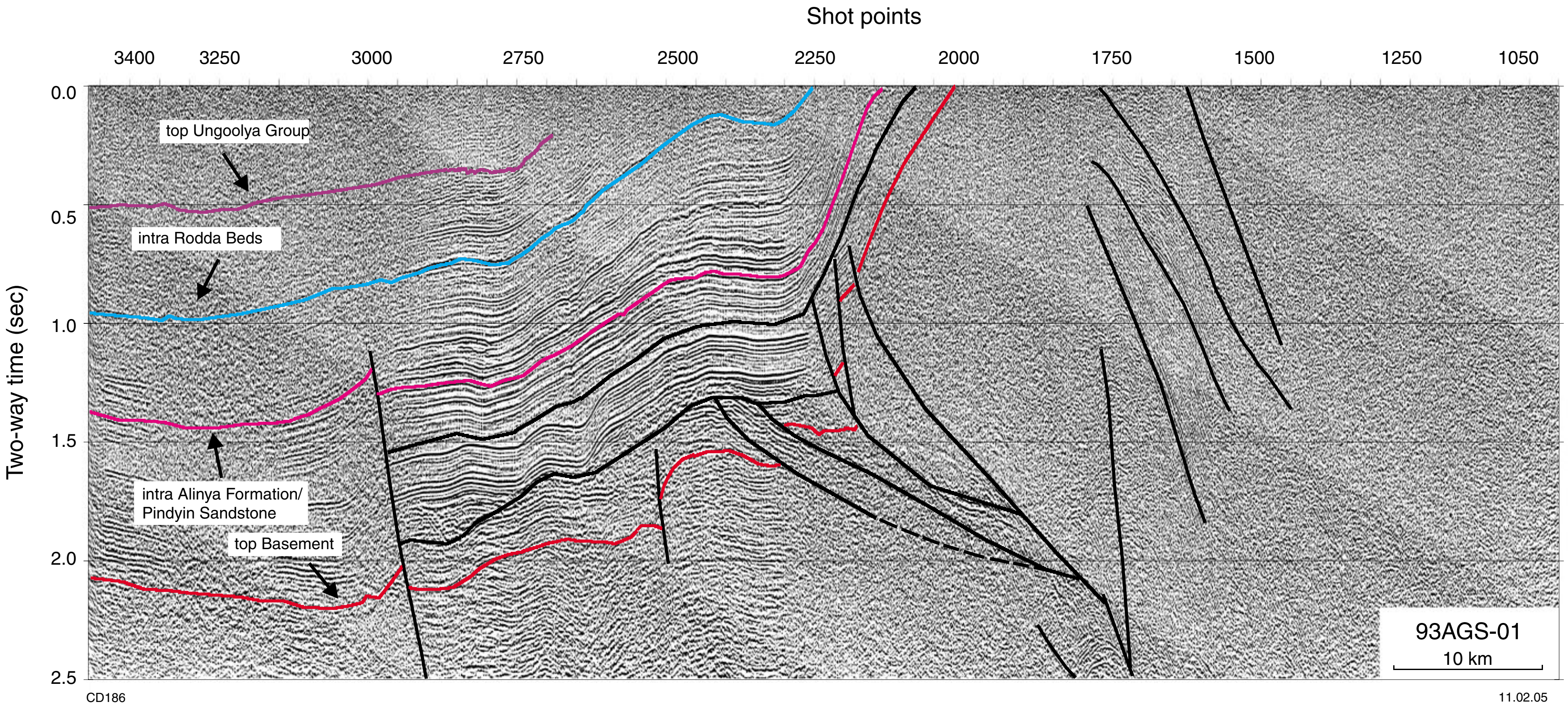

Figure 19. Seismic line 93AGS-01 from the Birksgate area, eastern Officer Basin, showing the folded Officer Basin sedimentary section and thrust faults from the southern margin of the Musgrave Complex (modified from Leven and Lindsay, 1995). The location of this figure is shown in Figure 3

Basin. The coarsening-upward trend of basin fill, with significant influx from the Musgrave Complex as fluvial incursions, is not present.

Several significant episodes of uplift are indicated by regional unconformities within the Neoproterozoic, Palaeozoic, and Mesozoic basins of central Australia. These episodes have been documented within the western Officer Basin through well-log correlation, interpretation of seismic data, and limited outcrop studies (Perincek, 1998; Apak and Moors, 2000a,b, 2001; Apak et al., 2002a; Moors and Apak, 2002; Simeonova and Iasky, 2005). They are associated with events documented in other basins of the Centralian Superbasin and Adelaide Rift Complex, and define the supersequence boundaries within the Officer Basin. Apak and Moors (2000a,b, 2001, 2002) and Moors and Apak (2002) attributed the uplift and consequent unconformities to the Miles Orogeny, Areyonga Movement, Petermann Orogeny, Delamerian Orogeny, Rodingan Movement, and Alice Springs Orogeny.

Mesoproterozoic

The accretion and intracratonic deformation of central Australian terranes (West Australian, North Australian, and Mawson Cratons) occurred between 1600 and 1000 Ma, with extensive magmatism in the Mawson Craton, particularly on the South Australian side (Myers et al., 1996). The magmatism (Gawler Range Volcanics and Hiltaba Suite) was linked to a possible mantle plume by Blissett et al. (1993). Assembly of these three cratons was completed between 1300 and 1100 Ma, with the crustal fragments combining to form Proterozoic Australia, which was an early component of the Rodinian supercontinent (Myers et al., 1996). The initial collision was between the West Australian and North Australian Cratons, followed by collision with the Mawson Craton (South Australian – East Antarctic continent) at c. 1300 Ma, and subsequently by intracratonic reactivation affecting basement and cover at c. 1200 Ma (Myers et al., 1996; Clarke et al., 2000). The orogenic emplacement of the Albany–Fraser Orogen onto the Yilgarn Craton was completed by Stage I of Clarke et al. (2000) at c. 1345–1260 Ma.

Sutures between these three cratons are defined by 'Grenville-age' (c. 1300–950 Ma) orogenic belts (Myers et al., 1996; Clarke et al., 2000; Dawson et al., 2003), namely the Albany–Fraser Orogen, Musgrave Complex, and Rudall Complex, which coincide with worldwide orogenic events that record the assembly of Rodinia. Similar tectonic histories have been recorded for the Albany–Fraser Orogen (Clarke et al., 2000; Dawson et al., 2003), the Wilkes Province of Antarctica (Fitzsimons, 2000), and parts of the Musgrave Complex, implying they were part of the same orogenic belt (White et al., 1999). The Albany–Fraser Orogen was uplifted and eroded at c. 1260–1215 Ma, prior to Stage II (Clarke et al. 2000, Dawson et al., 2003). This was followed by the emplacement of several dyke swarms (Boyagin, Fraser, Gnowangerup, and Wheatbelt Dyke Swarms) into the Albany–Fraser Orogen and Yilgarn Craton along pre-existing structures at 1215–1202 Ma, and granitic magmatism at c. 1200–1180 Ma (Dawson et al., 2003). These events were linked to a regional thermal anomaly caused by a mantle plume (Dawson et al., 2003). High-grade metamorphism and substantial crustal thickening occurred within the Musgrave Complex to the north at c. 1200–1150 Ma (Myers et al., 1996), with extensive granitoid magmatism at c. 1190–1150 Ma in the Musgrave Complex, and 1180–1140 Ma in the Albany–Fraser Orogen (Myers et al., 1996; Clarke et al., 2000; Dawson et al., 2003).

A major episode of late Mesoproterozoic mafic magmatism has been recorded over western and central Australia, with the main injection of magma between 1078 and c. 1070 Ma (Wingate et al., 2004). At this time, major dyke swarms, layered mafic–ultramafic intrusions, and bimodal volcanic rocks were emplaced over about 1.5 × 106 km^2 (Wingate et al., 2004), covering the West Australian, South Australian (Mawson), and North Australian Cratons, and forming the Warakurna LIP. Wingate et al. (2004) inferred from its large areal extent and short duration that this LIP was emplaced above a mantle-plume head.

Neoproterozoic

The extensive, intracratonic Centralian Superbasin developed over the West Australian, North Australian, and South Australian Cratons between c. 830 and 750 Ma (Walter and Gorter, 1994; Walter et al., 1995). The basement beneath the superbasin was intruded by a c. 800–830 Ma episode of mafic magmatism (Gairdner Dyke Swarm, Amata Suite, and various volcanic rocks) that has been related to a mantle plume (Zhao et al., 1994; Wingate et al., 1998). This mantle plume may be part of a superplume that could have triggered the initial breakup of the Neoproterozoic supercontinent of Rodinia (Li et al., 2001), which has been estimated at 750 Ma. Zhao et al. (1994) and Walter et al. (1995) also related the c. 800 Ma mantle plume to the formation of the Centralian Superbasin. Deposition of hundreds of metres of marine and fluvial sediments within the superbasin began with Supersequence 1.

Apak et al. (2002a) attributed the unconformity immediately beneath the Officer Basin to the Miles Orogeny. Both the Miles and Edmundian Orogenies are constrained in age by the older Warakurna LIP (c. 1070 Ma) and the younger Mundine Well Dyke Swarm (755 Ma), and possibly relate to a thermal event at 980 Ma recognized by Occhipinti and Reddy (2003). However, based on correlations between equivalent successions in the Amadeus and Officer Basins and Adelaide Rift Complex, the probable age of onset of deposition in the Officer Basin is 850–820 Ma (Close et al., 2003; Grey et al., 2005). An earlier phase of rift deposition (Bloods Range beds and associated rocks) is recognized in central Australia (Close et al., 2003), but if the Miles Orogeny is much older than this, it may not relate to the development of the Officer Basin. There does appear to have been uplift at around 900 Ma (Occhipinti and Reddy, 2003), but currently there is not enough evidence to link this to any orogeny.

Supersequence 1

Deposition in the western Officer Basin began with fluvial to shallow-marine Neoproterozoic sediments (Townsend Quartzite) deposited on Mesoproterozoic–Palaeoproterozoic orogenic belts and basins, or Archaean and ?Proterozoic cratons. Limited field evidence of sedimentary transport directions for the Townsend Quartzite and laterally equivalent Dean Quartzite, Heavitree Quartzite, and Pindyin Sandstone (Daniels, 1970, 1974; Morton and Drexel, 1997; Lindsay, 1999; Stevens and Apak, 1999) suggests that the present-day Musgrave Complex was emergent during the deposition of the lower part of the Supersequence 1, although the most-detailed palaeocurrent studies, by Grigson (1982) and Watts (1982), show significant transport parallel to the complex, rather than from it. Zircon provenance studies by Camacho et al. (2002) confirmed that the Musgrave Complex was emergent from c. 700 to 550 Ma. Deposition of siltstone and shale (Lefroy Formation) followed a marine transgression and subsequent decrease in energy levels. Apak and Moors (2000b) suggested that the Lefroy Formation may be a deeper water facies of the Townsend Quartzite.

Relative regression led to shallow-marine to hypersaline coastal conditions, in which widespread mudstone, dolomite, and evaporites (Browne Formation) were deposited. The evaporites later formed diapirs (e.g. Madley, Woolnough Hills, and Browne diapirs) and other halotectonic structures that have both complicated and influenced the structure within the basin (Apak and Carlsen, 2003; Carlsen et al., 2003). The top of the Browne Formation is eroded on the crest of many folds and diapiric structures, and along the northern margin of the basin. In the Yowalga and Lennis areas, an angular unconformity commonly separates the Browne Formation from younger Neoproterozoic units, such as the Lupton or Lungkarta Formations, or Phanerozoic units (Apak and Moors, 2000a,b, 2001). The same may be true in the Waigen area.

Deposition in the area continued under tectonically quiet conditions; the Hussar, Kanpa, and Steptoe Formations, overlying the Browne Formation, were deposited in similar environments, with repeated progradational cycles of mixed siliciclastic and carbonate sediments, and minor evaporites (Apak and Moors, 2000a,b, 2001) indicative of regular small-scale sea-level fluctuations.

Areyonga Movement (end of Supersequence 1)

A hiatus that separates Supersequences 1 and 2 in the eastern Officer Basin has been linked with the compressional Areyonga Movement. This event is recognized as the first regionally extensive tectonic event to affect the western Officer Basin (Apak and Moors, 2000a,b, 2001). The Areyonga Movement commenced in the central part of Australia as Rodinia began to break up (between 750 and 800 Ma; Wingate and Giddings, 2000; Condie, 2001) and Laurentia separated from Gondwana (Baillie et al., 1994; Walter and Veevers, 1997; Veevers, 2000) along the eastern margin of Proterozoic Australia, which led to the formation of the Palaeo-Pacific Ocean.

Folding and faulting of Supersequence 1 strata, with associated significant salt movement and extensive erosion, characterized this movement in the western Officer Basin, especially in basin-margin areas and over salt-emplacement features (Carlsen et al., 2003). The Browne diapir, initiated by the Areyonga Movement, is part of a major salt wall that extends over 100 km with piercement structures over 10 km wide (Apak and Moors, 2000b).

Supersequence 2 strata appear to be absent in the western Officer Basin, except perhaps in the northwest Paterson Orogen, where Bagas (2003) noted detrital-zircon age signatures from the Throssell Range Group characteristic of Supersequence 2 in the Amadeus Basin.

Supersequence 3

The 650–580 Ma collision of east and west Gondwana resulted in the closure of the Mozambique Ocean at c. 580 Ma, continued opening of the Pacific Ocean, and widespread rifting at c. 600 Ma accompanied by Marinoan glacial deposition in Australia (Veevers, 2000, 2001). Deposition of Supersequence 3 strata at this time, represented by the Wahlgu Formation and possibly Lupton Formation, was associated with the widespread Marinoan glaciation (Grey et al., 1999, 2005; Apak and Moors, 2001; Moors and Apak, 2002). The depositional environment was still predominantly shallow marine, with glacially derived clastic sediments deposited by debris flow and turbidity currents (Carlsen et al., 1999). Only 200–300 m of sedimentary rocks are recorded in the main part of the western Officer Basin, although a complete section has not been measured (Apak and Moors, 2000b), and the section in the northwest Officer Basin (Savory region) appears to extend to a higher stratigraphic level than elsewhere. Both the amount of deposition of Supersequence 3, and the amount of erosion after deposition of Supersequence 3, are quite variable, particularly in the Gibson and Yowalga areas (Moors and Apak, 2002; Apak and Carlsen, 2003).

Petermann Orogeny (start of Supersequence 4)

The hiatus between Supersequences 3 and 4 may be associated with the earliest stages of the Petermann Orogeny (about 550 Ma; Bagas and Smithies, 1998), which is the most extensive tectonic event in the evolution of the region. This compressional structural event initiated and reactivated thrust faults and diapirs, and produced gentle folding of the Neoproterozoic succession throughout the western Officer Basin, with locally intense deformation along its northeastern margin.

The fragmentation of the Centralian Superbasin has been attributed to the Petermann Orogeny (Baillie et al., 1994; Walter and Gorter, 1994; Walter et al., 1995). Baillie et al. (1994) suggested that the Petermann Orogeny was related to the collision of East Gondwana with Africa, and that the latter may have produced a trans-Australian continental shear along the Paterson–Petermann orogenic zone. Gravity, magnetic, and seismic data indicate that the Musgrave Complex was thrust over the Officer Basin's margin at that time (Leven and Lindsay, 1995; Lindsay and Leven, 1996; Carlsen et al., 2003).

More than 15 km of uplift has been recorded along the northern margin of the Musgrave Complex during this orogeny, with large-scale folding and thrusting of the southern Amadeus Basin (Close et al., 2003). In the western Officer Basin, Apak and Moors (2001) and Carlsen et al. (2003) considered that the southward-directed overthrust of the Musgrave Complex caused additional thin-skinned shortening and a large crustal load that contributed to further subsidence and asymmetry of the Waigen and adjacent areas. In the eastern Officer Basin, Moussavi-Harami and Gravestock (1995) estimated that up to 3000 m of sedimentary rocks were eroded during this orogeny.

Supersequence 4

During the Petermann Orogeny, rapid uplift of the Musgrave Complex took place, resulting in deposition of mainly siliciclastic Supersequence 4 strata (Lungkarta Formation, Punkerrri Sandstone, ?Vines Formation, and ?Lupton Formation). Perincek (1997) and Stevens et al. (2002) considered these units to represent a prograding deltaic to shallow-marine shelf environment. Farther northwest, the Lungkarta Formation onlaps and thins over pre-existing structural highs (Moors and Apak, 2002, Fig. 17). The gravity image of the Waigen area (Fig. 9) shows a gravity low associated with increased sedimentary thickness, which suggests rapid subsidence in the area. Further evidence for rapid rates of sedimentation in the Waigen area is found in Vines 1, which intersected 2 km of conglomeratic rocks of the ?Lower Cambrian Vines Formation, within which most of the large clasts are unweathered. This indicates the formation was deposited syntectonically with rapid uplift of the Musgrave Complex in the earliest Cambrian, presumably during the Petermann Orogeny (Apak et al., 2002b; Stevens et al., 2002). The reworked Neoproterozoic–Cambrian cusp fauna in the Vines Formation (Apak et al., 2002; Grey et al., 2005) may well be derived from the Lungkarta Formation, and suggest that the Vines Formation was deposited after the Lungkarta Formation rather than being a coarser grained, coeval variant of it.

Palaeozoic

Delamerian Orogeny (end of Supersequence 4)

The Delamerian Orogeny is recognized in central Australia as a Middle to Late Cambrian deformational phase that occurred after deposition of the Marla Group in the eastern Officer Basin and prior to, and possibly coeval with, extrusion of the Kulyong Formation (Table Hill Volcanics correlative). In the western Officer Basin, it is recognized as a phase of mild deformation separating Supersequence 4 from the Table Hill Volcanics, and thus the western Officer Basin from the overlying Gunbarrel Basin. The Cambrian succession is found in South Australia (the Marla Group) and is absent in Western Australia, unless some outcrops of Wanna and Lennis Sandstone have been misidentified or the Vines Formation is younger. During the orogeny, tectonic highs within the area were rejuvenated and eroded (Apak and Moors, 2000b, 2001; Moors and Apak, 2002).

The Delamerian Orogeny caused reactivation of diapiric movement (e.g. Browne, Madley, and Woolnough Hills diapirs), folding, and faulting, and initiated widespread deposition of flood basalts (Phillips et al., 1985; Townson, 1985) and further uplift of the Musgrave Complex (Perincek, 1998). Baillie et al. (1994) linked the outpouring of these basalts to renewed continental breakup along the eastern and northern margins of Australia.

Gunbarrel Basin

Widespread extrusion of the Table Hill Volcanics during the Late Cambrian marked the Delamerian Orogeny and beginning of the Gunbarrel Basin (Hocking, 1994). This event is represented by a distinct reflection on seismic sections (Moors and Apak, 2002, Figs 18 and 19) and is used as a regional marker in the western Officer Basin, but is absent from some parts of the Gibson area due to post-depositional uplift (Apak et al., 2002a; Moors and Apak, 2002). Salt diapirs, probably triggered or reactivated by the Alice Springs Orogeny, have penetrated or folded the Table Hill Volcanics in some areas (Apak et al., 2002a; Apak and Carlsen, 2003). Eastern areas of the Centralian Superbasin changed from an extensional to compressional tectonic and depositional regime during the Late Ordovician, beginning with the Rodingan Movement (Bradshaw and Evans, 1988; Haines et al., 2001). The effect of the Rodingan Movement, if any, in the western Officer Basin is difficult to assess due to the very poor constraints on the age and distribution of the section between the Table Hill Volcanics and Paterson Formation. Deformation, if any, is gentle.

The Lennis Sandstone and Wanna Formation are constrained in age only by the late Middle Cambrian Table Hill Volcanics and the Carboniferous–Permian Paterson Formation. By comparison with successions in the Amadeus and Canning Basins, they are tentatively regarded as Ordovician and Early–Middle Devonian respectively. Van de Graaff (1972) and Jackson and van de Graaff (1981) interpreted them as shallow-marine sand-wave deposits, although other published descriptions suggest a partly eolian origin is also possible. Widespread compression caused extensive reverse faulting during the Devonian–Carboniferous Alice Springs Orogeny in the eastern Officer Basin (Gravestock, 1997), but this is less apparent in the Western Australian succession. The youngest sedimentary rocks included in the Amadeus Basin in central Australia are those affected by the Alice Springs Orogeny (Lindsay and Korsch, 1991; Shaw, 1991), and Upper Carboniferous and Lower Permian glacigene rocks are excluded from this basin. In South Australia, units of this age are assigned to the Arckaringa Basin rather than the Officer Basin (Hibbert, 1995). In Western Australia, the Phanerozoic succession including and overlying the Table Hill Volcanics in the Officer Basin area is less complete, thinner, and less extensive, and is grouped into a single basin — the Gunbarrel Basin. With a future increase in knowledge, a division may be made.

Widespread, continental-scale glaciation took place in the Late Carboniferous (Backhouse, 1999; Stevens and Apak, 1999) and Early Permian. The glacio-lacustrine to fluvioglacial Paterson Formation accumulated during several advances and retreats of continental ice sheets. The collision of Gondwana and Laurussia during the Early Carboniferous Alice Springs Orogeny, which caused uplift within western and central Australia, has been suggested as the trigger for this widespread glaciation (Veevers and Powell, 1989; Veevers, 2000, 2001).

Mesozoic–Cainozoic

The region was emergent between the Early Permian and Early Cretaceous, until a widespread transgression deposited fluvial sediments (Loongana Sandstone) followed by marine clastic sediments (Madura Formation). This was followed by a regression in the Late Cretaceous, after which the basin remained above sea level (Iasky, 1990). There was minor Eocene fluvial deposition (Hampton Sandstone) at the margin of the Eucla Basin under humid conditions, followed by shallow-marine carbonate deposition over the Eucla Basin in the Middle to Late Eocene and Miocene. Arid conditions persisted in most of the area underlain by the Officer Basin (Hocking et al., 2001).

Hydrocarbon potential

The petroleum potential of the western Officer Basin has been assessed most recently by Simeonova and Iasky (2005), Hamilton et al. (2004), Haines et al. (2004), Hocking (2002), Moors and Apak (2002), and Apak and Moors (2000b, 2001), and that of the eastern Officer Basin, within South Australia, by Morton and Drexel (1997). The Neoproterozoic succession contains potential source rocks, seals, and reservoirs in both the eastern and western Officer Basin, as does the Cambrian to Ordovician succession in the eastern Officer Basin (Gravestock and Morton, 1997a; Sansome, 1997). In the western Officer Basin, the Phanerozoic succession is thin, and consequently has minimal petroleum potential.

Vines 1, the single stratigraphic well in the Waigen area, only provides data for reservoir, seal, and source rock analysis of the uppermost Neoproterozoic – lowest Cambrian section (Vines Formation). The gas show recorded in Vines 1 at 1482.9 m (Apak et al., 2002b), although minimal, indicates a potentially effective petroleum system and suggests that this frontier area merits further evaluation. In the deeper portions of the Waigen area, older parts of the Officer Basin succession are inferred from isolated exposures (Grey et al., 2005), particularly adjacent to the Musgrave Complex. Due to the lack of seismic data, information from nearby wells and analogies with the neighbouring Birksgate Sub-basin and Yowalga and Lennis areas have been used to assess the petroleum potential of the Waigen area.

Reservoirs

Sedimentary rocks with good to excellent reservoir characteristics are present in the Officer Basin. In the western Officer Basin, adjacent to the Waigen area, these are mainly sandstones with recorded porosities of up to 15–20% and permeabilities of up to 1000 mD (Havord, 1998; Stevens and Apak, 1999; Apak and Moors, 2000b, 2001). In the eastern Officer Basin sandstones have average porosities of 10–25% and permeabilities of up to 8000 mD (Sansome, 1997). The sandstones are typically clean with low clay content, and indicate that reservoir quality is not a significant exploration risk. Carbonate facies in the western Officer Basin are extensively dolomitized with little significant porosity and permeability, most likely due to cavity filling with anhydrite or halite cement during early diagenesis (Apak and Moors, 2000b, 2001b; Moors and Apak, 2002). Therefore, they are not primary exploration targets, unless fracturing and karstification have improved their reservoir characteristics (Apak and Moors, 2000b; Carlsen et al., 2003).

Supersequence 1

The Townsend Quartzite on the southern edge of the Musgrave Complex in the western Officer Basin is not considered a primary reservoir due to intense silicification, although it is possible depositional porosity may have been preserved until the critical moment in some areas (Apak and Moors, 2000b, 2001). Some samples show quartz overgrowths, which occludes porosity (Jackson and van de Graaff, 1981; Shell Company of Australia Ltd, 1983). Much of the silicification may be a near-surface feature originating through evaporative groundwater pumping and silica precipitation (as in silcrete formation; van de Graaff, 1983), and so should not be considered a major factor in assessing the reservoir potential of the Townsend Quartzite. Log-derived average porosities (1.4%) from sandstone at the base of Kanpa 1A, initially interpreted as Townsend Quartzite, are poor, but this may be an older Mesoproterozoic unit (Grey et al., 2005). The Pindyin Sandstone, a laterally equivalent unit in South Australia, outcrops in the Birksgate Sub-basin and is assumed to be widespread in the deeper, undrilled portion of the Officer Basin (Sansome, 1997; Primary Industries and Resources South Australia, 2003). Core samples of a presumed correlative of the Pindyin Sandstone from Giles 1, the only well to intersect this unit, recorded an average porosity of 11.8%, with values ranging from 3.8 to 22.5%, and permeability values reaching 1538 mD (Sansome, 1997). Rocks with similarly preserved porosity and permeability may extend at depth westwards of the Birksgate Sub-basin into the Waigen area.

The Browne Formation is predicted to be at depth in the Waigen area and typically has poor to fair reservoir characteristics, except in an eolian facies noted in the northern part of the western Officer Basin (the Lancer Member in GSWA Lancer 1; Haines et al., 2004). Parts of the Pindyin Sandstone in Giles 1 in South Australia may be eolian and have excellent reservoir characteristics, and similar facies may be present in the Waigen area. The overall porosity is characteristically low, with most log-derived porosities averaging 2%. In the Yowalga area, core porosities of up to 18% and permeabilities typically less than 1 mD were recorded from carbonate rocks in Empress 1/1A (Havord, 1999; Stevens and Apak, 1999), and up to 9.5% and 0.865 mD in Yowalga 3 (Shell Company of Australia Ltd, 1981). Anomalously high permeabilities recorded within a halite-bearing interval of the Browne Formation in Empress 1/1A (372 mD at 1301.4 m, 396 mD at 1521.2 m; Havord, 1999) are attributed to the accidental removal of some halite during the preparation of the plugs (Stevens and Apak, 1999). Log-derived porosities of 7–15% for oolitic, argillaceous dolomites were noted in Yowalga 3 (Shell Company of Australia Ltd, 1981). Minipermeameter values recorded from dolomites in Empress 1/1A range from about 0.004 to 1 mD (~1367–1388 m; Stevens and Apak, 1999, plate 1). Core analyses from Empress 1/1A indicate that widespread filling of pore space by halite and carbonate minerals has occluded most of the primary porosity (Stevens and Apak, 1999; Apak and Moors, 2000b).

Medium- to coarse-grained sandstones in the Hussar Formation are possibly the best potential reservoirs in the Neoproterozoic section of the central western Officer Basin, and are inferred at depth within the Waigen area. Measured porosities of up to 21% compare well with log-derived porosities of up to 28.2% from wells within the Lennis and Yowalga areas. The best values are recorded from Empress 1/1A (e.g. 21% and 2690 mD at 1116.2 m, 19.8% and 1270 mD at 911.8 m; Havord, 1999). This is not typical of the well, in which permeabilities are generally around 100 mD (Stevens and Apak, 1999). However, minipermeameter values of up to 1 Darcy have been recorded in the sandstones (~863–1015 m and 1105–1135 m; Stevens and Apak, 1999, plate 1). Maximum log-derived porosities of 15–17% were calculated for the Hussar Formation in Yowalga 3 and Kanpa 1A (Townson, 1985).

The carbonate rocks within the Hussar Formation, where intersected, have very little to negligible porosity (e.g. Lungkarta 1, <0.1%; Kanpa 1A, 0.4 – 1.5%), except possibly in vugs in the dolomite where secondary porosity has developed due to dissolution of evaporites (e.g. in Empress 1A). Anhydrite forms most of the cement in the carbonate rocks and has destroyed most of the original porosity. Log-derived porosities of 1–2% are typical and permeability is virtually zero (Apak and Moors, 2000b; Moors and Apak, 2002).

The Kanpa Formation has highly variable reservoir characteristics, with the sandstones displaying the best porosities and permeabilities. The sandstone beds are typically less than 10 m thick (Apak and Moors, 2000b, 2001), reducing the likelihood of being good reservoir targets; core porosity values range from 1.6 to 23% and permeabilities from 0.001 to 361 mD, although the sandstones typically have porosity values of between 7 and 13% and low permeability (<2 mD). Core porosity values for the carbonate rocks range from 2.4 to 10.2% with permeabilities ranging from 0.001 to 0.955 mD. Log-derived porosities from sandstone (6.8 – 14.8%) and carbonate rocks (1.5 – 14.9%) compare well with values from core porosities. The best values are recorded from Empress 1/1A within sandstone units (19% with a corresponding 361 mD at 832 m, and 13.7% with a corresponding 1.56 mD at 741.5 m).

Sandstones in the Steptoe Formation have good reservoir characteristics within adjacent areas and may form an exploration target in the Waigen area, particularly in areas where they can be reached at shallow depths (less than 600 m) in the crests of anticlinal structures and in unconformity traps (Apak and Moors, 2000b, 2001). Log porosities typically in excess of 15% (range of 12.2 – 25.6%) were recorded for a 128 m-thick sandstone interval in Kanpa 1A (Shell Company of Australia Ltd, 1983), and about 66 m of this interval has greater than 20% porosity, but no core analyses are available. In Empress 1/1A, the sandstones have plug porosities of 23%, with a corresponding permeability of 30 mD at 567.5 m (Stevens and Apak, 1999; Apak and Moors, 2000b). Additional minipermeameter values from the top of the Steptoe Formation (483–525 m; Stevens and Apak, 1999, plate 1) range from about 0.01 to 100 mD. Carbonate rocks from the Steptoe Formation have log-derived porosities of 2.4 – 4.6% in Kanpa 1A, which compare well with a core-derived porosity of 2.5% at 503.6 m in Empress 1/1A; however, the corresponding permeability was negligible (<0.001 mD). Carbonate rocks would only have good reservoir characteristics where there is significant karst development, as in Empress 1A (Stevens and Apak, 1999). Minor oil staining and fluorescence were seen in sandstones and dolomites (1139–1183 m) in Kanpa 1A (Shell Company of Australia Ltd, 1983), but wireline-log evaluation proved the reservoirs to be water-wet or very tight.

Supersequence 3

The Wahlgu Formation is a potential reservoir target, but has a high risk due to inadequate regional top seal. Seismic interpretation shows that the unit attains its greatest thickness within the adjacent Lennis area, and implies that the unit extends into the Waigen area. The 166 m-thick section in Empress 1/1A consists mainly of sandstone with numerous mudstone interbeds. Core-plug porosity ranges from 10.9 to 26.8%, with an average of 21.3%, and permeability values reach a maximum of 80.1 mD (Stevens and Apak, 1999; Apak and Moors, 2000b). The basal sandstone of the Wahlgu Formation has excellent permeability values based on minipermeameter measurements (200–1500 mD; Stevens and Apak, 1999, plate 1).

The Murnaroo Formation, a predominantly sandstone unit with minor shale interbeds, is widespread in the eastern Officer Basin, and considered a key petroleum target (Sansome, 1997) in the South Australian portion of the basin. The maximum known thickness of the Murnaroo Formation is 391 m (Morton, 1997), and a relatively thick section was intersected in Birksgate 1 (Morton, 1997; Grey, 1999), suggesting that the formation, or its lateral equivalent, could be present in the Waigen area. Reservoir quality is variable, with porosity values ranging from 3 to 20% with an average of 14%, and permeability ranging from 0.01 to 213 mD with an average of 20 mD (Sansome, 1997; Primary Industries and Resources South Australia, 2003).

A 31.1 m-thick unnamed sandstone, which conformably overlies the Wahlgu Formation in Empress 1A, has excellent porosity and permeability (32.4% and 810 mD at 294.7 m). This unit was included in the Wahlgu Formation by Apak and Moors (2000b, 2001), but is considered a separate unit by Grey et al. (2005). The sandstone could be part of Supersequence 3 (a correlative of the higher parts of the Boondawari Formation, as exposed in the northwestern Officer Basin), or Supersequence 4 (Lungkarta Formation).

Supersequence 4

Sandstone intervals in the Lungkarta Formation are possible potential reservoirs, although no core analyses are available for this formation, and there is no lithological control within the Waigen area. Log analysis from Kanpa 1A showed that a thin sandstone bed from the Lungkarta Formation (formerly 'McFadden Formation equivalent') had an average porosity of 18.9% (Shell Company of Australia Ltd, 1983). These thin beds are not truly representative of the formation, which, based on seismic data, may be up to 1200 m thick.

Although there are no porosity or permeability measurements from the Punkerri Sandstone, it is a potential reservoir within the Waigen area due to its thickness and wide extent. It has not been intersected in any drillholes, but it outcrops in the Waigen area and Birksgate Sub-basin, where it is over 1200 m thick at its type section (Jackson and van de Graaff, 1981; Morton, 1997). In the northeastern part of WAIGEN, a lower sandstone unit (200 m thick) and an upper quartz arenite unit (400 m thick) with some fine-grained sandstone and siltstone intercalations could be attractive reservoirs. This unit is expected at depth within the Waigen area.

The Vines Formation is a potential reservoir, as reservoir facies may improve with distance from the Musgrave Complex (Apak et al., 2002b), where conglomeratic deposition gives way to sandier facies. Good to excellent reservoir characteristics were recorded in sandstones above 780 m (Units 4–6), but fair to very poor characteristics were recorded below this depth (Units 1–3). Core porosity values for Unit 5 range from 22.4 to 27.6% with permeabilities from 9.5 to 818 mD, and for Unit 4 from 4 to 23.3% and up to 928 mD. No core measurements were taken for Unit 6, but log-derived values range from 3 to 25% with minipermeameter values ranging from 48 to 64 mD. The log porosity for Unit 5 ranges from 20 to 32% (corresponding minipermeameter values of 21–291 mD) and Unit 4 is 0–26%. The core porosities compare well with the log-derived porosities, but Apak et al. (2002b) noted that the log values are unreliable because the hole was cased and only gamma-ray and neutron logs were available.

The core porosities for Unit 3 within the Vines Formation are 1.7 – 17.7% with permeabilities up to 48 mD, Unit 2 are 2.7 – 5.9% with permeabilities of less than 0.01 mD, and for Unit 1 are 2.4 – 4.9% with permeabilities of less than 0.01 mD. Only two samples from Unit 3 had fair porosity and permeability (17.7% with 48 mD at 997.05 m; 15.6% and 3.8 mD at 999.65 m; Apak et al., 2002b, appendix 9). Another sample at 1050 m had a porosity of 15.3%, but the corresponding permeability was very low (0.04 mD). The log porosity values are in good agreement with the core porosities (0–18% for Unit 3; 0–5% for Unit 2; 0–4% for Unit 1; Apak et al., 2002b). The minipermeameter values for Units 2 and 3 were up to 0.18 mD.

The change in reservoir character around 780 m within the Vines Formation was attributed to compaction, matrix clays, and anhydrite and carbonate cements, which have destroyed primary porosity (Apak et al., 2002b). Exceptions exist where the cements have been dissolved, creating secondary porosity (e.g. intergranular and fracture porosity; Apak et al., 2002b). Porosity and permeability significantly decrease with depths greater than 1050 m (Apak et al., 2002b).

Seals

Within the Officer Basin, many of the Neoproterozoic to Lower Cambrian formations contain halite, anhydrite, mudstone, or siltstone that could provide effective regional or local seals for both oil and gas (Table 1). Tight, impermeable carbonate rocks, present in most of the formations, may also form effective intraformational and local seals, although there is a high risk of fracture failure due to their brittle nature. Seal risk is highest for the less-deeply buried, sand-prone units, such as the Wahlgu and Lungkarta Formations (Apak et al., 2002a).

Siltstone and mudstone intervals within the Lefroy Formation are potential sealing units for reservoir facies if present within the underlying Townsend Quartzite or Pindyin Sandstone. In most areas, erosion has removed the top part of the formation, so it is a risky seal. The formation is fairly thick (up to 250 m thick at its type section on TALBOT, Western Australia) and may continue into South Australia as far as the ?correlative Alinya Formation (a 200 m-thick shaly unit in the Pindyin Hills on LINDSAY, South Australia; Grey et al., 2005). The siltstone and mudstone intervals range from about 15 m thick in BMR Talbot 4, to 25 m thick in BMR Talbot 3, and up to about 120 m thick at the type locality.

In the Yowalga area, massive halite units within the Browne Formation (Apak and Moors, 2000b) and siltstone and evaporites from the Alinya Formation in the Birksgate Sub-basin (Sansome, 1997) provide excellent regional to semi-regional top seals for potential subsalt plays, as well as lateral seals for stratigraphically higher traps. These seals would also constrain petroleum carrier beds over large portions of the region (Apak and Moors, 2000b, 2001; Moors and Apak, 2002). A similar distribution of salt and siltstone is predicted for the Waigen area, due to the regional continuity of these units deduced from

Table 1. Summary of the petroleum potential of the western Officer Basin and Birksgate Sub-basin

Unit	*Source*	*Reservoir*	*Seal*	*Comments*
Permian–Carboniferous				
Paterson Formation	no	high – very high φ and k	?intraformational	Gas-cut mud, fluorescence, and trace oil in Browne 1 and 2
?Devonian–Ordovician				
Wanna Formation	no	moderate – high φ and k	no	
Lennis Sandstone	no	moderate – very high φ and k	no	
Cambrian				
Table Hill Volcanics	no	low–moderate φ and very low k	no	
earliest Cambrian				
Vines Formation	no	<780 m: moderate – very high φ and k (some low φ and k) >780 m: very low – low φ and k (2 samples moderate φ)	intraformational (?semi-regional or local)	Minor gas show in Vines 1
Lungkarta Formation	?	intergranular φ noted, moderate log φ	intraformational and ?regional	No core analysis done
Punkerri Sandstone	?	possible (thick sections of sandstone present)	no	Only noted in outcrop
Neoproterozoic				
Dey Dey Mudstone[(a)]	yes	no	regional	Oil shows and fluorescence in Karlaya 1 and Marla 9 (South Australia)
Murnaroo Formation[(a)]	no	low–moderate φ and very low – moderate k	no	Oil stains in Lake Maurice West 1(South Australia)
Wahlgu Formation	?	moderate – very high φ and low–moderate k basal sandstone: moderate – very high k	intraformational	
Steptoe Formation	yes	sandstone: moderate – very high φ and very low – low k carbonate rocks: low φ and negligible k	intraformational	Minor oil staining and fluorescence in Kanpa 1A
Kanpa Formation	yes	sandstone: low–moderate φ and k (typically moderate φ and very low k) carbonate rocks: low–moderate φ and negligible – very low k	intraformational	Minor HC show in Hussar 1; fluorescence and oil stains in Kanpa 1A
Hussar Formation	yes	sandstone: moderate – very high φ and k carbonate rocks: very low φ and k	intraformational	Background gas in Lungkarta 1; bitumen in Hussar 1; oil bled from core in NJD 1
Browne Formation/ Alinya Formation[(a)]	yes	Browne: very low – moderate φ and very low – low k Alinya: no	regional and semi-regional (evaporites and siltstone)	Gas-cut mud, fluorescence, and trace oil in Browne 1; gas show in Dragoon 1
Lefroy Formation	possible	no	possible (requires underlying reservoir)	Not adequately sampled
Townsend Quartzite/ Pindyin Sandstone[(a)]	no	Townsend: possible if primary φ preserved Pindyin: low–moderate φ, moderate – very high k	no	

NOTES:
(a) South Australian units
φ: porosity
k: permeability
HC: hydrocarbons

wells and seismic lines from both the western and eastern Officer Basin.

Shale, mudstone, and siltstone units form thick, reliable intraformational seals for reservoirs in the Hussar, Kanpa, and Steptoe Formations. Based on drillhole and seismic data, these seals are typically widespread, fairly thick, and of good quality (Apak and Moors, 2000b; Apak et al., 2002a). These units can reach thicknesses of over 100 m in the Hussar Formation (Kanpa 1A). The presence of similar shaly beds in the Waigen area is expected in the deeper, undrilled section.

The Dey Dey Mudstone is widespread in the eastern Officer Basin and is likely to be a major regional seal. The unit ranges from 86 m to possibly 900 m (based on seismic data; Morton, 1997) and thickens towards the northern boundary of the Officer Basin, implying a significant thickness in the Waigen area, although it is just 176 m thick in Birksgate 1 (952–1128 m; Morton, 1997; Grey, 1999).

Thin intraformational mudstones, siltstones, and possibly muddy diamictites within the Wahlgu Formation may be good potential seals, if they are laterally continuous. However, these facies may be missing due to erosion or discontinuous deposition, and therefore carry a high risk. In some places, the section between the Wahlgu Formation and overlying Lungkarta Formation is absent (Grey et al., 2005), so this again represents a major risk. The 'cap dolomite' at the top of the Wahlgu Formation may also be a potential seal, although it has been removed by erosion prior to deposition of the overlying Lungkarta Formation in places, such as in Lancer 1.

Thick mudstone and siltstone interbeds within the Lungkarta Formation may provide effective, intraformational seals for sandstone facies of the same formation or regional seals for reservoirs within older, immediately underlying units. These intervals vary in thickness: 14.5 m in BMR Westwood 2 (a section of interbedded mudstone and siltstone); about 30 m in Mason 1 and 2 (siltstone); 90 m in Hussar 1 (dense, tight siltstone and mudstone); and 105 m in Lungkarta 1 (interbedded siltstone, dolomite, and minor sandstone). Grey et al. (2005) suggested that the disparity in rock type indicates some intersections have been incorrectly identified. Alternatively, the lithological changes mean the Lungkarta Formation varies substantially between wells. This means these seals may be laterally discontinuous, and therefore there is some risk as to their effectiveness.

Four samples from mudstone and diamictite units within the Vines Formation in Vines 1 (598, 644, 682, and 930 m) were analysed for sealing capacity. All the samples had excellent seal potential with calculated permeability values ranging from 0.00003 to 0.00007 mD (Apak et al., 2002b, appendix 10), but the lateral extent of these intraformational units is unknown.

Intraformational claystone and mudstone intervals in the Paterson Formation could form seals, but are liable to be thin and laterally discontinuous, sandy, or even absent in some areas, and shallow, unlike in the Canning Basin where similar intervals within the correlative Grant Group form effective seals in the Boundary, Sundown, and West Terrace oilfields.

Source rocks and maturity

In the other areas of the western Officer Basin, analyses of available organic petrological and geochemical data show that oil- and gas-prone source rocks are attributed to thin, shaly beds in the Browne, Hussar, Kanpa, and Steptoe Formations (Ghori, 1998a,b, 2000, 2002a). Such deposits with fair to excellent hydrocarbon-generating potential have been intersected in Browne 1 and 2, Empress 1/1A, Hussar 1, Kanpa 1A, LDDH 1, NJD 1, BMR Throssell 1, and Yowalga 3 (Ghori, 1998a,b, 2000, 2002a). The best source rocks were recorded from NJD 1 (Gibson area) and Empress 1/1A (Yowalga area), with the highest result from NJD 1 at 502.6 m in probable Mesoproterozoic rocks (Hocking, 2002), with 21.5% total organic carbon (TOC) and a $S_1 + S_2$ value of 136.11 mg/g rock (Ghori, 2002a). The source-rock intervals in NJD 1 are probably lower Kanpa Formation (Hocking, 2002). The only subsurface data from the Waigen area indicate that the Vines Formation has no source potential. Limited maturity data suggest that it is late mature to possibly overmature for oil generation (Apak et al., 2002b; Ghori, 2002b).

The bulk of organic matter present within the western Officer Basin is of oil- and gas-generating Type-II kerogen (Ghori, 2000, 2002a). Organic petrology and Rock-Eval pyrolysis indicate that the Neoproterozoic section ranges from immature to overmature, although most samples are within the oil-generative window. The present-day oil window is about 1000 m deeper in the Yowalga area than in the Gibson area (Ghori, 2002a), which could mean that the oil window is even deeper within the Waigen area. Basin modelling indicates that the main phase of oil generation in the Neoproterozoic section was during the latest Neoproterozoic, with minor phases during the Cambrian and Permian–Triassic (Ghori, 1998a, 2000, 2002a). If the latter is applicable, then Palaeozoic rocks may be valid seals; if the former, then very long trap preservation is required.

In the Birksgate Sub-basin, potential source rocks in the Neoproterozoic section are thin, black shales and redbeds in the Alinya Formation (Browne Formation correlative), and mudstones in the Dey Dey Mudstone (Marinoan, but younger than known Wahlgu Formation). Similar source facies could also be present in the Waigen area. Analyses indicate poor to fair organic richness and TOC values up to 0.62% for the Alinya Formation (average 0.24%; Gravestock and Morton, 1997a), but possibly as much as 1.47% for the Dey Dey Mudstone and Narana Formation (Supersequence 4; range 0.03–0.81%, average 0.11; Gravestock and Morton, 1997a; Primary Industries and Resources South Australia, 2003). Kerogen in the Alinya Formation is gas-prone (Type III–IV), but in the Dey Dey Mudstone it is oil-prone (Type II–III) (Gravestock and Morton, 1997a). Both units are within the oil-generative window in the Murnaroo Platform (Gravestock and Hill, 1997). Similar trends are expected for the Birksgate Sub-basin, but there are no maturity data at present to confirm this. The higher maturity values

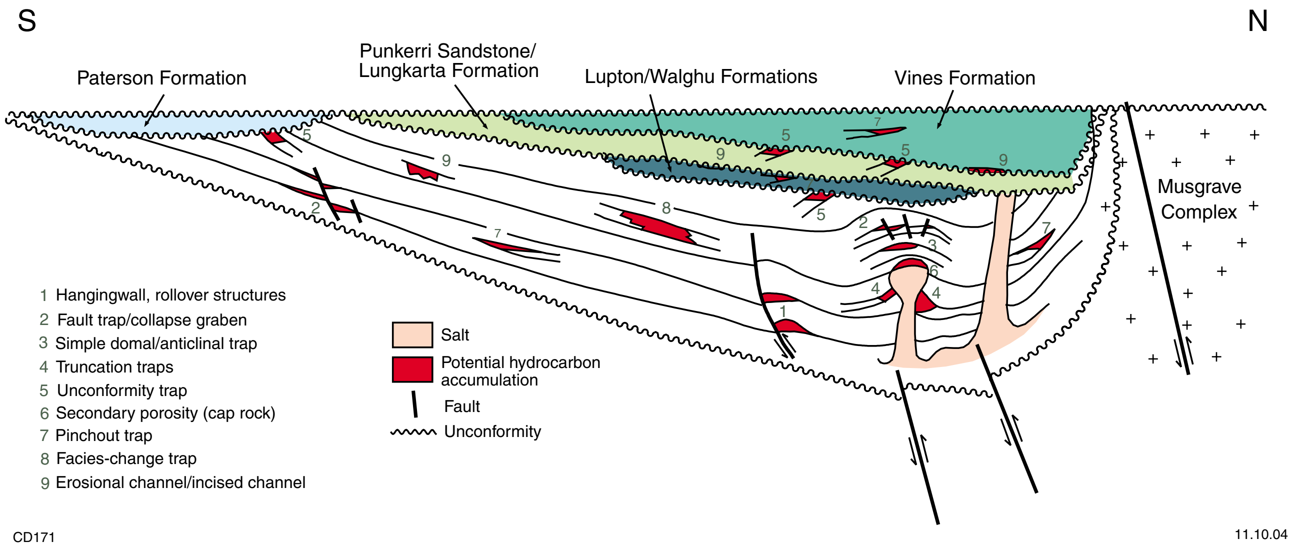

Figure 20. Schematic petroleum plays within the Waigen area

from the Vines Formation indicate older units have passed through the oil-generative window in the Vines area, but rocks farther from the Musgrave Complex of the Waigen area, where the geological history is closer to that of the Murnaroo Platform, may still be prospective.

Traps

The main objectives for petroleum exploration in the western Officer Basin have been a wide range of trap configurations in which Neoproterozoic reservoirs are sealed by salt in diapiric or anticlinal structures. Based on seismic data from the Yowalga and Lennis areas and the Birksgate Sub-basin, trap types range from simple domal or anticlinal traps, and faulted anticlines over salt walls and pillows, to stratigraphic and compressional structures (Japan National Oil Corporation, 1997; Apak and Moors, 2000b, 2001; Apak et al., 2002a; Moors and Apak, 2002; Carlsen et al., 2003). Similar traps should be present in the Waigen area (Fig. 20), but remain speculative, as there are no seismic data.

Neoproterozoic thrust zones, initiated during the Areyonga Movement and reactivated during the Petermann and Delamerian Orogenies, may be present at depth within the Waigen area, in which case hangingwall rollover structures would be the main targets, if reliable seals are present. Risks associated with these traps include leaking along tensional crestal faults and reactivation during post-migration tectonic phases (Apak and Moors, 2000b; Moors and Apak, 2002; Carlsen et al., 2003).

There is no direct evidence of salt within the Waigen area. Salt walls in the Lennis area terminate west of the former Neale Arch, and their continuation into the Waigen area is not seen in the gravity data. If diapirs are present at depth, as in the Lennis area, the main phase of salt movement would have been during the Areyonga Movement, which, according to the geohistory modelling of the Lennis area (Apak and Moors, 2002; Ghori, 2002a), created traps for the first phase of hydrocarbon generation and migration. Several possibilities of trap formation would be present, mostly related to halotectonics (Fig. 20). Reactivation and deformation of these structures by later tectonic phases clearly poses a great risk to trap integrity.

Stratigraphic traps may constitute the majority of traps found in the Waigen area if halotectonic traps are absent, and would include unconformity traps where Neoproterozoic reservoir rocks are truncated at the base of the Paterson Formation, Lupton/Wahlgu Formations, or Vines Formation and sealed by intraformational mudstone, diamictite, and siltstone within these same units (Fig. 20). Other possible stratigraphic traps include pinchout traps and lateral-facies-change traps, and for much of Supersequences 1 and 3 strata, incised channels filled by reservoir-quality sedimentary rocks and sealed by transgressive shale (Apak and Moors, 2000b, 2001; Moors and Apak, 2002; Fig. 20). Risks associated with all of these traps include development of a reliable top and base seal, and charge timing. Similar traps have been suggested within the eastern Officer Basin (Gravestock and Morton, 1997b; Primary Industries and Resources South Australia, 2003).

Prospectivity

Most of the wells in the western Officer Basin are either mineral exploration drillholes (27) or petroleum stratigraphic tests (27), with only nine new-field wildcat wells. Due to the sparsity of outcrop and subsurface data within the western Officer Basin, any assessment of the petroleum prospectivity is poorly constrained. However, the few documented hydrocarbon shows indicate that a petroleum system was operational at some time during the basin's history, although it is unclear whether or not it produced economic accumulations. With only one deep stratigraphic drillhole and very limited seismic data within the Waigen area, the prospectivity of this area is highly speculative; however, the gas show in Vines 1 indicates that the area warrants further investigation.

Based on limited maturity data within the Waigen area, the Vines Formation is late mature to possibly overmature for oil generation (Apak et al., 2002b; Ghori, 2002b). No other maturity data are available for this area; however, maturity data from the adjacent Lennis, Yowalga, and Gibson areas indicate that the Neoproterozoic section ranges from immature to overmature, with most samples within the oil-generative window. Similarly, maturity data from the eastern Officer Basin show that possible reservoirs within the Murnaroo Platform, and possibly Birksgate Sub-basin, are presently within the oil-generative window. The relatively greater maturity of the Vines Formation indicates greater burial, uplift, and stripping in the Waigen area during the Palaeozoic than elsewhere in the basin. This significantly increases the risks of traps being breached, but dramatically increases the area and amount of section that has passed into or through the maturity window.

The modelled peak expulsions of hydrocarbons for Neoproterozoic source rocks are latest Neoproterozoic, Cambrian, and Permian–Triassic, which suggest that for traps to be effective, they should have formed before the Triassic. Traps related to the Areyonga Movement and Petermann and Delamerian Orogenies are attractive drilling targets, especially with respect to charge timing, but possible reactivation during later tectonic phases may compromise their integrity. In most cases, these traps would have formed before the last hydrocarbon-expulsion phase.

There have been few valid tests of structural traps and none for stratigraphic traps within the western Officer Basin; in light of its untested potential, the demise in exploration in the area since the 1980s seems unwarranted. New play possibilities within Supersequence 4 rocks (i.e. Punkerri Sandstone, and Lungkarta and Vines Formations), as well as Supersequence 3 rocks (Murnaroo Formation and Dey Dey Mudstone) from the Birksgate Sub-basin if they extend into the study area, are promising within the Waigen area, and have not been recognized in the other areas of the western Officer Basin. Plays from Supersequence 3 (Wahlgu Formation) and Supersequence 4 rocks in the Waigen area have not been previously postulated within the western Officer Basin.

Discussion and conclusions

The Waigen area is the least-explored part of the western Officer Basin. The only seismic line available is of poor quality, and the only deep stratigraphic hole, Vines 1, may only be significant for the zone close to the Musgrave Complex. The other stratigraphic hole in the area (BMR Wanna 1) was completed in the late Palaeozoic Paterson Formation. In order to assess the petroleum potential of the Waigen area, the closest petroleum exploration and stratigraphic wells in the adjacent Lennis area and Birksgate Sub-basin in the eastern Officer Basin, South Australia must be considered, along with shallow, mineral drillholes on the periphery of the area.

Potential-field data indicate that the Waigen area contains a depocentre up to 11 km thick in which a Neoproterozoic – Lower Cambrian succession and possible underlying Mesoproterozoic succession are preserved, and covered by a relatively thin Phanerozoic section. This area is the thickest section of preserved sedimentary strata in the western Officer Basin, and the high maturity of the section in Vines 1 indicates that it was even thicker prior to major erosion sometime in the Palaeozoic. The presence of kyanite within the Dean Quartzite from PETERMANN RANGES (Scrimgeour et al., 1999) and HULL AND BLOODS RANGE (Close et al., 2003) in the Northern Territory suggests that this unit was buried to depths between 8 and 15 km before being uplifted close to the surface. The proximity of these sections make it reasonable to assume similar uplift, at least adjacent to the Musgrave Complex, in the Waigen area. The sedimentary section shallows abruptly to the north and west towards the Mesoproterozoic Musgrave Complex and Archaean Yilgarn Craton respectively. Depth to basement calculated from the isostatic residual gravity data, broadly shows that basement is shallower in the western part of the Waigen area, with the exception of the Cooper Graben, which is a northerly trending trough near the margin of the Musgrave Complex where the estimated depths to basement are up to 10 km. The Waigen area appears to be continuous with the Birksgate Sub-basin in the eastern Officer Basin, South Australia.

The Townsend Quartzite and Lefroy Formation (the lower part of Supersequence 1) outcrop adjacent to the Musgrave Complex in the Waigen area. Some sandstone outcrops within the area may be either Kanpa or Hussar Formation, but they cannot be assigned unequivocally. Supersequence 4 (Punkerri Sandstone and Vines Formation) and possible Supersequence 3 (Lupton Formation) strata are present as outcrop and in the only drillhole in the area. Outcropping rocks of the overlying Gunbarrel Basin include the Table Hill Volcanics, Lennis Sandstone, Wanna Formation, and Paterson Formation.

Regional gravity and magnetic surveys and the semi-detailed Waigen gravity survey provide the only significant data covering the area. These data reveal the nature of magnetic crystalline basement below the western Officer Basin and its relationship with outcropping basement areas. Shallow, magnetic basement from the Musgrave Complex and Albany–Fraser Orogen completely dominates the TMI image in the Waigen area; the magnetic response of the basement below the Officer Basin is subdued by intervening non-magnetic sedimentary rocks. Because conventional image-processing techniques provide limited enhancement of basement features in the Waigen area, a new filtering technique based on the wavelet transform was used to augment this signal. This method incorporated the isostatic residual gravity data to vary the level of enhancement of the aeromagnetic data over the basin. The resolution of the basement was considerably improved over the deeper parts of the sedimentary section when compared to the TMI image. This new technique, referred to as the variably downward-continued method, provided the basis for the revision of the Officer Basin subdivisions in the region.

Based on the variably downward-continued image, the Waigen area and the surrounding areas can be subdivided into nine domains of distinct magnetic character: Domain 1 is the Musgrave Complex; domains 2, 3, and 5 are mainly within the Yowalga and Lennis areas; domain 4 is almost entirely within the Waigen area; and domains 6–9 are within the eastern Officer Basin, South Australia. The variably downward-continued image highlights subtle features not seen in the TMI and first vertical derivative images.

The entire Waigen area and surrounds, excluding the Musgrave Complex and subcropping Gawler Craton, are dominated by an overall northwesterly structural trend in both the gravity and magnetic data (i.e. lineaments and elongate anomalies). Some of these features include linear magnetic lows within domains 2 and 3 that correlate with either salt walls or salt-related features. Minor northeasterly and northerly trending lineaments truncate or displace the northwesterly trending features.

The most complex magnetic pattern is observed in domain 4, in which deep-crustal, circular magnetic features are interpreted as reverse remanently magnetized magma chambers, possibly of mafic–ultramafic composition, reflecting underplating of the crust by a mantle plume. These intrusions all have the same polarity, implying simultaneous intrusion and rapid crystallization during a period when the magnetic field was reversed relative to the present-day field. These bodies are related to either the c. 1075 Ma magmatic event proposed by Wingate et al. (2004), or a c. 510 Ma magmatic event proposed by Hanley and Wingate (2000). Wingate et al. (2004) inferred a link between the Warakurna event (c. 1075 Ma) and plate-boundary forces along the Australian–Antarctic continental margin. Such a lithospheric break may explain the arcuate shape of magnetic features near the Albany–Fraser Orogen. If a plume were present at that time, the magma would have followed this pre-existing zone of weakness and formed plutons along the Albany–Fraser Orogen front. Therefore, it is more likely that the intrusions are related to the c.1075 Ma event, although the c. 510 Ma event cannot be overlooked without further evidence.

The circular anomalies in domain 4 have a broad, northerly trend that seems to coincide with a set of northerly trending lineaments, which collectively form part of a regional crustal-scale feature termed the Lasseter Shear Zone. The trend of the anomalies curves around to the southeast in the southern part of the Waigen area, and aligns with known mafic circular intrusives in the Coompana Block, South Australia.

The potential-field data delineate the continuation of the Albany–Fraser Orogen within domain 4. The data clearly show that the orogen deviates east of its previously inferred position along the Neale Arch. The Albany–Fraser Orogen swings around to the east beneath the Waigen area, where it is truncated by lineaments associated with the Lasseter Shear Zone, and continues towards the Musgrave Complex to the north. The majority of magnetic highs within domain 4 could correspond to the Fraser Complex of the Biranup Complex. Outcropping Fraser Complex, recorded in the south, appears to be continuous with gravity and magnetic anomalies farther north.

The Albany–Fraser Orogen, initially having a straight northeast trend, was probably deformed and rotated during uplift and thrusting of the Musgrave Complex, resulting in its current shape. As the Musgrave Complex was thrusted and uplifted to the southwest over the Officer Basin, it collided with the rigid Albany–Fraser Orogen. As thrusting continued, the orogen was pushed towards the east, creating a small, triangular area of low magnetic response between the Musgrave Complex and Albany–Fraser Orogen (between domains 1, 2, and 4), and initiating of local extension. Similar localized extension is implied for the very deep Cooper Graben, located on the edge of the Albany–Fraser Orogen.

The regional continuity of stratigraphy across the western and eastern Officer Basins shown by wells and seismic data suggests that Neoproterozoic to Lower Cambrian source rocks, reservoirs, and seals in these areas extend into the Waigen area. The reservoirs are typically clean sandstones with low clay content and constitute a low exploration risk, as core analyses indicate good to excellent characteristics in most parts of the Officer Basin. Carbonate rocks are extensively dolomitized with very little porosity or permeability and are not primary targets. If the seals in adjacent areas are laterally continuous, the potential exists for good-quality, adequately thick, intraformational and local seals in the Waigen area.

The only direct evidence of petroleum potential in the Waigen area is from Vines 1, which intersected only the uppermost Neoproterozoic – Lower Cambrian (Supersequence 4) section. A minor gas show recorded in this well suggests the presence of a potentially effective petroleum system. The only geochemical data for the area are from Vines 1, and indicate that the section is late mature to overmature for oil generation. Maturity data from the adjacent areas in the western Officer Basin suggest that the Neoproterozoic section is immature to overmature, with most samples within the oil-generative window. Similarly, maturity data from the eastern Officer Basin show that reservoirs within the Murnaroo Platform and possibly Birksgate Sub-basin are still within the oil-generative window, so a prospective transitional zone containing mature to overmature strata may be present in the Waigen area. Basin modelling from the western Officer Basin indicates that the main phases of oil generation in the Neoproterozoic section were possibly during the latest Neoproterozoic, Cambrian, and Permian–Triassic (Ghori, 1998a, 2000, 2002a).

There are very few valid tests of play types in both the eastern and western Officer Basins. New play possibilities within Supersequence 4 rocks and equivalent Supersequence 2 and Supersequence 3 rocks known in the Birksgate Sub-basin would be promising if they extend into the Waigen area, but have not been recognized in other areas of the western Officer Basin. The main plays for petroleum exploration include hangingwall rollovers and four-way dip anticlines sealed intraformationally, diapiric traps, and truncation of Neoproterozoic reservoirs against an unconformity sealed by overlying mudstone, diamictite, or siltstone. The major risks with all of these plays are deformation and reactivation of these structures by later tectonic phases, and the presence of suitable source rocks.

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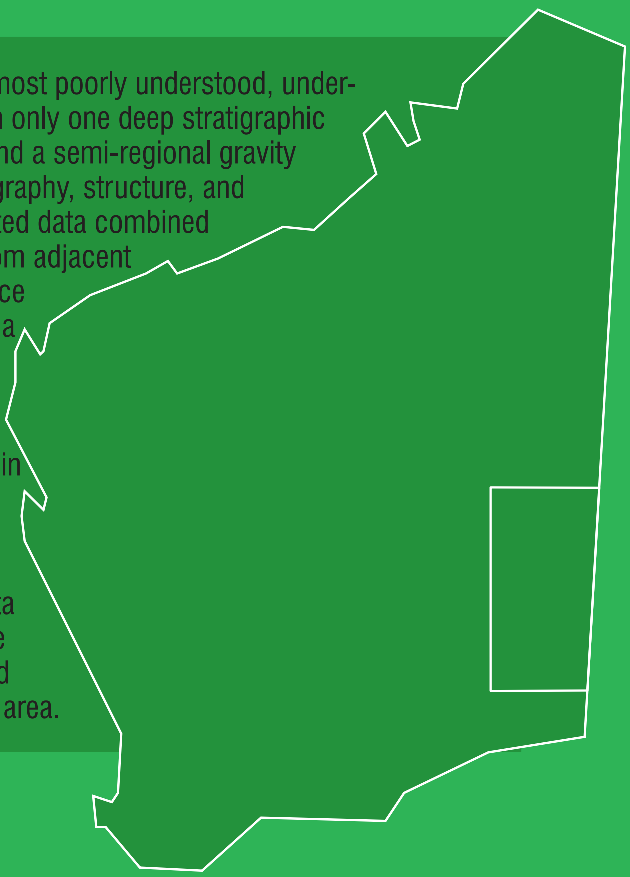
D'ERCOLE et al.

Geology, geophysics, and hydrocarbon potential of the Waigen area
Officer Basin, Western Australia

REPORT 100

The Waigen area of the Officer Basin is one of the most poorly understood, under-explored regions in onshore Western Australia, with only one deep stratigraphic well, a few shallow mineral exploration drillholes, and a semi-regional gravity survey. This Report is a reassessment of the stratigraphy, structure, and petroleum potential of the region based on this limited data combined with regional geophysical data and drillhole data from adjacent areas. A new filtering technique was used to enhance the aeromagnetic data in the region, and has led to a revision of subdivisions and a new interpretation of the tectonic history of the area. The Waigen area includes a depocentre that contains possibly the thickest Neoproterozoic – Lower Cambrian section in the western Officer Basin. A gas show in Vines 1, drilled near the thrusted margin with the Musgrave Complex, indicates there may be a potentially effective petroleum system in the area. Maturity data from adjacent areas suggest that the majority of the Neoproterozoic section is within the oil window, and there are promising play possibilities in the Waigen area.



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