REPORT
77

GOVERNMENT OF
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BASIN DEVELOPMENT AND PETROLEUM EXPLORATION POTENTIAL OF THE LENNIS AREA, OFFICER BASIN WESTERN AUSTRALIA

by S. N. Apak and H. T. Moors

GEOLOGICAL SURVEY OF WESTERN AUSTRALIA

DEPARTMENT OF MINERALS AND ENERGY

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A view of the spinifex and sandplains of the Lennis area, western Officer Basin.

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Basin development and petroleum exploration potential of the Lennis area, Officer Basin, Western Australia

by

S. N. Apak and H. T. Moors

Abstract

This Report provides a new interpretation for the petroleum systems and play types of the Lennis area, based on an analysis of all available seismic data. The consistent seismic character of the Browne, Hussar, Kanpa, and Steptoe Formations allows them to be correlated with confidence from the Yowalga area to the Lennis area, and indicates that their Neoproterozoic environments of deposition and structural histories were similar.

Regional structural events that affected the western Officer Basin were not particularly severe in the Lennis area. However, the presence of thick sections of the seismically interpreted Wahlgu Formation (Supersequence 3) and McFadden Formation equivalent (Supersequence 4) in the Lennis area indicates the presence of active tectonism and subsidence that was complicated by reactivation of salt movement during deposition of these formations.

As in the Yowalga area, the authors are confident that source rocks, reservoirs, and seals for petroleum are also present in the Lennis area. A number of trapping styles, from simple fault traps, simple anticlines, and stratigraphic traps (depositional and erosional) to halokinetic traps, are present. Some of these features are potentially large, and may have an excellent chance for multiple pays. Geothermal modelling of the deepest part of the area suggests that an oil charge would probably have been expelled from Supersequence 1 strata during the Cambrian. This represents a favourable relationship with respect to timing of the initial deformation during the Areyonga Movement (c. 750 Ma). Further deformation during deposition of the Wahlgu Formation and McFadden Formation equivalent may have breached early traps, but deposition at this time also triggered a later phase of petroleum generation, and the new traps were in place for this later charge. The facies within the rim synclines adjacent to the salt walls may have different reservoir, source-rock, and seal potential to that of the remaining area, thereby providing additional exploration targets.

Additional stratigraphic drilling would be required to provide local control for the composition of the various formations present in the Lennis area. This is especially important for the Wahlgu Formation and McFadden Formation equivalent, which have significant depositional thicknesses in this area and have yet to be adequately tested. The data presented here indicates that the petroleum potential of the Lennis area could be significant.

KEYWORDS: geological structure, stratigraphy, sequence stratigraphy, geochemistry, basin analysis, petroleum potential, structural evolution, Lennis area, Officer Basin, Western Australia

Introduction

The Officer Basin (Fig. 1) is the third largest onshore basin in Australia. It covers an area of 320 000 km^2 in Western Australia and has a sedimentary section in excess of 6 km. Because of the volume of sedimentary rock present, and the high content of carbonate and salt that elsewhere in the world is associated with prolific petroleum reserves (Warren, 1989; Alsharan and Nairn, 1997), the petroleum potential of the basin has been highly rated by recent workers (Perincek, 1997, 1998; Carlsen et al., 1999; Apak and Moors, 2000a,b). Historically, a Neoproterozoic age has been considered unfavourable by the petroleum industry (Phillips et al., 1985); however, giant oil- and gasfields are known from rocks of this age in Russia (Kontorovich et al., 1990;

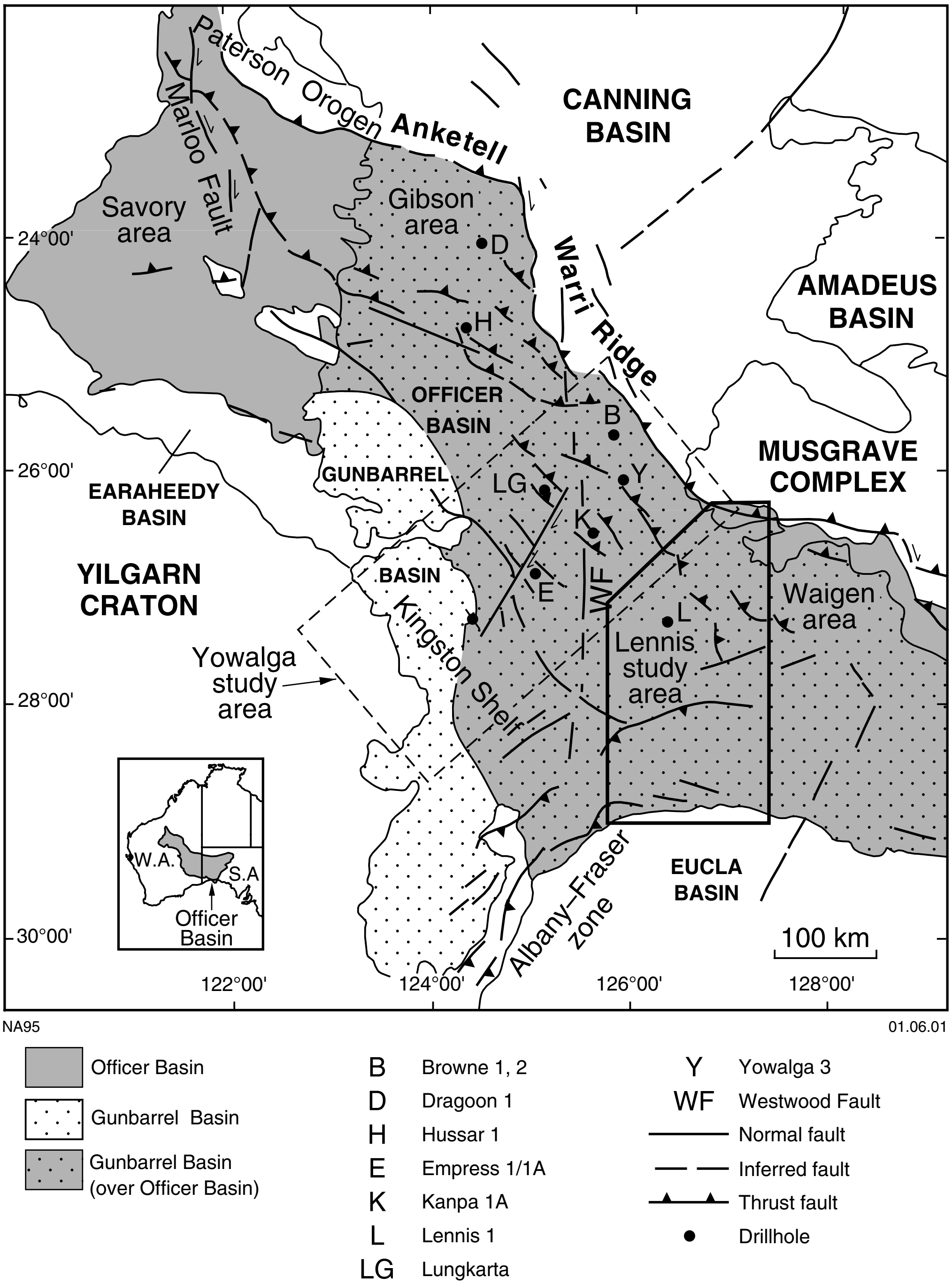


Figure 1. The western Officer Basin, showing major structural elements and sub-areas

Kuznetsov, 1997) and Oman (Alsharan and Nairn, 1997).

In an effort to encourage the petroleum exploration industry to realise the potential of the Officer Basin, the Geological Survey of Western Australia (GSWA) commenced a review of available data in 1994. This review has been supplemented by additional data from stratigraphic corehole drilling, geophysical surveys, and geochemical analyses in critical areas (Fig. 2a; Carlsen et al., 1999). The Yowalga area has the greatest seismic and well control within the basin and was chosen as the first area to be studied in detail, in order to provide a useful template for other portions of the basin (Apak and Moors, 2000b). This Report on the Lennis area (Fig. 1) is the second detailed Report in this series on a specific region of the basin. The Lennis area is located immediately east of the Yowalga area, but contains only 1200 km of regional seismic data and one well, Lennis 1, with a penetration of 614.5 m. Therefore, some of this Report relies heavily on the preceding Report that deals with the Yowalga area.

The Lennis area contains the region that has been previously defined as the Lennis Sub-basin, based on potential-field data (Townson, 1985). However, where seismic data are available there appears to be no evidence of an individual depocentre in this region. Therefore, the authors prefer to regard the region simply as the Lennis area.

In the Yowalga area, the middle Neoproterozoic Supersequence 1 has been subdivided into a number of genetic units (Apak and Moors, 2000a). The basic sequence concepts and terminology of Van Wagoner et al. (1990) that were applied to the Yowalga area have also been used in the Lennis area. The sequence-stratigraphic units coincide closely with the lithostratigraphic subdivisions previously defined by Townson (1985). Seismic data indicates that Supersequence 1 strata are continuous between the Yowalga and Lennis areas. The Yowalga area was subsiding at a greater rate than the Lennis area during the deposition of Supersequence 1 strata, as evidenced by the presence of thicker Supersequence 1 strata in the Yowalga area (approximately 4–5 km) than the Lennis area, which contains Supersequence 1 strata 2.5 – 4 km thick. However, the presence of a greater thickness of younger units such as the Wahlgu Formation and McFadden Formation equivalent in the Lennis area (greater than 1.3 km in thickness) indicates greater subsidence rates during deposition of these units in the Lennis area compared with the Yowalga area where they have a thickness of 0.2 – 0.8 km. The application of sequence-stratigraphic concepts, together with new results from structural analysis, has improved our understanding of the evolution of the Lennis area. This has assisted in the identification of additional petroleum plays, as well as reducing the risk in predicting the distribution of source rocks, reservoirs, and seals.

Previous investigations

Due to its isolation, difficult access, and relatively hostile environment, the Officer Basin initially received little geological attention. Petroleum exploration began in the early 1950s with exploration by companies such as Frome Broken Hill and Australasian Oil Exploration, but they were mainly concerned with the Phanerozoic succession of rocks. Early exploration activities relied mainly on surface mapping, until a consortium comprising Hunt Oil, Hunt Petroleum, Placid Oil, and Exoil was granted exploration permits in the 1960s. These companies acquired aerial and land magnetic data, gravity data, and 1033 km of seismic reflection data (partly in the Lennis area), and drilled five wells. These wells were Browne 1 and 2, Yowalga 1 and 2, and Lennis 1, which had a combined penetration of 2896 m. Lennis 1, the only well drilled in the Lennis area (Fig. 2a), was terminated at a total depth of 614.5 m in the Table Hill Volcanics. Due to the fact that only minor oil and gas shows were encountered in Browne 1 and 2 in the Yowalga area (Hunt Oil Company, 1965), all tenements were dropped.

The early exploration discovered salt diapirs, which the Bureau of Mineral Resources (BMR), now the Australian Geological Survey Organisation (AGSO), began to investigate in the 1960s. In 1967, GSWA started mapping in the area as part of their statewide 1:250 000 mapping program (Fig. 3), concentrating mainly on the Musgrave Complex (Daniels, 1974). In order to accelerate the mapping, a joint operation between GSWA and BMR was initiated to cover other parts of the Officer Basin (Daniels, 1970, 1971; Jackson, 1976, 1978; Kennewell, 1977a,b; Bunting et al., 1978). As well as surface mapping, gravity data and 19 line-km of seismic refraction data were acquired. In 1972, a series of short stratigraphic coreholes were drilled in the Lennis area (Fig. 2b; Perincek, 1996). All of these data were incorporated into a joint BMR–GSWA Bulletin on the Officer Basin (Jackson and van de Graaff, 1981).

As a result of this improved knowledge, Shell Company of Australia acquired exploration permits in the Yowalga and Lennis areas. The company recorded 4682 line-km of seismic reflection data (mostly in the Yowalga area) and drilled three deep wells (none in the Lennis area), the deepest being Yowalga 3 to 4196 m. As a result of its investigations, the company divided the Officer Basin into sub-basins, improved the stratigraphic subdivision by adding additional formations, and discussed basin development from the point of view of petroleum exploration (Townson, 1985). In the absence of significant shows, Shell Company of Australia relinquished its tenements in 1984 and 1985.

The most recent petroleum investigation was carried out by Japan National Oil Corporation (JNOC) under a special prospecting authority (SPA No. 1/95–96) covering most of the Yowalga area (Apak and Moors, 2000b, fig. 2). They flew a high-resolution aeromagnetic survey totalling 86 782 line-km and reprocessed 50 key seismic lines (2165 line-km). In addition, drill cuttings from wells in and around the Yowalga area were analysed for source-rock potential, and detailed thermal maturation histories were completed for the area. The SPA has now expired and basic data containing JNOC's interpretations (Japan National Oil Corporation, 1997) are on open file at GSWA.

There are more detailed reviews of the earlier phases of exploration, with statistics on drilling, and geophysical and geochemical surveys, in Jackson and van de Graaff (1981), Perincek (1998), and Ghori (1998a).

Current GSWA investigation

The Officer Basin is being studied by GSWA as part of a Petroleum Exploration Initiative set up by the State Government of Western Australia in 1994, with encouragement from the petroleum industry, in order to investigate underexplored areas of the onshore basins.

The initial phase of the investigation comprised the collection of all open-file data on the Officer Basin, validation of the data, and the construction of an integrated reinterpretation. All of the seismic lines were reinterpreted, formation tops were repicked in all wells, and additional organic geochemical analyses were performed on samples from key wells. Perincek (1996, 1997, 1998) published these data in three reports. A fourth publication (Stevens

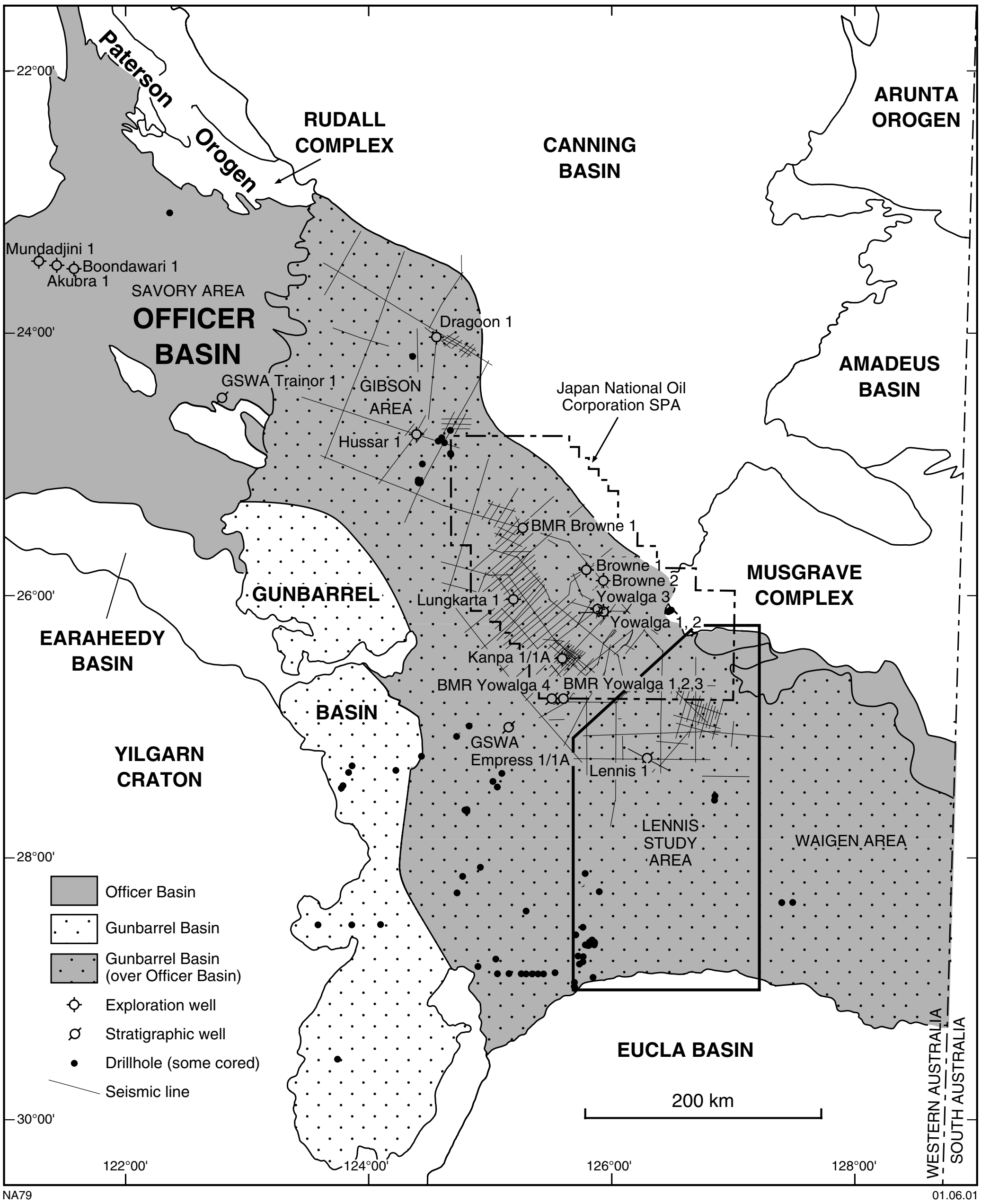


Figure 2. a) Location of petroleum exploration wells, stratigraphic tests, mineral exploration drillholes, and complete seismic coverage over the western Officer Basin

and Carlsen, 1998) covers the 'Savory Sub-Basin', now referred to as the northwestern Officer Basin (Bagas et al., 1999). Corehole drilling of Trainor 1 (Stevens and Adamides, 1998) and Empress 1 and 1A (Stevens and Apak, 1999) provided additional information for a fifth publication (Carlsen et al., 1999) that concentrates on the petroleum potential of the basin in relation to a new source-rock model developed from Empress 1 and 1A. Recently, in a sixth publication, Apak and Moors, (2000b) described the Yowalga area, where the greatest amount of seismic and well data are available. The application of sequence stratigraphy has provided a new interpretation of the configuration and evolution of the western Officer Basin, as well as a better definition of its petroleum systems. In this Report, the seventh publication of the project, an attempt has been made to assess the petroleum potential of the adjoining Lennis area, using concepts established for the Yowalga area, even though the Lennis area has less seismic control and no significant well control (Fig. 2a).

Location and access

The Lennis area is a remote and underpopulated region of Western Australia, and is 1300 km northeast of Perth. Nearby population centres include Cosmo Newbery, Warburton, Jameson, Blackstone, and Wingellina. There

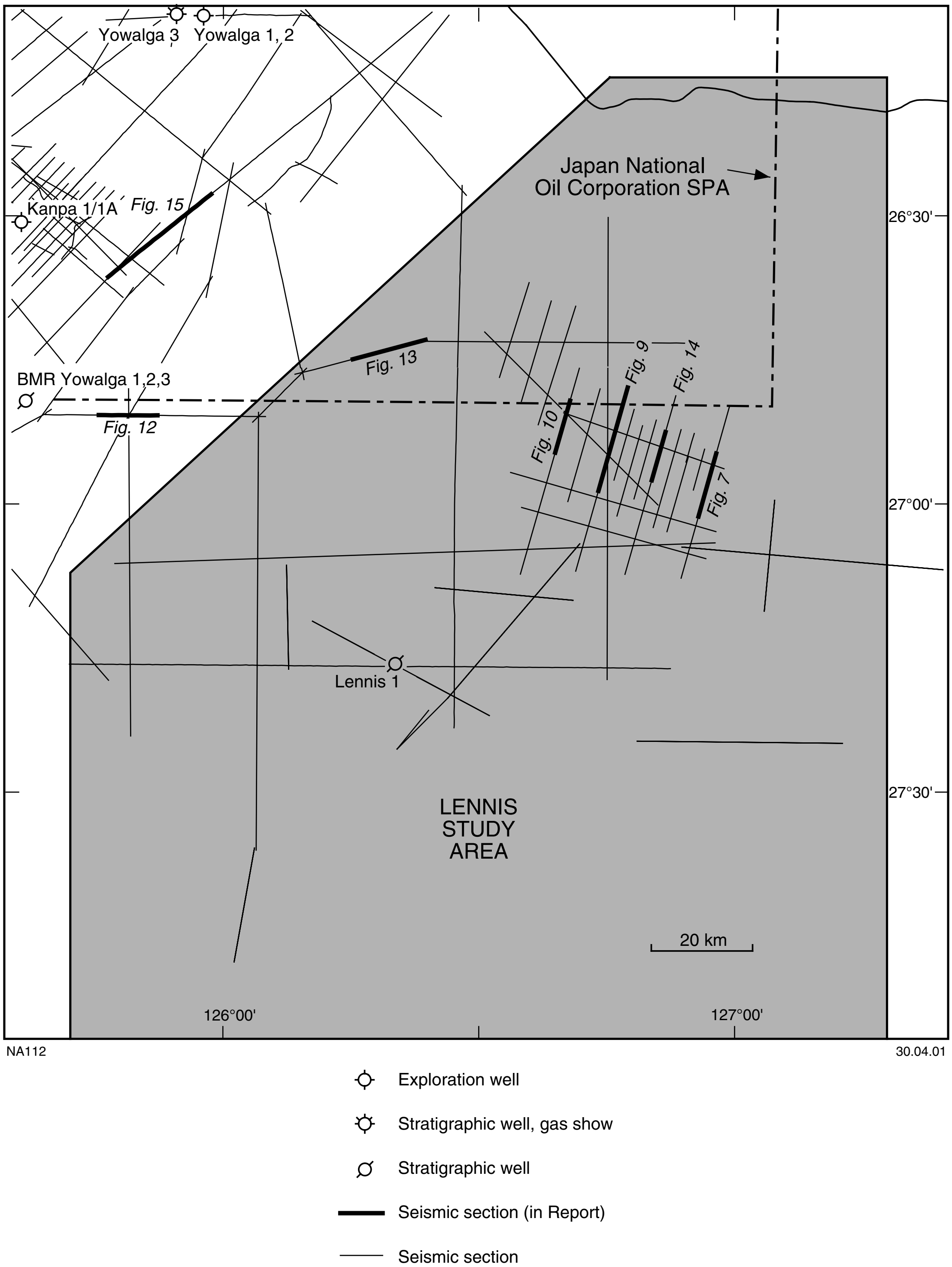


Figure 2. b) Location map showing seismic coverage and wells in the Lennis area

are no active pastoral developments in the area and infrastructure is therefore basic. A number of roads such as the Great Central Road, Emu Road, and parts of the Gunbarrel Highway (Fig. 3) are maintained. Sealed roadways end at Laverton and Wiluna, the last substantial towns. The remaining roads are gravel and of varying quality. Numerous roads and tracks, constructed during mineral and petroleum exploration, still exist and provide additional four-wheel drive access.

Physiography, climate, and vegetation

The area generally lacks relief, with an elevation of 450–600 m Australian Height Datum (AHD) that slopes downward to the southwest. Ranges of Mesoproterozoic rocks border the Officer Basin to the north, forming the Warburton and Tomkinson ranges. In the Lennis area low-

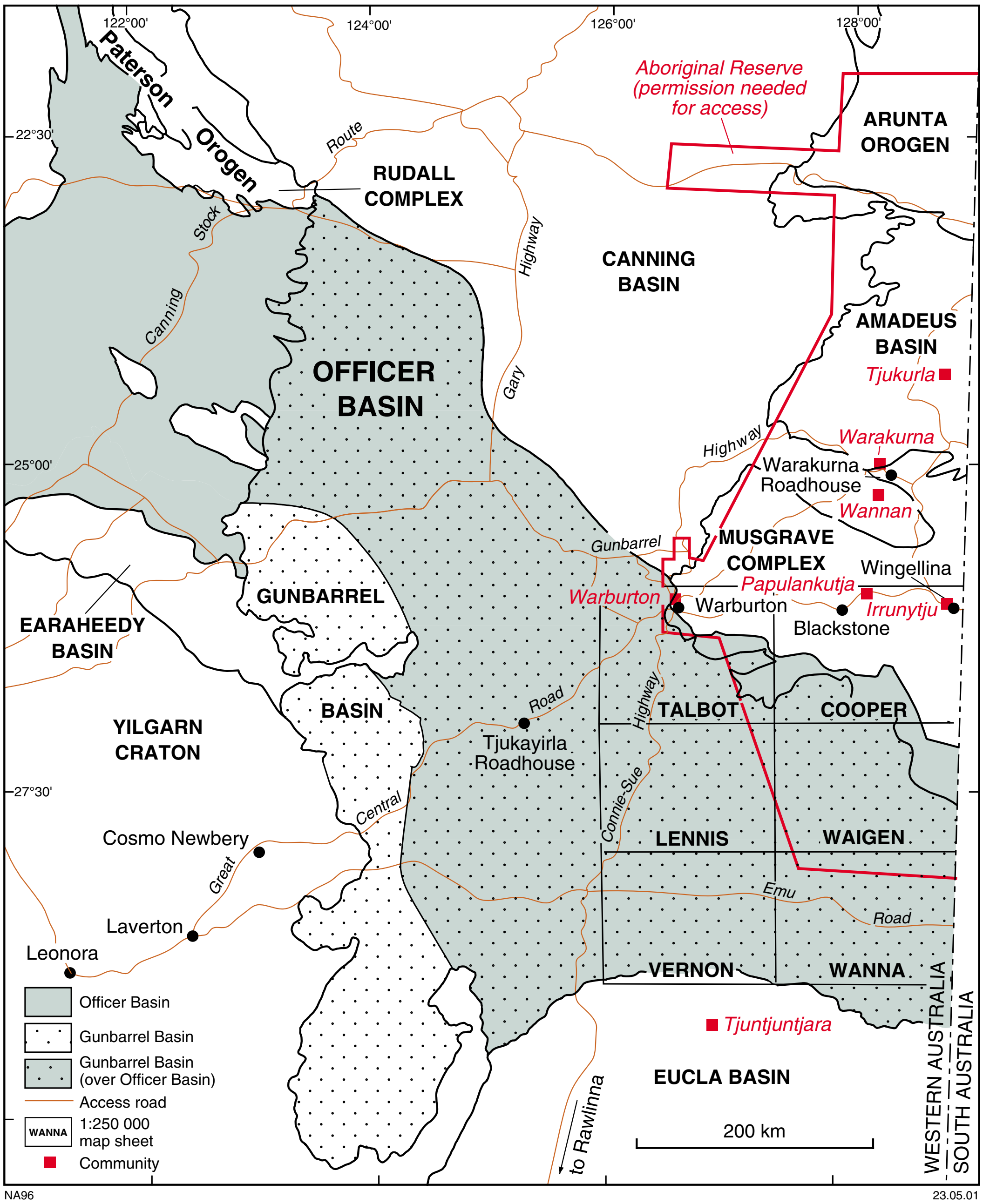


Figure 3. Access routes in the western Officer Basin and location of 1:250 000 map sheets in the Lennis area

elevation, laterite-covered scarps are present, and the lowlands consist of calcrete tracts or laterally extensive dunefields in which dunes reach 10–15 m in height.

The climate is arid, with an irregular annual rainfall of 150–200 mm. Summertime maximum temperatures commonly reach above 40°C between November and March, whereas during the winter months of June to August the minimum temperature commonly falls below 0°C.

Ground cover consists of spinifex and other grasses on the sandy soils, and the luxuriance of the vegetation increases on the dunes. A large range of shrubs is present between the grass and the open, stunted tree cover that is dominated by mulga (shrubby acacia). A range of other trees are scattered between the mulga or in copses in favourable growing conditions (Jackson and van de Graaff, 1981; Daniels, 1970, 1971, 1974; Jackson, 1976, 1978; Kennewell, 1977a,b). Beard (1974) has provided specific data on vegetative and climatic conditions.

Stratigraphy

Poor outcrop, the limitations of Neoproterozoic biostratigraphy, and a sparsity of fossils make the establishment of a stratigraphy for the Officer Basin tentative. Parts of the stratigraphic section are unknown in outcrop and have been seen only in wells, although they can be mapped from seismic data. In addition, significant sedimentary packages mapped from seismic data remain untested by drilling. Petroleum exploration has been a driving force in establishing the current stratigraphic nomenclature. The stratigraphy of the Officer Basin has been described by Jackson and van de Graaff (1981), Townson (1985), Phillips et al., (1985), Williams (1992, 1994), Perincek (1997), and most recently by Carlsen et al. (1999) and Apak and Moors (2000a,b). Field studies and analysis of Empress 1A core have established the stratigraphic relationship of the *Baicalia burra* and *Acaciella australica* Stromatolite Assemblages (Stevens and Apak, 1999), thus enabling the use of these common fossils as stratigraphic markers throughout the basin. Advances in acritarch biostratigraphy are also proving useful (Grey and Cotter, 1996; Grey and Stevens, 1997; Cotter, 1999; Hill et al., 2000). In addition, stable-isotope analyses have been done on organic and carbonate carbon, oxygen, and strontium throughout the Empress 1 and 1A core, and a number of correlations have been made to isotopic curves in other basins (Stevens and Apak, 1999; Hill and Walter, 2000; Hill et al., 2000). In Empress 1 and 1A, the potassium–argon age of continental flood basalt in basement is 1058 ± 13 Ma, whereas the age of the Table Hill Volcanics (also a continental flood basalt) is 484 ± 4 Ma (Stevens and Apak, 1999). These dates constrain the age of the western Officer Basin succession, but it is expected that further changes will be made to formation and sequence tops within the basin.

The stratigraphic column presented in Figure 4 is the authors' current interpretation of the depositional ages of the sedimentary units and intervening tectonic events present in the Officer Basin. Of current concern is the establishment of the chronological range and magnitude of the various tectonic phases observed in the Officer and adjacent basins. Because drilling has not yet intersected a number of key stratigraphic units and unconformities, which are identifiable on seismic data, the current chronological range is based on conventional fieldwork. As new data become available, it is expected that further changes will be made for some of these events. Because no definitive chronology has been established for the structural phases affecting the Officer Basin, the scheme used by the Petroleum Initiatives program over the past six years has been used in this Report.

The geology of the Neoproterozoic and lower Palaeozoic strata capped by the Table Hill Volcanics is the main focus of this project. With very limited outcrop, except for the lower formations adjacent to the Musgrave Complex, and no significant well control, the authors were forced to extrapolate information on the formations collected from other areas with control. The continuity and character of the seismic data suggests that the succession in the Lennis area is very similar to that deposited in the Yowalga area to the west. The following summary of the stratigraphy has been condensed from observations in the Yowalga area (Apak and Moors, 2000a,b) and those of the following authors: Jackson and van de Graaff (1981), Phillips et al. (1985), Townson (1985), Williams (1992, 1994), Perincek (1997), and Carlsen et al. (1999).

Neoproterozoic

Townsend Quartzite and Lefroy Formation

In outcrop, the Townsend Quartzite unconformably overlies the Musgrave Complex and consists of up to 370 m of clean sandstone (Townson, 1985) grading into the siltstone and shale of the overlying Lefroy Formation. In well intersections (Kanpa 1A and BMR Talbot 1), the base of these units was not reached and the Browne Formation disconformably overlies the Townsend Quartzite. The interpreted depositional environment of the outcropping Townsend Quartzite is shallow marine to fluvial (Daniels, 1974; Jackson and van de Graaff, 1981; Watts, 1982; Grigson, 1982).

Data on the Lefroy Formation are also very sparse, being available only from outcrop and shallow drilling near the Musgrave Complex (BMR Talbot wells) and a

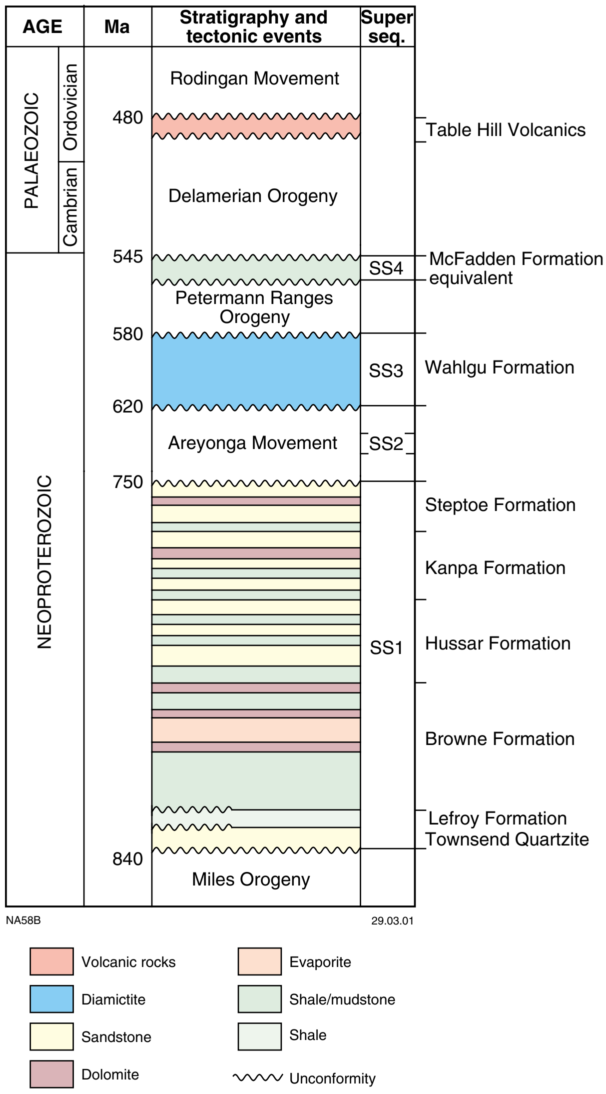


Figure 4. Generalized stratigraphy and tectonic events in the Yowalga–Lennis area, western Officer Basin

possible short intersection in Empress 1A (Stevens and Apak, 1999). In Empress 1A, the ?Lefroy Formation unconformably overlies the pre-Officer Basin strata with a thin, basal lag conglomerate. Lithologies identified are grey or maroon, well-bedded siltstone, claystone, and fine sandstone. The sediments were deposited in a low-energy, deeper water marine environment close to or below wave base. Apak and Moors (2000b) have suggested that the Lefroy Formation is a deeper water facies of the Townsend Quartzite.

Browne Formation

There is no outcrop of the Browne Formation in the Lennis area. Jackson (1976) first used the name 'Browne Evaporites' for the evaporites in shallow wells on BROWNE*. Yowalga 3 and Kanpa 1A were the first significant intersections of this unit and it was named the Browne Formation by Cockbain and Hocking (1989). The lower contact of the Browne Formation is disconformable on the ?Lefroy Formation in Empress 1A and the Townsend Quartzite in Kanpa 1A. Its upper contact is conformable with the overlying Hussar Formation, except in areas of diapiric intrusion such as in Browne 1 and 2 where it may be unconformably overlain by Palaeozoic or younger strata. The formation has been intersected in the Yowalga area in Browne 1 and 2, Empress 1A, Kanpa 1A, and Yowalga 3, which has the thickest section (greater than 2308 m). The Browne Formation is composed predominantly of red shale and siltstone interbedded with stromatolitic dolomite, halite, minor anhydrite, and sandstone. Thick halite deposits are present in Empress 1A, Kanpa 1A, and Yowalga 3. Units of solid halite up to 10 m thick were cored in Empress 1A. Well data also indicate much thicker halite beds, interbedded with thin silty and shaly horizons, in Yowalga 3 and Kanpa 1A (Apak and Moors, 2000a,b). Although not tested by drilling, the similar seismic character to that of the Yowalga area, including halokinetic features, suggests that similar lithologies are present in the Lennis area.

In the Browne Formation (Fig. 5) the narrow range of facies variations, from shallow marine to sabkha, indicates tectonic stability and a balance between sediment input and the creation of accommodation space during deposition. It is difficult to define any structural control on deposition because of the poor resolution of subsalt seismic data and the lack of wells that fully penetrate the formation. The *Acaciella australica* Stromatolite Assemblage has been identified in the dolomite of the Browne Formation in Yowalga 3 and Empress 1A, and is a useful correlation tool.

Hussar Formation

The name 'Hussar beds' was proposed informally by Townson (1985), and later elevated to Hussar Formation by Cockbain and Hocking (1989). The Hussar Formation conformably overlies the Browne Formation, and is conformably overlain by the Kanpa Formation. The Hussar Formation has been penetrated in Hussar 1, Kanpa 1A, Lungkarta 1, Yowalga 3, and Empress 1A, and the greatest thickness was penetrated in Yowalga 3 (897 m).

The Hussar Formation is composed of sandstone, mudstone, dolomite, and minor evaporite, with conglomerate locally developed. The formation contains repeated progradational cycles deposited in shelf, shoreline, tidal flat, and fluvial environments in which upward-coarsening shoreface sandstones predominate. Some of these units are considered to be the principal reservoirs in the western Officer Basin. The depositional model and facies variations for the Hussar Formation are shown in Figure 6. A very low-relief basinal setting is proposed. Dolomite units contain *?Tungussia* form indet. and the *Baicalia burra* Stromatolite Assemblage, and the planktonic acritarch *Cerebrosphaera buickii* is present in siltstone and mudstone sections in Empress 1A (Grey, 1999). The similarity of the seismic character of this formation in the Lennis and Yowalga areas suggests that the sedimentary successions in both areas are similar.

Kanpa Formation

The 'Kanpa beds' were proposed informally by Townson (1985) for intersections in Yowalga 3, Kanpa 1A, and Lungkarta 1, and later upgraded to formation status by Cockbain and Hocking (1989). The Kanpa Formation conformably overlies the Hussar Formation and is conformably overlain by the Steptoe Formation in Empress 1 and 1A, and Kanpa 1A. However, in Yowalga 3 and Lungkarta 1, and as observed on seismic data in the Lennis area (Fig. 7), the top of the Kanpa Formation is eroded to various degrees. Where the Steptoe Formation is not present, post-Supersequence 1 strata overlie the Kanpa Formation.

The thickest penetrated section of the Kanpa Formation is in Kanpa 1A (516 m). The formation consists of dolomite, mudstone, shale, siltstone, and sandstone, with minor evaporite and chert. Clear-water carbonate lithologies are dominant in the Kanpa Formation. The predominant depositional setting was probably shallow marine to tidal flat, with carbonate deposited in oxidizing to slightly reducing conditions (Fig. 8).

The interpreted depositional environments and facies variations for the Kanpa Formation are similar to those of the Hussar Formation. Both formations were deposited on a gentle ramp sloping into the basin axis. In the Yowalga area, individual depositional cycles of shallow-marine carbonate and sandstone may be correlated between the two formations, and appear to be a function of sea-level changes. Sabkha facies were locally developed during regressive phases (Apak and Moors, 2000a,b).

In Empress 1A, dolomite commonly contains stromatolites of the *Baicalia burra* Stromatolite Assemblage, and mudstone units contain abundant cyanobacterial filaments and fragments of cyanobacterial mat, together with the probably planktonic acritarch *Cerebrosphaera buickii*, a key species in this stratigraphic interval (Grey, 1999). The

* Capitalized names refer to standard 1:250 000 map sheets, unless otherwise indicated

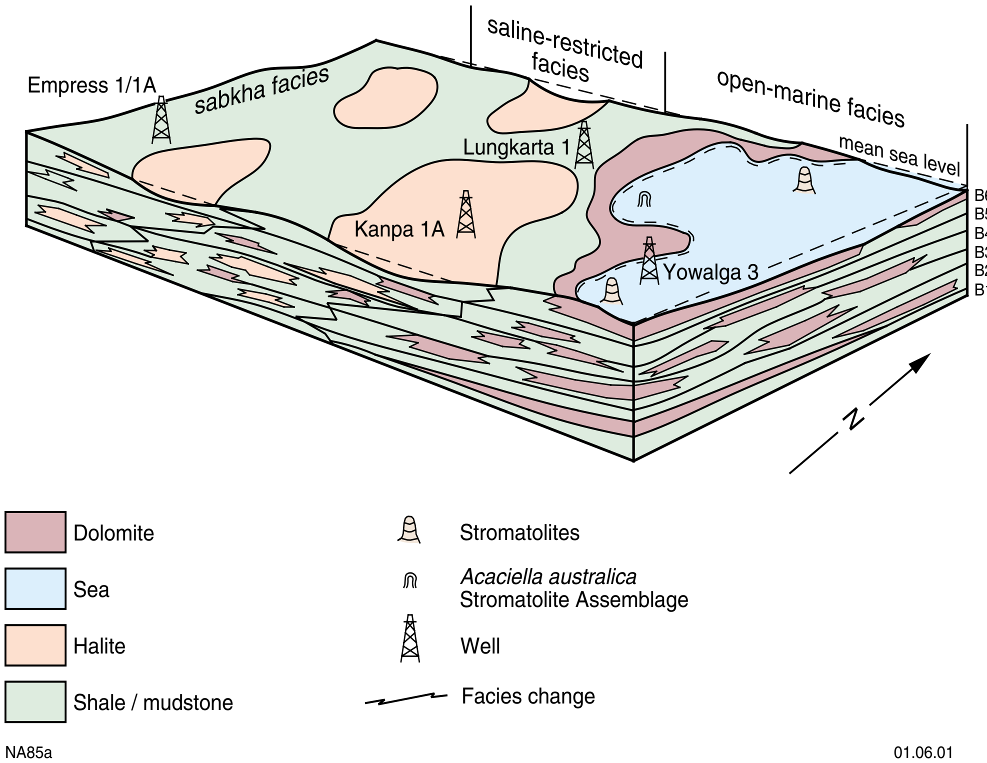


Figure 5. Depositional model for the Browne Formation generated for the Yowalga area (after Apak and Moors, 2000b). A similarity in seismic character indicates that it can be extrapolated to the Lennis area

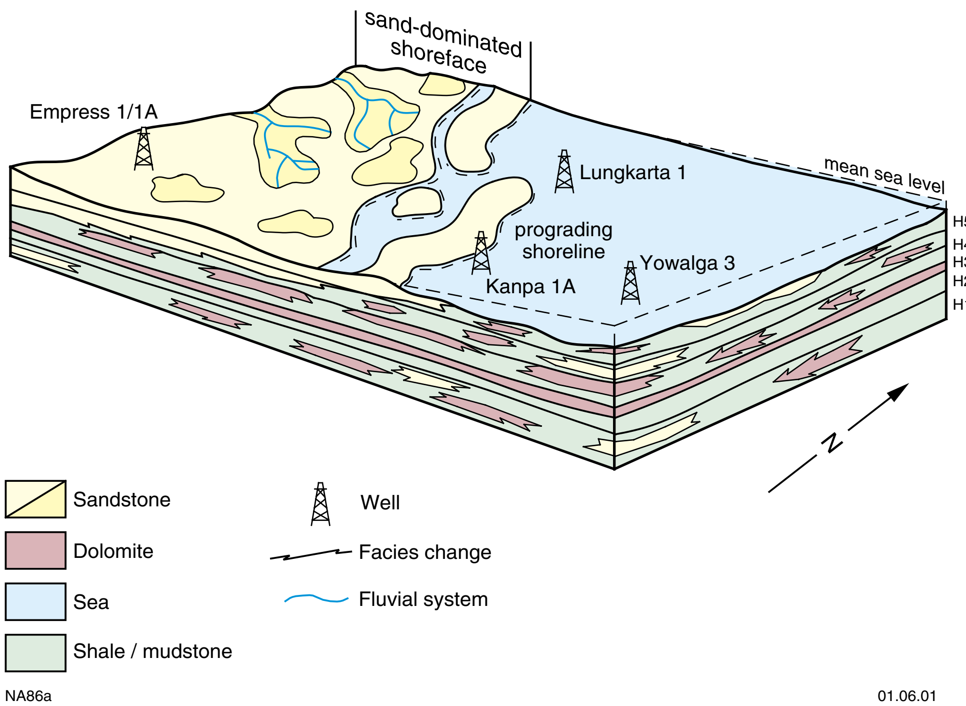


Figure 6. Depositional model for the Hussar Formation generated for the Yowalga area (after Apak and Moors, 2000b). A similarity in seismic character indicates that it can be extrapolated to the Lennis area

similarity of the seismic character of the formation between the Lennis and Yowalga areas suggests that the sedimentary successions are very similar in both areas.

Steptoe Formation

The Steptoe Formation does not outcrop in the Lennis area. The name 'Steptoe beds' was proposed informally by Townson (1985) for a unit penetrated in Kanpa 1A, and later upgraded to formation status by Cockbain and Hocking (1989). The Steptoe Formation conformably overlies the Kanpa Formation. The upper boundary of the Steptoe Formation is an erosional unconformity with the overlying McFadden Formation equivalent in Kanpa 1A (Perincek, 1997), and with the overlying Wahlgu Formation in Empress 1 and 1A (Apak and Moors, 2000b). In the study area, the Steptoe Formation was penetrated by Kanpa 1A (472 m) and Empress 1 and 1A (132 m). However, it has been eroded entirely from the Lungkarta 1, Yowalga 3, and Browne 1 and 2 areas, and has been partly eroded in Empress 1 and 1A and some areas in the Lennis area (Fig. 7) during the Areyonga Movement and Petermann Ranges Orogeny (Apak and Moors, 2000b).

In Kanpa 1A, the Steptoe Formation consists of dolomite, mudstone, claystone, and sandstone. In Empress 1 and 1A, above the claystone-dominated basal transgressive deposits, the formation consists of sandstone, mudstone, loose sand, and dolomite. The Steptoe Formation was deposited within a range of restricted low-energy, shallow-marine shelf or lagoonal depositional environments. The dolomite contains stromatolites of the *Baicalia burra* Stromatolite Assemblage, including *Tungussia wilkatanna* in Empress 1 and 1A (Grey, 1999). The similarity of the seismic character of the formation between the Lennis and Yowalga areas suggests that the sedimentary successions are lithologically very similar.

Wahlgu Formation

In Empress 1 and 1A, a glacially influenced marine deposit unconformably overlies the Steptoe Formation and is unconformably overlain by the Table Hill Volcanics (Apak and Moors, 2000b). This deposit consists of predominantly massive and cross-bedded sandstone, and in the upper part contains a thin dolomitic horizon that has been interpreted to be equivalent to the Marinoan 'cap dolomite' (Grey et al., 1999; Stevens and Apak, 1999). The Marinoan cap dolomite forms the top of the Marinoan glacial strata of Supersequence 3 in the Amadeus Basin and Adelaide Rift Complex (Preiss et al., 1978; Walter et al., 1979). This glacial unit is therefore also considered to belong to Supersequence 3 (Grey et al., 1999). The

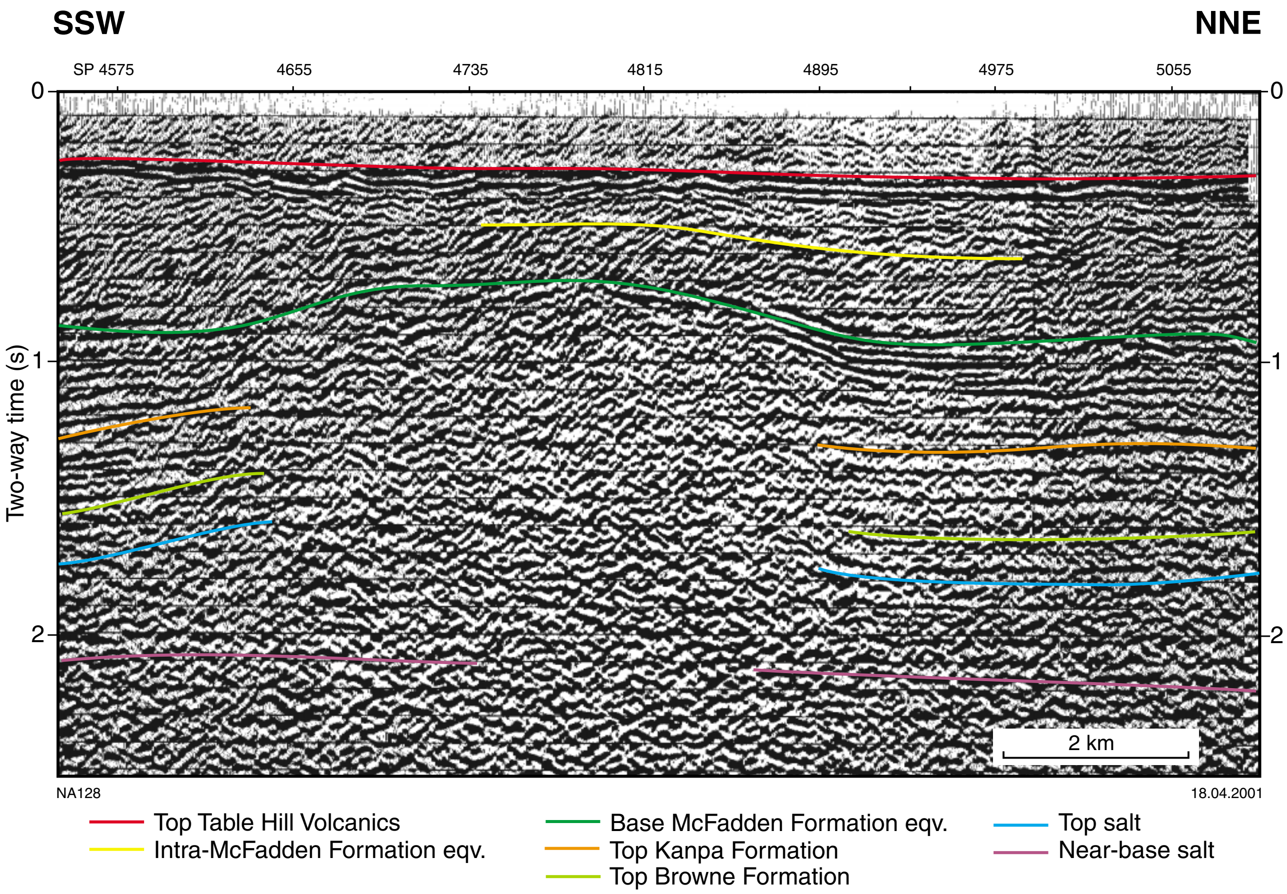


Figure 7. Seismic line T82-136, showing erosion of units underlying the Base McFadden Formation equivalent (including the Kanpa Formation). For location of the seismic line see Figure 2b

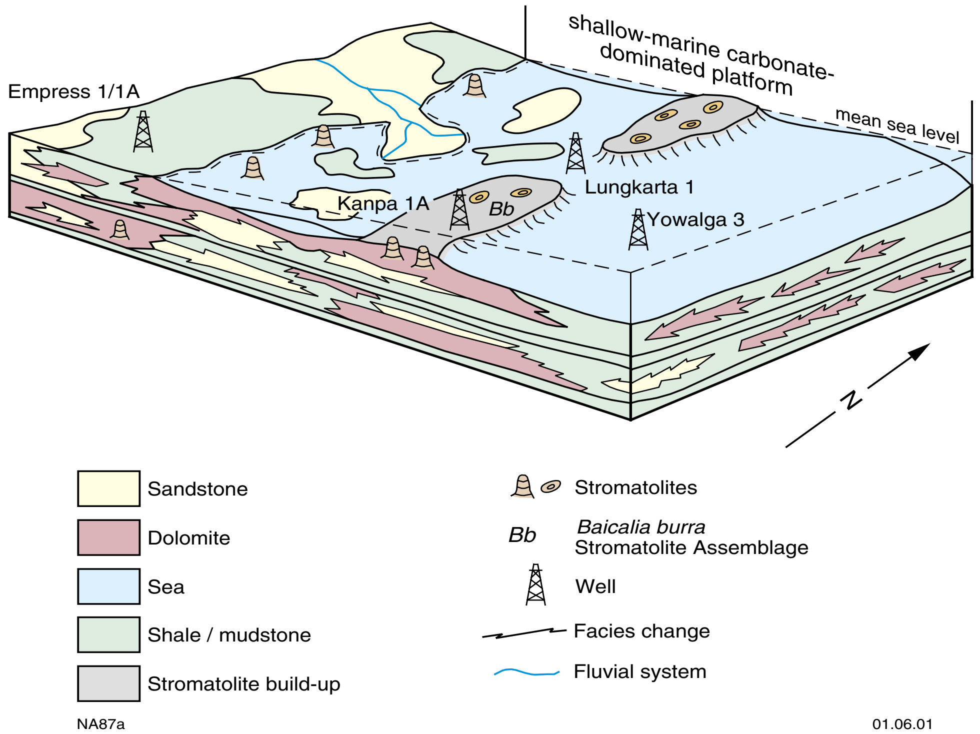


Figure 8. Depositional model for the Kanpa Formation generated for the Yowalga area (after Apak and Moors, 2000b). A similarity in seismic character indicates that it can be extrapolated to the Lennis area

unnamed sandstone that overlies the cap dolomite with a gradational contact (Stevens and Apak, 1999) is considered to be part of this unit (Apak and Moors, 2000b).

This glacial deposit was tentatively correlated to outcrops of the Lupton Formation and named as ?Lupton Formation in Empress 1 and 1A (Stevens and Apak, 1999). Around its type section at Lupton Hills, on the southern flank of the Musgrave Complex, the Lupton Formation consists of massive conglomerate with scattered boulders, and sandstone interbedded with siltstone and diamictite (Jackson and van de Graaff, 1981). Elsewhere, the Lupton Formation lies unconformably on the Townsend Quartzite and the Lefroy Formation (Jackson and van de Graaff, 1981), thus indicating a severe erosional period prior to its deposition. The age of the Lupton Formation is uncertain, and in the light of new information that the Vines 1 stratigraphic well provides it may be younger than Supersequence 3 strata (Apak et al., in prep.). A new name, the Wahlgu Formation, has been proposed to replace the use of ?Lupton Formation in Empress 1 and 1A (Grey et al., in prep.) In this Report, Wahlgu Formation is used for the Supersequence 3 glacial deposits to prevent further confusion in stratigraphic correlation within the Officer Basin.

In the Lennis area, the seismically interpreted Wahlgu Formation, which lies between the Top Steptoe Formation unconformity and the Base McFadden Formation equivalent unconformity, comprises two distinct seismic facies (Fig. 9). The basal unit is the thickest portion and has a mounded character, with low amplitude and short lateral continuity of seismic events. In contrast, the upper unit has only a few high-amplitude events with large lateral extent. Although no wells have intersected the unit, the basal chaotic, mounded facies is probably a lowstand system of fans, whereas the more continuous upper facies is more like a highstand system, or a period of sediment starvation and slow regionally extensive deposition. The formation is much thicker in the Lennis area than in the Yowalga area. The usual thickness of the Wahlgu Formation in the Lennis area is around 300 m, but towards the salt walls it reaches a thickness in excess of 500 m.

McFadden Formation equivalent

Significant thicknesses of the McFadden Formation equivalent were intersected in Hussar 1, Kanpa 1A, and Lungkarta 1, and were previously interpreted as the Babbagoola Formation (Phillips et al., 1985; Townson, 1985). This unit is separated from both underlying and overlying units by seismically identifiable unconformities (Townson, 1985; Perincek, 1997). Perincek (1997) correlated the unit to the McFadden Formation, which outcrops in the Savory area. Following seismic studies, Apak and Moors (2000b) confirmed that this unit, which was penetrated by the three wells mentioned above, is laterally equivalent to the McFadden Formation of the Savory area. The McFadden Formation equivalent in the Savory area consists of medium- to coarse-grained

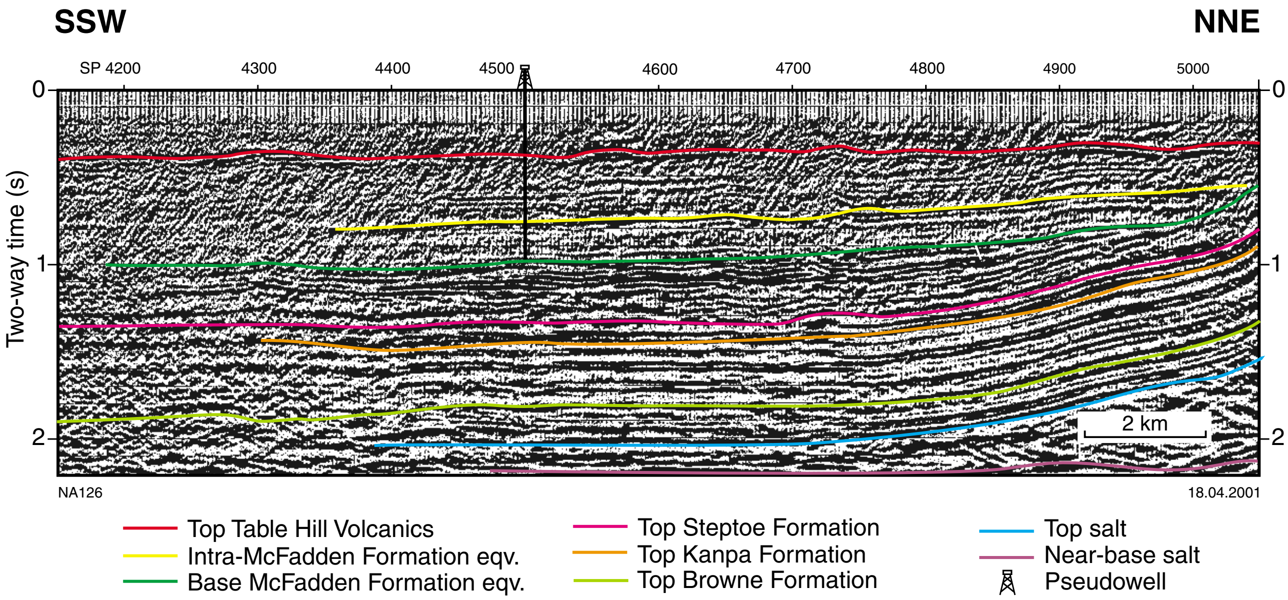


Figure 9. Seismic line T82-138, showing the seismic character of the Wahlgu Formation beneath the Base McFadden Formation equivalent. For location of the seismic line see Figure 2b

sandstone, and minor shale and siltstone, and represents a prograding deltaic to shallow-marine shelf depositional environment (Williams, 1992; Perincek, 1997). Based on seismic data, the unit reaches a maximum thickness in the Lennis area of 1200 m, near the salt walls. It is probably in this area that Shell Company of Australia located the maximum thickness of the formation in the western Officer Basin (Townson, 1985).

In the Lennis area, on seismic data the McFadden Formation equivalent is characterized by three clear seismic horizons (Fig. 9): a basal unconformity event that is partly conformable and partly disconformable, an intra-formation marker, and an upper unconformity with the overlying Table Hill Volcanics. The basal unit shows the greatest variation in thickness, as deposition was contemporaneous with salt movement. Salt-withdrawal synclines adjacent to diapiric structures show beds of constant thickness onlapping the basal unconformity, indicating a substantial submarine basin in front of, and between, the salt walls (Fig. 10). Depending on the activity of the diapiric wall, deposition either covered the salt structure with a thick sequence of strata older than the intra-McFadden Formation equivalent horizon (Fig. 7, SP 4775), or only just barely covered it with the same horizon before the event represented on the seismic data took place (Fig. 10, SP 5890). Deposition subsequent to the intra-McFadden Formation equivalent event is more uniform, with the major changes in thickness present adjacent to salt structures, where the beds have been rotated and removed by erosion before the extrusion of the Table Hill Volcanics (Fig. 9). A more regional truncation is present to the west (see line 80-1 on Plate 1), where the McFadden Formation equivalent strata are truncated by erosion pre-dating the Table Hill Volcanics.

Because there are no well intersections of the McFadden Formation equivalent in the Lennis area, although there are thin intersections in Kanpa 1A and Lungkarta 1 in the Yowalga area, control on lithologies in the study area is lacking. In the salt-withdrawal rim synclines adjacent to diapiric features, the strata have been uplifted by the movement of salt. The intra-McFadden Formation equivalent reflector loses strength as the formation thins westwards. This thinning reflects the fact that the Lennis area was subsiding more rapidly than the Yowalga area during deposition of this unit.

Palaeozoic

Table Hill Volcanics

Extrusion of the Table Hill Volcanics marked the commencement of a new depositional sequence that has been formally assigned to the Gunbarrel Basin (Hocking, 1994). The Table Hill Volcanics can be correlated seismically over a large portion of the western Officer Basin and they outcrop on the northeastern margin of the basin, near the South Australian border. They consist of porphyritic and amygdaloidal tholeitic basalt for which ages of 575 ± 40 Ma (Compston, 1974) and Middle to Upper Cambrian (Moussavi-Harami and Gravestock, 1995; Perincek, 1997) have been proposed. However, K–Ar radiometric dating of samples from Empress 1 and 1A (Stevens and Apak, 1999) indicates an Lower Ordovician age of 484 ± 4 Ma.

Sequence stratigraphy

In the Lennis area, the absence of well control for the Officer Basin succession precludes sequence-stratigraphic analysis. However, the availability of a reasonably good dataset for the Yowalga area, immediately to the west of

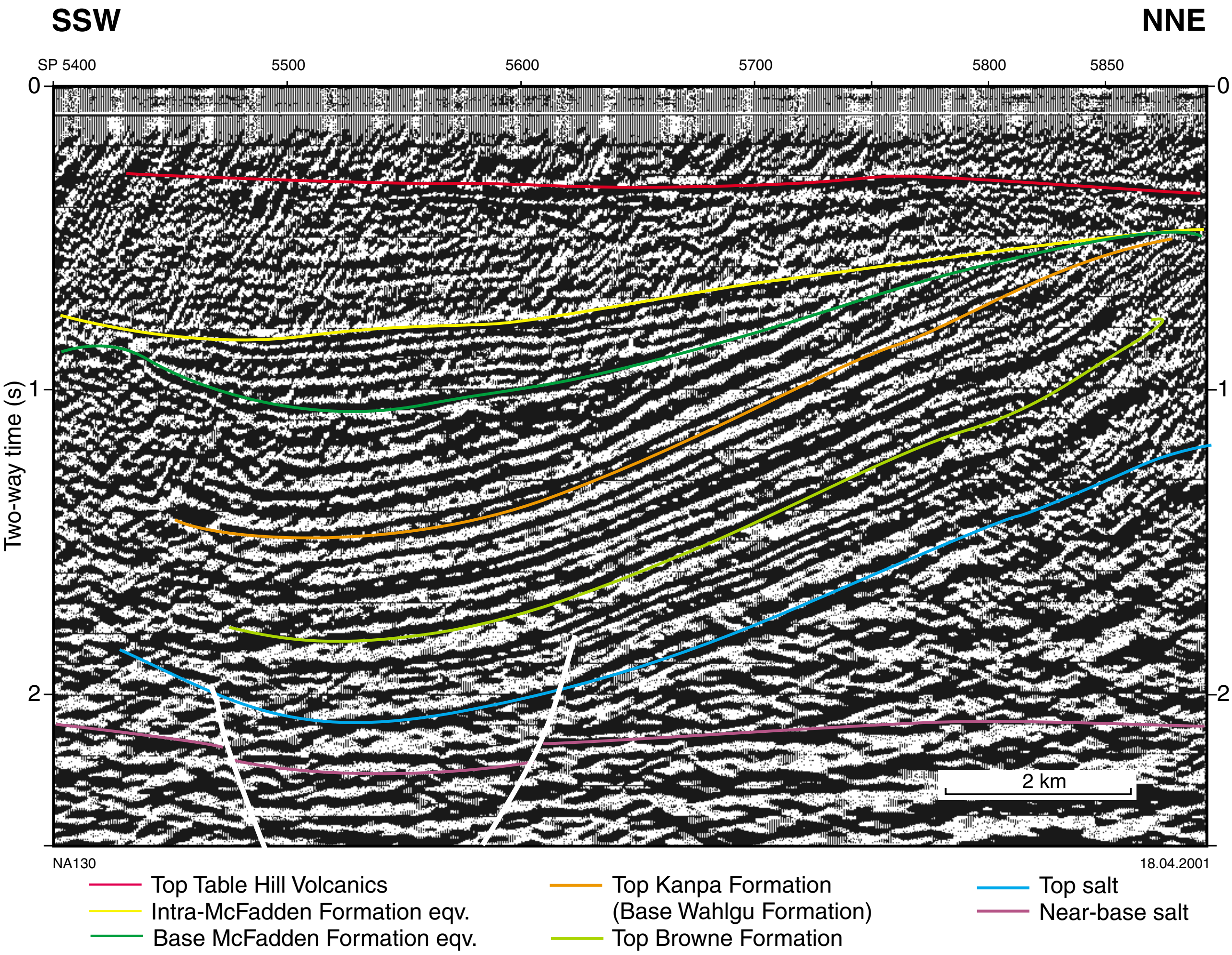


Figure 10. Seismic line T82-139, showing a rim syncline between salt walls. The rim syncline is infilled by the Wahlgu Formation, which onlaps on to the northern salt wall. The younger McFadden Formation equivalent infills the rim syncline and onlaps on to both the northern and southern salt walls. For location of the seismic line see Figure 2b

the Lennis area, is a starting point for a detailed sequence-stratigraphic study. This data consists of deep exploration wells, core data from Empress 1 and 1A, and seismic lines. Well parameters, substantiated by seismic data, can be correlated with confidence across the Yowalga area (Apak and Moors, 2000a,b). The similarity of the seismic character of the Officer Basin succession in both the Yowalga and Lennis areas suggests that the same sequence-stratigraphic hierarchy persists into the Lennis area. Unfortunately, the seismic control does not allow correlation at all levels and the authors have not attempted a detailed study of the sequence stratigraphy for the Lennis area.

The sequence stratigraphy of the Yowalga area (Apak and Moors, 2000a,b) provides a rationale for the evaluation of the basin history and petroleum potential of the Lennis area. A brief summary of facies and lithologies for each sequence is presented, with the understanding that although details may change, lithological associations should remain similar. The lower two units of the Officer Basin succession, the Townsend Quartzite and Lefroy Formation, lack adequate control and could not be characterized even in the Yowalga area, and hence are not discussed here. This Report provides a brief overview of the overlying Browne to Steptoe Formations.

Within the Browne Formation (here referred to as Sequence B) in the Yowalga area, six parasequence sets have been identified in well intersections and are correlateable on seismic data over a wide area (Apak and Moors, 2000a,b). The similar seismic character of the Lennis area suggests that the Browne Formation is composed of similar parasequence sets, some of which may be continuous between the two regions. Each depositional cycle commences with a basal transgression marked by a mudstone that produces an abrupt increase in American Petroleum Institute (API) units on gamma-ray logs. These transgressions are followed by dominantly open-marine facies in the central area and sabkha to restricted hypersaline, shallow-water facies in the marginal areas. The smaller scale of salt-induced structuring (especially salt-mobilized thrusting) may indicate that the volume or distribution of salt intervals in Sequence B in the Lennis area is less than in the Yowalga area.

Within the overlying Hussar Formation (Sequence H), five parasequence sets have been identified in well intersections and can be correlated seismically over a wide area (Apak and Moors, 2000b). The dark-grey mudstone at the base of each parasequence in the Yowalga area is interpreted as reflecting deposition in a quiet environment below storm wave base. These mudstone deposits indicate rapid and widespread transgressions that suggest rises in sea level. Sandstone horizons within Sequence H exhibit mostly sharp upper and lower surfaces and represent high-energy depositional events in a shallow-marine environment, probably a shoreface to lower shoreface environment. They are interbedded and overlain by laminated to thinly bedded shelf to lagoonal mudstone facies. Once again the seismic character of the Lennis area suggests that this formation consists of cycles similar to those described in the Yowalga area.

In the Yowalga area, two parasequence sets have been identified in well intersections within both the Kanpa Formation (Sequence K) and Steptoe Formation (Sequence S). These parasequences can be correlated over wide areas using seismic data. However, in some places the Steptoe Formation was severely eroded during the Areyonga Movement and Petermann Ranges Orogeny, and for this reason can not be correlated laterally with confidence. As discussed above for other sequences, the similar seismic characteristics of the Lennis area suggest that the Kanpa and Steptoe Formations probably consist of similar parasequence sets to those identified in the Yowalga area.

Geophysics

Geophysical coverage of the Lennis area includes gravity, magnetic, radiometric, and seismic surveys (Fig. 2b). More specific data on individual surveys can be found in Perincek (1998). The section below comments mainly on the seismic data and on the seismic interpretation of Durrant and Associates (1998).

The recognition of sub-basins within the Officer Basin was based on field mapping, potential-field data, and the use of long-line aeromagnetic traverses conducted by BMR in 1954. Oil exploration in the early 1960s led to a number of additional aeromagnetic and gravity surveys. Unfortunately, the interpretations of the gravity and magnetic data did not concur. The differences were due, at least in part, to the character of the basement, which is variably composed of igneous, metamorphic, and sedimentary rocks.

Stratigraphic drilling provided information on the density and magnetic susceptibility of the Officer Basin strata and basement, thus enabling better geophysical models to be generated and more valid estimates of depth to basement to be made (Shevchenko and Iasky, 1997). Seismic surveys and additional drilling in the western Officer Basin provided control points. However, simple potential-field solutions proved to be model dependent and substantial adjustments have had to be made to depth-to-basement maps following stratigraphic drilling. The authors' experience has been that where there is no well control such maps are likely to be substantially in error. The Lennis Sub-basin was defined using potential-field data that clearly suggest a restricted area of thick sedimentary strata (Fig. 11a). The depth to the deepest seismic-map horizon for the same area (Fig. 11b) does not show a depocenter of Neoproterozoic strata in the same area. This proves that the potential-field data is influenced by lithologies below the Officer Basin strata.

Seismic data

GSWA contracted Durrant and Associates to interpret seismic-reflection data over the seismic grid available in the Lennis area. The seismic data used was final-stack processed sections, as provided by the petroleum exploration companies under the Petroleum Act. Where available, migrated or weathering–static corrected sections were used to control the final-stacked interpretations. This seismic data was tied to the synthetic seismogram of the Kanpa 1A well, using formation tops provided by GSWA. Six different horizons were interpreted. These were the Top Table Hill Volcanics, Base McFadden Formation equivalent, Top Kanpa Formation, Top Browne Formation, intra-Browne Formation marker (top mobile salt), and Base Neoproterozoic (near-Base Browne Formation), with basement picked on some regional lines. Steep dips in the strata that are the result of salt movement are seen on seismic sections, thus making their interpretation difficult. This is especially apparent on the lines shot parallel to the two main salt walls (line T82-150 on Plate 1). These salt walls disrupt the sedimentary succession and necessitated jump-correlation of seismic events to continue the interpretation across them. This methodology was generally satisfactory in most cases (Durrant and Associates, 1998).

The seismic lines were digitized and shift corrections made to tie the various surveys. In general, the high-quality continuous seismic marker corresponding to the Table Hill Volcanics was used to establish an adjustment of up to 100 msec in two-way time (TWT) required in the seismic surveys. Durrant and Associates produced the time-structure maps of the seismic horizons (Plate 1) and isochron maps were produced from these (Plate 2).

Data coverage

In 1965–66, a consortium led by Hunt Oil Company carried out the 270 km Lennis North seismic survey. The quality of the survey was poor, with only the better reflectors such as the Table Hill Volcanics showing lateral continuity. Shell Company of Australia conducted seismic surveys in the Lennis area in 1980, 1981, and 1982 (Townson, 1985; Perincek, 1998). These surveys comprised regional lines and some detailing grids, but seismic coverage over most of the Officer Basin remains sparse (Fig. 2b). The lines used in this study are listed in Table 1.

Data quality

The original quality of the early 1980s seismic data for most of the basin is poor (Perincek, 1997). Strong-

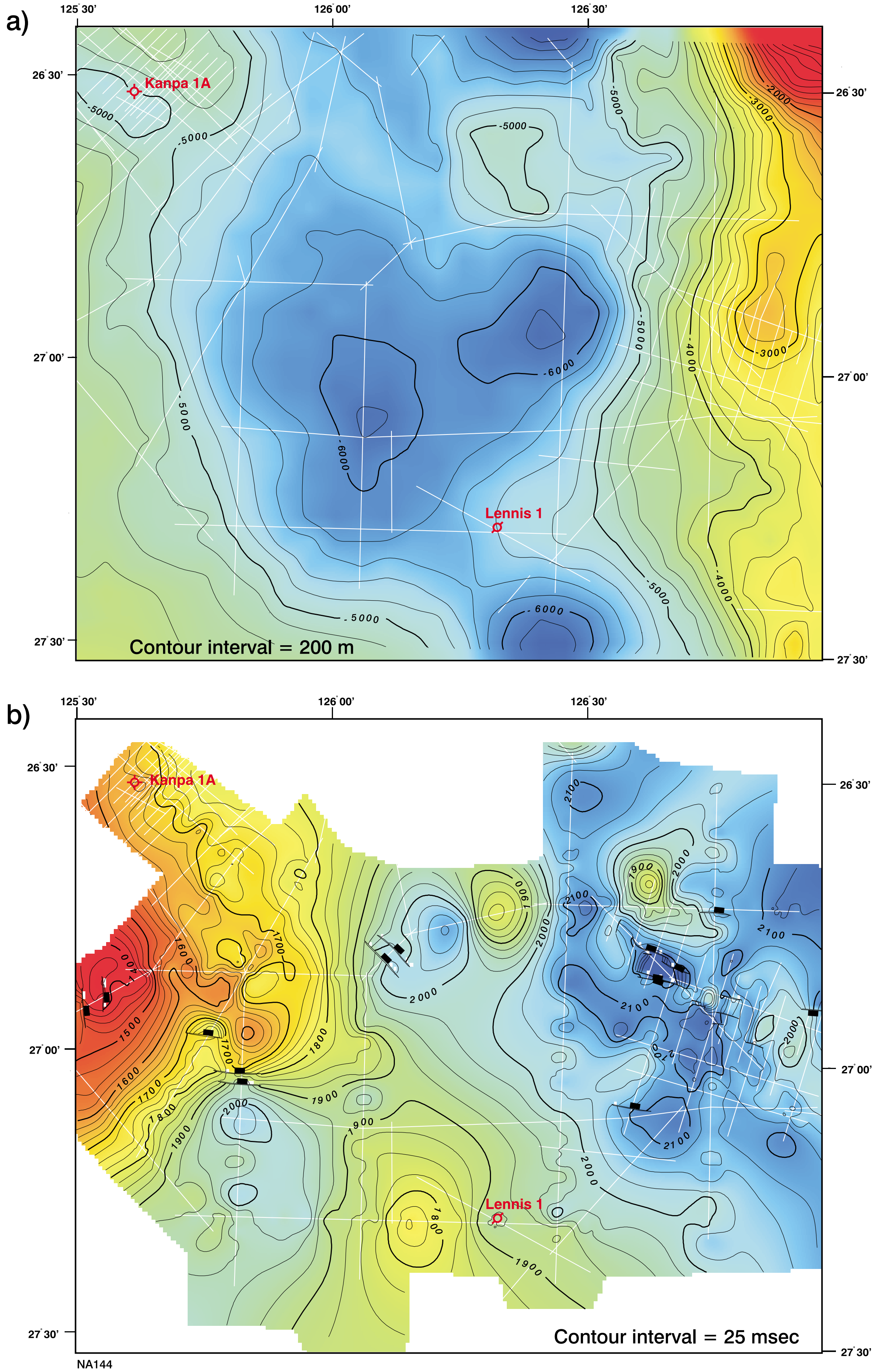


Figure 11. Comparison between the geometry inferred by a) depth to basement from potential-field data (Shevchenko and Iasky, 1997) and b) seismic two-way time to Base Browne Formation (Durrant and Associates, 1998)

amplitude events that represent the major unconformities (e.g. Base Table Hill Volcanics) and transgressive surfaces can be correlated with confidence, although they are discontinuous in some places mainly due to salt emplacement and complex faulting. In the adjacent Yowalga area, Japan National Oil Corporation reprocessed similar acquired seismic data, which resulted in a dramatic improvement in quality (Apak and Moors, 2000b). Modern reprocessing should also improve the data in the Lennis area to a comparable degree.

Seismic control in the Lennis area is very limited, with a grid of lines 2.5 – 5 km apart over the salt-wall region, but only a 20–50 km regional seismic spacing over the rest of the area. Consequently, structural control on time and isochron maps is very loose, and comments made on structural closure or even thickness trends should be considered with this in mind.

Structural interpretation

The structure of the Officer Basin is complex, having been affected by a number of regional events (Fig. 4). The major structures (Fig. 1) were established in the basement rocks before Neoproterozoic deposition commenced (Myers et al., 1996). Deformation in the Officer Basin was at least partially controlled by these basement structures during subsequent tectonic events. None of these tectonic phases were particularly severe in the Lennis area; crustal shortening being minor, as indicated by large stable, undeformed areas. Apart from thrusting associated with the Musgrave Complex, the major deformation was associated with salt movements. Differential subsidence between the Lennis area and other parts of the western Officer Basin such as the Yowalga area is reflected in the structure of the post-Supersequence 1 strata. In the Lennis area, the substantial thicknesses of the Wahlgu Formation and McFadden Formation equivalent probably rejuvenated salt movement, further complicating the pre-existing structure. The present-day deformation can be shown to be the combination of a number of phases of movement. Folding is gentle, with low dips except in association with salt-piercement features.

Table 1. Seismic lines used in this Report

Line number	*Shotpoint range*
80-1	2 001 – 2 973
80-3A	335 – 555
80-3B	245 – 465
80-5	1 800 – 2 100
T82-136	4 575 – 5 055
T82-137	5 225 – 5 665
T82-138	4 600 – 5 000
T82-139	5 410 – 5 850
T82-150	2 001 – 3 325

NOTE: Details are from the K82A seismic survey and extension survey

Faulting

Although Townson (1985, fig. 4) suggested abundant faulting in the Lennis area based on aeromagnetic and Landsat data, faults are difficult to identify on seismic data, as shown by the dearth of faulting on the Durrant and Associates maps (Plate 1). GSWA therefore carried out its own fault interpretation using a first vertical derivative image of the Bouguer gravity data. This image also suggested the presence of numerous faults, but only for the largest faults such as the Westwood Fault did the gravity, magnetic, and Landsat interpretations coincide. This is partly explained by the fact that the three methods rely on different physical properties of the rocks, have a different density of control points, and have different algorithms. Although the gravity data clearly identified the salt walls, the magnetic data may have been more influenced by the high magnetic susceptibility of the shallow Table Hill Volcanics. A combination of potential-field and seismic data suggests that faults are abundant in the Lennis area, but that they probably have small throws.

The dominant fault trend derived from the potential-field data strikes to the northwest and downthrows to the south, whereas a subsidiary set of faults strikes orthogonally to the northeast (Townson, 1985). The major Westwood Fault strikes to the north and there are only a few other lineaments with a similar orientation. The Westwood Fault system orientation is the same as in the better understood Yowalga area to the west (Apak and Moors, 2000b). The orientation of the faults cannot be deduced from the seismic data, as few faults cut more than one line. However, the potential-field data suggest that the orientation of the seismic data to the faulting is appropriate for detecting faults of this orientation, so their lack of detection cannot be explained in this way.

Normal faults are difficult to see on the seismic data. Line T82-136 (Fig. 7) shows a number of typical offsets of the Table Hill Volcanics (e.g. SP 4575 and 4735) that have 20–30 msec displacements, but they do not persist with depth. On line 80-3A, between SP 475 and 515 (Fig. 12), there appears to be a more convincing normal fault with an associated antithetic fault. Throws are less than 70 msecs.

Within the Browne Formation, listric thrust faults lubricated by salt are common in the Yowalga area to the west, but appear to be less common in the Lennis area. One of these faults can be seen on seismic line 80-3B (Fig. 13), around SP 305. The fault shown in this seismic line steepens as it rises through the section. The structure so formed has been eroded by the unconformity at the base of the McFadden Formation equivalent. In the seismic section, this structure has also been displaced over 200 msec by a later rejuvenation that persisted (although with less amplitude) after the Table Hill Volcanics were extruded.

The linearity and orientation of the salt walls in the northern part of the Lennis area suggests that they were controlled by faulting. Seismic line T82-137 (Fig. 14) shows a displacement of seismic horizons on either side of a salt wall (SP 5465 to 5625). Careful examination of this seismic line shows that the displacement is not fault related, but instead is due to the presence of a wedge of ?salt on the southern side of the fault. The presence of this salt wedge may indicate a depositional fault that created a half graben in which the salt was locally deposited and later assisted in its mobilization. There appears to be less evidence of salt within the Browne Formation in the Lennis area than in the Yowalga area to the west.

Maps of the major salt walls indicate a southeasterly trend that extends from the Yowalga area into the Lennis area (Apak and Moors, 2000b, fig. 12). Thus it is feasible that a major salt wall or a number of salt walls may exist north of the limits of the seismic control in the Lennis area.

Folding

Folds in the Lennis area are open, reflecting the mildness of the orogenic phases that took place there. The limited seismic control over the area means that the nature, size, and distribution of folds cannot be delineated with confidence. Most of the folds recognized are associated with drape over deeper salt-enhanced features.

Seismic line 80-3A (Fig. 12, SP 335 to 475) shows an example of a low-amplitude open fold that is nearly 10 km in length and in which the amplitude is in excess of 100 msec. The fault at the eastern end of the structure may create additional closure. The presence of the rollover structure that includes strata from basement to the Table Hill Volcanics indicates post-Ordovician deformation.

Larger structures are associated with thrusting along salt-lubricated listric faults. Seismic line 80-3B shows one such feature between SP 305 and 465 (Fig. 13). In this case, the fault has been rejuvenated after the formation of the unconformity at the base of the McFadden Formation equivalent, but prior to this it extended only partly through the Supersequence 1 strata, with the uppermost units folded over the fault tip. The apparent relief on this fault could have been 400 msec (approximately 500 m) prior to fault rejuvenation that displaced the peneplained surface by an additional 200 msec (approximately 250 m) and minor movement after deposition of the Table Hill Volcanics. In this case, reactivation of the faults may have destroyed the integrity of the trap while enlarging the structure, but other examples of lesser amplitude and with a simpler history are also present in the region.

The largest structures are associated with salt walls in the north of the Lennis area. These salt walls do not always penetrate the whole of the Officer Basin succession, so four-way dip closure is sometimes present, but more commonly diapirism in the deeper horizons is complete and the initial anticlinal trap is split into two facing salt-sealed three-way dip closures. The largest anticlinal feature is seen at the Base McFadden Formation equivalent horizon unconformity overlying the southern salt wall (Plate 1). Here an anticline with a length in excess of 40 km, a vertical relief of 200 msec (approximately

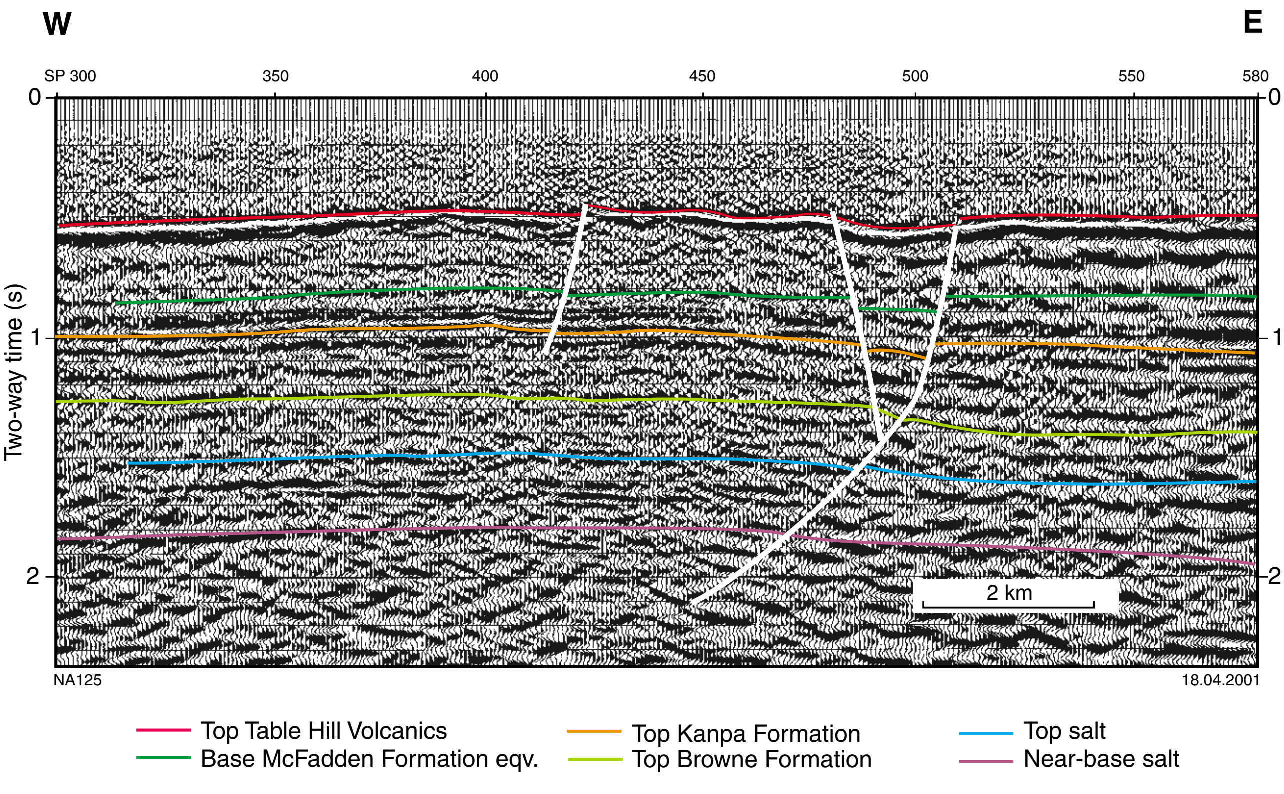


Figure 12. Seismic line 80-3A, showing a low-amplitude anticline with structuring from Supersequence 1 to the Table Hill Volcanics. For location of the seismic line see Figure 2b

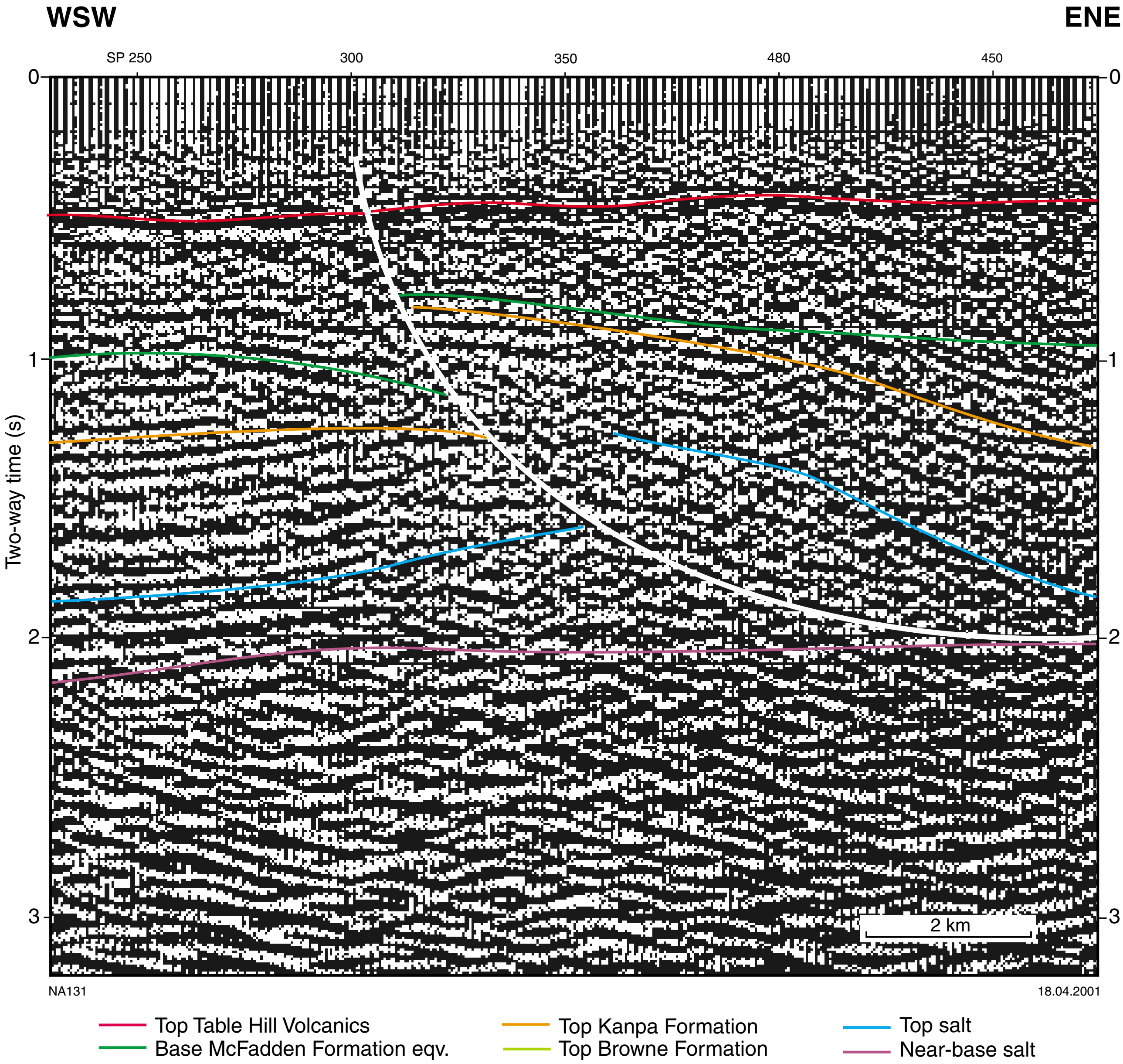


Figure 13. Seismic line 80-3B, showing multiple rejuvenation of a salt-lubricated thrust fault in the Browne Formation. For location of the seismic line see Figure 2b

400 m), and 260 km^2 of closure has been mapped. Other three-way dip-closed structures in the same salt-wall complex cover areas from 50 to 250 km^2, and have an even greater vertical relief.

Salt movement

Based on seismic data, the distribution of salt within the Browne Formation in the Lennis area appears to be more restricted than in the Yowalga area. As mentioned above, the listric thrusting so common in the Yowalga area (Apak and Moors, 2000b) is virtually absent in the Lennis area. This could be due to an absence of uplift and gravity-sliding mechanisms (Apak and Moors, 2000b), or to the absence of pervasive salt beds. Other salt indicators such as swells or welds are also rare, except adjacent to the salt walls in the north of the area, thus implying an absence of thick salt beds in the Lennis area.

A number of salt diapirs have long been recognized from surface mapping in the Officer Basin (Jackson, 1976). Some of these have a linear form and linear alignments have been identified (e.g. the Browne Diapir). Subsequent seismic interpretation has found additional salt walls that continue beyond the small surface outcrops and that can be mapped over large distances (Apak and Moors, 2000b). In the Lennis area, salt walls with lengths in excess of 120 km have been mapped by Durrant and Associates (Plate 1). The linear form and north-westerly strike of these salt walls suggest that their injection has taken advantage of space created by faulting.

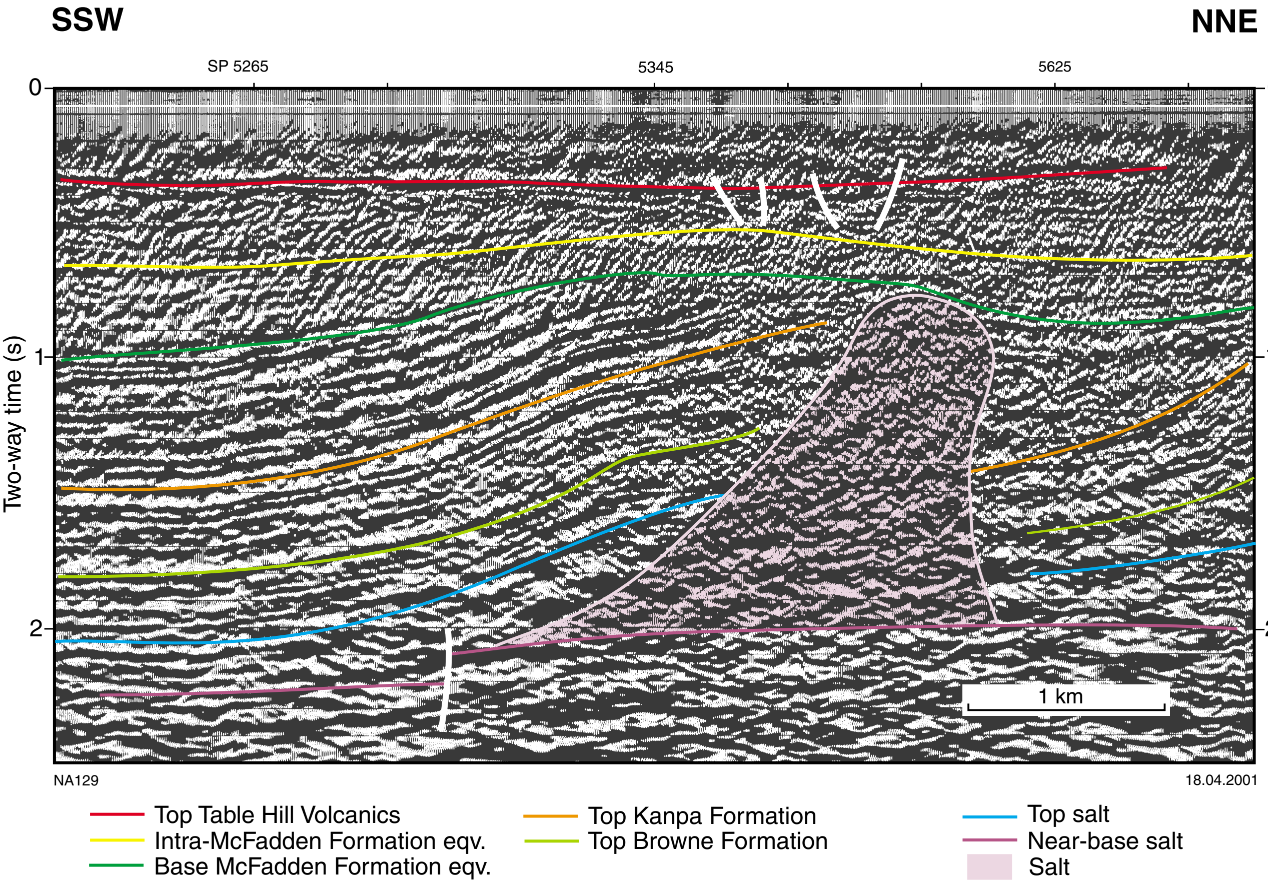


Figure 14. Seismic line T82-137, showing a salt wall with a salt wedge to the south. Seismic horizons are displaced by salt movement, not by faulting. For location of the seismic line see Figure 2b

In the Lennis area, salt appears to be restricted along such salt walls and these faults may have been the reason for the location of halite deposition. These faults may have been active during deposition of the Browne Formation, thus forming a half graben suitable for the accumulation of halite, or they may have controlled the geometry of the basin in other ways. The timing of salt movement differs between the Lennis and Yowalga areas. In the Yowalga area, significant salt movement appears to have been triggered by the Areyonga Movement (Apak and Moors, 2000b) and occurred once, with only minor rejuvenation. The authors assume that the Areyonga Movement also initiated movement in the Lennis area, but in this area significant rejuvenation has taken place during a number of tectonic phases. This can be seen in the multiphase movement of salt-lubricated faults such as the listric fault on seismic line 80-3B near SP 305 (Fig. 13). Clearly the major movement was during the Areyonga Movement, when Supersequence 1 strata were thrust over themselves. Movement continued after deposition of the Wahlgu Formation, as the thrust block was progressively elevated and eroded. This is shown by the convergence of the Top Kanpa Formation and Base McFadden Formation equivalent horizons. After major peneplanation, thrusting along the fault continued, thus disrupting the latter horizon. At a later stage, further thrusting took place after the emplacement of the Table Hill Volcanics.

Another example of salt movement demonstrating withdrawal of salt into the salt walls is shown by sedimentary infill of the peripheral rim synclines. Seismic line T82-139 (Fig. 10) is a good example of a rim syncline between two salt walls. The main thickening of the Wahlgu Formation is in the upper bedded unit (Fig. 10), but onlap onto the rising salt diapir (Fig. 7) shows that there was already substantial relief present during deposition of this unit. Later salt emplacement is confirmed by the rotation of the Wahlgu Formation and erosion of this formation before deposition of the McFadden Formation equivalent. This angular contact is only evident adjacent to the salt diapirs. A few kilometres away, where these strata onlap into a subsiding synchronous rim syncline, the contact becomes conformable between these two units (Fig. 9). Further salt movement during the deposition of the lower McFadden Formation equivalent is shown by the thinning of this unit over the salt diapirs. The thinning appears to be due to elevation of the diapirs rather than erosion. Salt movement has also arched the intra-McFadden Formation equivalent marker horizon. Most salt movement had ceased and peneplanation had been completed by the time the Table Hill Volcanics were deposited (Fig. 7), but rejuvenation that clearly arches the Table Hill Volcanics is also evident (Fig. 15, line 80-5).

The deposition of a substantial thickness of Supersequence 3 (Wahlgu Formation) and Supersequence 4

(McFadden Formation equivalent) successions probably accounts for the continued mobility of salt in the Lennis area. In the Yowalga area, these units are thin and insufficient to initiate secondary salt movements. Greater subsidence during deposition of these formations indicates that diapirism was a response to sediment loading. On Figure 9, the reflector at the base of the McFadden Formation equivalent is conformable within the basin, but unconformable near the salt wall, thus indicating syndepositional salt movement. The effect of the Souths Range Movement, Petermann Ranges Orogeny, and Delamerian Orogeny on initiation or mobilization of the salt is not obvious. The asymmetry of salt emplacement, where salt was emplaced preferentially from the north of the salt walls rather than from the south, indicates that tectonism played a part in the salt movements.

Structural history

A number of basin-forming models have been proposed for the origin of the Officer Basin (Lambek, 1984; Walter and Gorter, 1994; Zhao et al., 1994; Carlsen et al., 1999). As a result of a study of the Yowalga area (Apak and Moors, 2000a,b), a better understanding of the litho-stratigraphy of the basin is now available, thus enabling a more complete sequential reconstruction of the basin's development. Even so, critical portions of the basin have not yet been penetrated by drilling or covered by seismic data. The Lennis area is best regarded as a remnant of a far larger basin that had very low relief and a depositional axis further to the north.

In the absence of well data, time-structure maps have been used to investigate the possibility of structural events, especially fault penetration from the basement. The following summary is based on the currently available geophysical data, including the interpreted seismic lines and time-structure maps (Plate 1) produced by Durrant and Associates (1998), and the seismic isochron maps (Plate 2) derived from these time-structure maps.

The oldest known stratigraphic units of the Supersequence 1 strata are the Townsend Quartzite and the overlying Lefroy Formation. Because well data are lacking and the quality of seismic reflectors from such deep horizons is poor, an interpretation was not attempted for these basal units in the Lennis area.

The overlying Browne Formation, which has a number of well intersections and also better quality seismic reflectors, is better understood than the older strata of Supersequence 1. However, in the Yowalga area only Kanpa 1A and Empress 1A have penetrated the entire unit. The presence of salt has resulted in structural complexity through diapiric injection and salt-lubricated faulting, which may make seismic interpretation difficult. The mobility of the salt has resulted in dramatic variations in the thickness of the unit, but some structural information can be obtained from the seismic horizons discussed below.

Base Browne Formation horizon or near-base salt

The Base Browne Formation (near-base salt) horizon was clearly traced from Kanpa 1A into the study area. The horizon shows a gradual dip to the northeast until it is

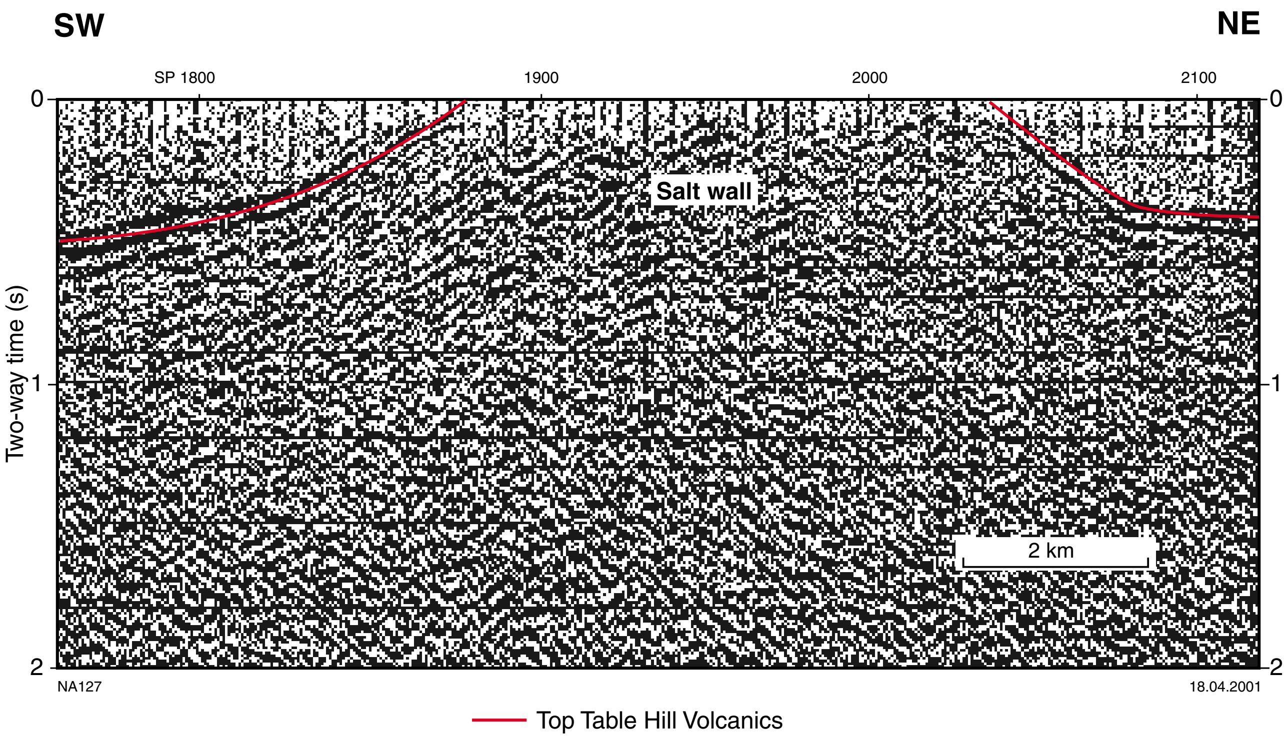


Figure 15. Seismic line 80-5, showing salt movement post-dating the Table Hill Volcanics. For location of the seismic line see Figure 2b

noticeably 'pulled-up' by the high-velocity seismic data of intrusive salt in the northeastern region of the Lennis area. This was the most faulted horizon mapped by Durrant and Associates who identified 20 faults, but all were of small displacement (Plate 1). Some structural closures have been mapped, but all are poorly controlled by the seismic data. The largest closure is due to a pull-up below the salt walls. Two other large structures, north and west of Lennis 1, are single line features with no obvious origin. One of the relatively smaller structural highs on the western part of the seismic map for this horizon (Plate 1) is probably the result of movement on the Westwood Fault.

Intra-Browne Formation marker and near-Top Browne Formation horizon

In contrast to the Base Browne Formation horizon (near-base salt), the intra-Browne Formation marker and near-Top Browne Formation horizon can only be correlated with a lower degree of confidence in the Lennis area. The intra-Browne Formation marker horizon (near-top mobile salt) is not clear on most seismic lines. It is, however, possible to map these horizons from their seismic character, particularly where the salt has migrated and caused truncations or seismic horizons to lose their continuity. The near-Top Browne Formation horizon is also indistinct throughout the project area. It has been mapped based on its stratigraphic location between the conformable Top Kanpa Formation above and the intra-Browne Formation marker below.

The structural maps of the intra-Browne Formation marker and the near-Top Browne Formation horizon are very similar, showing a general dip to the northeast, except in the vicinity of the salt walls where injection of salt has resulted in upturning and uplift of these horizons. Across the middle salt wall, these horizons are interpreted to be higher on the northern side than on the southern side. As this is not the case for the Base Browne Formation horizon, this feature is best explained as resulting from salt withdrawal on the southern side rather than displacement due to fault movement (Fig. 14). The diapiric upturning has resulted in a number of large salt-closed traps along both sides of all three salt walls. Faulting and other anticlinal features have a low amplitude and are poorly controlled.

Well intersections show that salt is distributed throughout the Browne Formation in the Yowalga area. On seismic data, the lower portion of the formation in the Lennis area shows thickness variations, and these can be attributed to the migration of salt. The intra-Browne Formation marker (top salt) to Base Browne Formation horizon (near-base salt) isochron implies a marked thinning of this interval for approximately 20 km south of the salt walls in the northeastern region of the Lennis area. The simple explanation for this is that salt migrated from this zone into the salt walls. However, as in the Yowalga area (Apak and Moors, 2000b), there appears to be a salt-budget problem associated with this interpretation because the salt walls could not contain all the evacuated salt. However, because the original salt content of the Browne Formation in this region is uncertain, the true boundaries of the salt walls are difficult to define in the study area. The continuity of the near-Top Browne Formation to intra-Browne Formation marker (top salt) isochron implies that mobile salt is absent in this part of the succession.

After deposition of the Browne Formation the Officer Basin had attained its final size, with infilling of all irregularities of the depositional surfaces. Deposition in the Lennis area continued under tectonically quiet conditions during deposition of the Hussar Formation. The overall configuration was of a shallow, low-relief depression. A major marine transgression at the base of the Hussar Formation resulted in a thick argillaceous deposit that covered the Yowalga area, and presumably also the Lennis area. In the Yowalga area, the Hussar Formation consists of five parasequence sets exhibiting uniform variations in thickness, but gradually thinning towards the basin margin in the southwest. Seismic data suggest that similar conditions were present in the Lennis area during deposition of the Hussar Formation.

Following deposition of the Hussar Formation, a substantial transgression again deposited another thick basal claystone (the basal Kanpa Formation). In the Yowalga area, the Kanpa Formation exhibits a similar thickness and areal distribution to the Hussar Formation, but only two parasequence sets have been recognized. A similar depositional sequence is probably present in the Lennis area. In the Yowalga area, these two formations were mapped individually, but in the Lennis area the Hussar and Kanpa Formations could only be mapped as a single sedimentary package. Seismic data and the seismic isochron map of the Top Browne Formation – Top Kanpa Formation interval clearly imply a uniformly thick distribution of these two formations over most of the Lennis area.

Top Kanpa Formation horizon

The seismic reflector at the top of the Kanpa Formation is a strong marker horizon throughout most of the project area, and is conformable with the underlying stratigraphic units that form the stiff-overburden to salt-cored structures. This seismic reflector has been tied with confidence to Kanpa 1A. Folding of the formation over salt-cored structures is common and the formation is truncated over the crests of some of these structures by the Base McFadden Formation equivalent unconformity. The Top Kanpa Formation horizon seismic map (Plate 1) is very similar to the Browne Formation horizon seismic maps, and shows a general dip to the northeast, with upturn and elevation of the strata over the salt walls in the northeastern portion of the Lennis area. Faulting and folding are uncommon and of low magnitude. The Top Kanpa Formation to Top Browne Formation isochron map (Plate 2) implies general thickening of these formations westwards into the northeasterly oriented thicker zone of strata. This may suggest that there was some kind of separation between the Lennis and Yowalga areas during deposition of these units.

The Steptoe Formation, the youngest unit of Supersequence 1, was deposited conformably on the underlying Kanpa Formation. On seismic data in the Yowalga and Lennis areas, it is clear that the upper part of the Steptoe Formation, which was affected by a phase of halokinetic faulting and folding during the Areyonga Movement, is eroded in all the wells that have been drilled. Significant amounts of erosion have occurred and the Steptoe Formation has been severely eroded, together with the underlying Kanpa Formation, particularly over salt-emplacement features (Apak and Moors, 2000a, fig. 7) and in basin-margin areas. The only well control is in crests where part of the sequence has been eroded, but complete sections are present off-structure. A similar erosional event during the Areyonga Movement can also be seen in the Lennis area (Fig. 10).

Base McFadden Formation equivalent unconformity

In the Lennis area, above the Top Kanpa Formation horizon, the next seismic horizon of younger strata is the Base McFadden Formation equivalent unconformity, which is characterized on seismic data by a series of subparallel unconformities. A single unconformity is apparent on all seismic lines (Durrant and Associates, 1998). Although it is not very clear on the seismic data, the underlying Wahlgu Formation seems to be less folded or deformed than the underlying Supersequence 1 strata in both the Yowalga and Lennis areas. This seismic horizon dips towards the salt walls to the north, rises over these salt walls (with one wall penetrating the sequence) and then rises again to the north towards the Musgrave Complex. Dips are less than for the underlying Supersequence 1 horizons. Another unconformity, between the Top Kanpa Formation and Base McFadden Formation equivalent unconformity seismic horizons can be recognized on seismic lines. This unconformity (Figs 9 and 10) is probably equivalent to the Areyonga Movement break between the Steptoe and Wahlgu Formations in the Yowalga area. Unfortunately, this key horizon has not been mapped in the study area. As can be seen on Plate 2, deposition of the glacigene Wahlgu Formation filled in much of the topography that resulted from the Areyonga Movement early in the Marinoan (Grey et al., 1999).

Although tillites have been described within the unit (Jackson and van de Graaff, 1981), these are now interpreted to be poorly sorted mass-flow deposits of a submarine fan (Carlsen et al., 1999). Striated and facetted pebbles are present, but they are regarded as more representative of the provenance of the material than the environment of deposition. The massive sandstone, cross-bedded sandstone, and minor laminated sandstone and diamictite seen in outcrop and in Empress 1 and 1A are all interpreted as mass-flow or turbidite deposits. Locally sourced material derived from the salt-injection highs could also be significant. The Wahlgu Formation is much thicker in the Lennis area than in the Yowalga area where subsidence was significantly greater during this period. The Wahlgu Formation has been distorted by salt injection, proving that salt movement took place after deposition of this unit. Following deposition of the Wahlgu Formation, the Petermann Ranges Orogeny is represented by the Base McFadden Formation equivalent unconformity in the western Officer Basin.

Deposition of the McFadden Formation equivalent followed the Petermann Ranges Orogeny. On seismic sections, these strata can be seen as an unconformable filling of the basin lows that onlap on and over the structural highs. The formation of rim synclines at this time suggests a further phase of salt mobilization. The McFadden Formation equivalent is a siliciclastic sequence that varies from sand-dominated to shale-dominated in different parts of the western Officer Basin. The seismic isochron map (Top Table Hill Volcanics to Base McFadden Formation equivalent, Plate 2) shows a pronounced thickening to over 700 msec in the region of the salt walls. It is probably here that Townson (1985) estimated a maximum thickness of 1200 m. The formation is much thinner in the Yowalga area, suggesting basin subsidence was more intense in the Lennis area during deposition of this unit. Deposition in the Officer Basin ceased with the Delamerian Orogeny, during which tectonic highs were rejuvenated and eroded.

Top Table Hill Volcanics horizon

Thin, extensive flows of the Table Hill Volcanics heralded the beginning of the Gunbarrel Basin depositional cycle. The Table Hill Volcanics are a series of thin tholeitic basalt flows of near uniform thickness that are present across the basin. They have been eroded at the surface on the northeastern side of the Lennis area. The seismic response of the top of this formation is clear and distinct on 95% of the seismic lines interpreted for this study and has been used as a regional tie marker in both the Yowalga and Lennis areas. The Top Table Hill Volcanics time-structure map (Plate 1) shows an area of low topographic relief with a sinuous, northwesterly oriented shallow axis. The horizon rises gently to the southwest and northeast. The underlying salt walls have also influenced the seismic reflector, which suggests possible later salt movement or a differential compaction over these features. Durrant and Associates (1998) have delineated only seven faults in this horizon, all with a small throw. However, the many dislocations of the horizon (Fig. 7) are probably due to additional minor faults. This subaerial unit represents the last phase of deposition in what must have been a largely emergent area for approximately 80 million years before subsidence initiated deposition of the Devonian Lennis Sandstone.

All the subsequent sedimentary cycles of deposition are at too shallow a depth to be effectively imaged by the existing seismic data. After the Rodingan Movement, the shallow-marine Lennis Sandstone was deposited across the basin. Lithologies range from shale to sandstone, with occasional matrix-supported conglomerates (Jackson and van de Graaff, 1981; Stevens and Apak, 1999). Uplift associated with the Devonian Alice Springs Orogeny terminated deposition in the restricted depocentre of the Gunbarrel Basin.

When deposition recommenced during the Carboniferous (Stevens and Apak, 1999), deposition of the

Paterson Formation encroached from the Canning Basin and covered much of the underlying basins with a thin veneer of glacigene sediment. From the Permian to the Cretaceous, the region was emergent until the next major sea-level highstand transgressed this low-relief area and deposited the argillaceous Samuel Formation. Since the Cretaceous, the flat, subdued relief of the area has been maintained, with periodic phases of river flow and erosion during wet periods followed by pediplanation and wind deflation during arid periods (Jackson and van de Graaff, 1981). A thin, superficial blanket of sand and clay has accumulated in the study area, and overlies a deep weathering profile that has leached the underlying sedimentary rocks.

Petroleum potential

Previous drilling

In 1965, a consortium led by Hunt Oil drilled the only petroleum exploration well (Lennis 1) in the Lennis area (Fig. 1). This well, which was stratigraphic in concept, was drilled to a total depth of 614.5 m in the Table Hill Volcanics and not surprisingly had no shows. It did, however, identify the prominent seismic reflector as being associated with the Table Hill Volcanics.

As part of their stratigraphic drilling program, the BMR drilled Neale 1A and 1B, Neale 2, and Neale 3 in 1972. Only Neale 1A and 1B penetrated below the Paterson Formation, but they failed to reach the Neoproterozoic sequence before being terminated at 205.75 m. Well summary sheets and references to the wells can be found in Perincek (1998).

Other shallow drilling in the Lennis area (Fig. 2b) was associated with oil-shale and mineral exploration, but few of these bores have a total depth of more than 200 m, and none of the bores intersected significant thicknesses of Neoproterozoic sedimentary rocks. Summary sheets for these bores are presented in Perincek (1998). During 1997, GSWA Empress 1 and 1A were continuously cored from 105 m to a total depth of 1624.6 m in the Yowalga area (Fig. 2a). As the only completely cored section through Supersequence 1, this is the key well for sedimentological studies of the Officer Basin in Western Australia.

Petroleum generation

In the absence of geochemical data specific to the Lennis area, deductions made in other parts of the western Officer Basin, mainly from the Yowalga area to the west (Apak and Moors, 2000b), have been applied to the Lennis area. An understanding of petroleum generation within an area requires detailed information on the quality, quantity, and distribution of potential source rocks within a sedimentary section, as well as the burial and thermal history of the section. Such information for the western Officer Basin has already been reported by Perincek (1998), Ghori (1998a,b), and Ghori (2000). Interpretation of these data suggests that good quality oil-prone source rocks exist throughout the Supersequence 1 strata. Maturation modelling was also undertaken for a representative pseudowell location in the Lennis area in order to try and quantify the timing of petroleum generation for this region. The full maturation modelling is presented in the Appendix and is discussed only briefly below.

Source-rock type

The principal source of organic material during the Neoproterozoic was restricted to cyanobacteria and less abundant planktonic acritarchs. Due to their reliance on photosynthesis, such organic material was produced mostly in relatively shallow-water to periodically emergent conditions. Gelatinous cyanobacterial mats were common, as illustrated by the abundance of stromatolites in Empress 1A in the Yowalga area. A detailed description of the source-rock facies, including production, transportation, and the preservation of organic material, has been presented in Carlsen et al., (1999). Additional comments on the accumulation of organic material in shallow-water oxic conditions typical of most of the Supersequence 1 strata have been provided by Apak and Moors (2000b).

All of the source-rock intervals so far identified have been in thin beds. This makes their detection and quantification from ditch cuttings virtually impossible, as each source-rock bed is diluted by non-source material in the composite ditch-cutting samples. By selecting only the most reliable data from a large database (Fig. 16), source rocks in the Officer Basin have been found to be characterized by type II kerogen (Ghori, 2000), which is as expected from a marine deposit of this age. The spread of source-rock quality towards type III kerogen (Fig. 17) is interpreted as being due to oxidation and degradation of the original biological contribution depleting some of the hydrogen. Pyrolysis of the samples releases a light-oil product with a substantial aromatics component, thus reflecting the tendency towards a type III kerogen (Ghori, 2000).

Strata that can be characterized as source-rocks have been identified by Rock-Eval in most formations of Supersequence 1. These include the Browne Formation (in Kanpa 1A and Yowalga 3), the Hussar Formation (in Empress 1A and Yowalga 3), the Kanpa Formation (in Empress 1A), and the Steptoe Formation (in Empress 1 and 1A, and Kanpa 1A). These intervals may be correlated with the other wells in the Yowalga area (Ghori, 1998a, figs 5, 6, and 7) that generally show at least some enrichment of the equivalent beds. Bearing in mind the limitations of the ability of cuttings to quantify thinly bedded source rocks, these correlations are extremely encouraging and suggest that the source rocks are widespread.

Not all the formations have been adequately sampled; for example, the Lefroy Formation is very poorly controlled. Based on geological principals, the Lefroy Formation is thought to have been deposited in the portion of the basin that contains the deepest water, possibly with extensive areas of quiet anoxic conditions. If this is so, thick source rocks of large areal extent could have been deposited in this unit and, as the Lefroy Formation

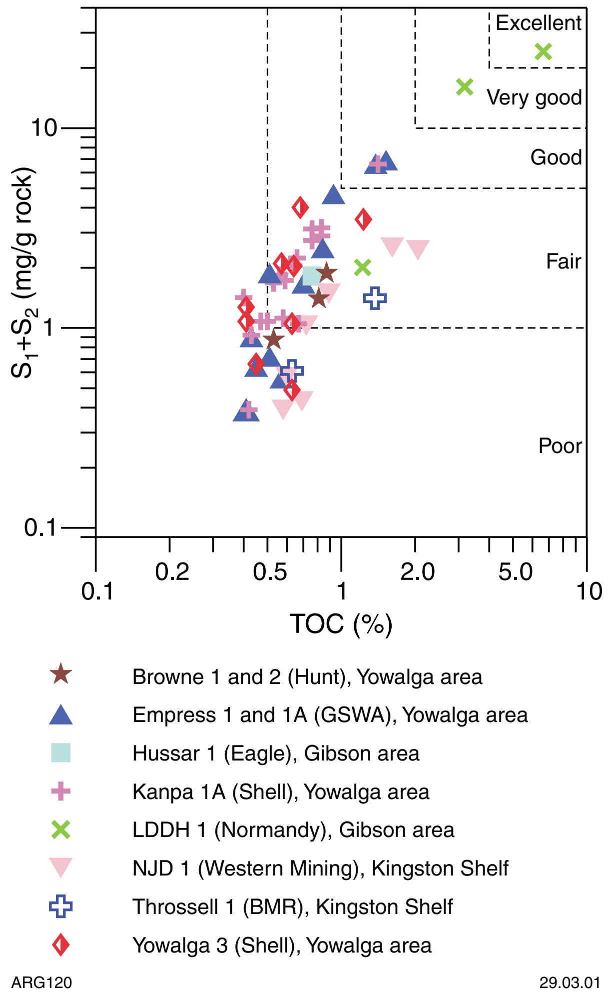


Figure 16. Petroleum-generating potential as a function of organic richness versus potential yield, for samples interpreted as reliable (after Ghori, 2000)

probably interfingers with the Townsend Quartzite, lateral migration of petroleum into these sands, if they still retained porosity, would have been relatively easy. Shale or salt seals could be effective in this petroleum system.

Source-rock maturation and petroleum generation

Geochemical modelling was undertaken in an attempt to identify the petroleum-generating potential of various portions of the Lennis area and the timing of such generation. As there is no well control available, a single pseudowell location, based on seismic data, was modelled to represent the whole region. Because the Lennis area contains a thinner sedimentary section than the Yowalga area, only one location typical of the deepest portion was chosen. Similar lithologies to those in the Yowalga area were assumed for each formation. The model should be representative of the deeper portions of the Lennis area, and other areas with a thinner sedimentary pile that would have attained lower levels of maturity and hence of generation.

Heat flow for the Lennis area was modelled using data from the Yowalga area and thus may be erroneous, as heat flow varies across the region (Apak and Moors, 2000b). The results of the modelling should therefore be regarded as indicative only, until some control becomes available.

The major difference between the Lennis and Yowalga areas is the relative thicknesses of the Supersequence 1 (Townsend Quartzite to Steptoe Formation) and younger Neoproterozoic (Wahlgu Formation and McFadden Formation equivalent) sedimentary units. In the Yowalga area, Supersequence 1 is thick enough to have initiated petroleum generation in its lower units, and burial by the thinner overlying sediments would only have had a slight incremental effect on generation. In the Lennis area, the thickness of the thinner Supersequence 1 succession was insufficient to initiate self-generation of hydrocarbons. Maximum generation did not commence until after late Neoproterozoic deposition. Compared to the Yowalga area, this resulted in a substantial delay in the timing of maximum petroleum generation.

In the absence of well control in the Lennis area, the temperature–depth relationships established from well data in the Yowalga area were extrapolated to the pseudowell location. When fitted to the predicted lithology–depth profile, it appears that the Lennis pseudowell location is

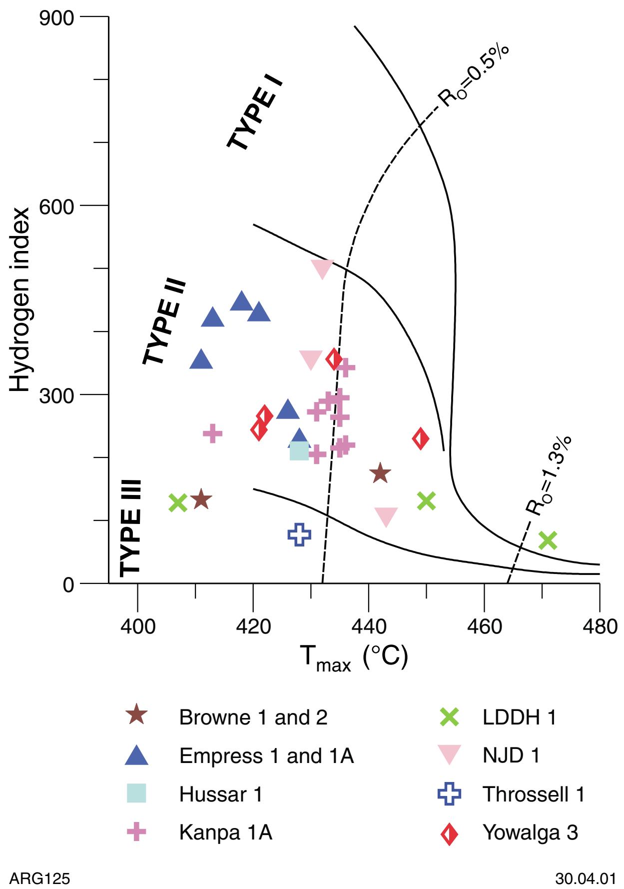


Figure 17. Type of kerogen as a function of T_{max} versus hydrogen index, from Rock-Eval pyrolysis (after Ghori, 2000)

in a region of relatively low heat flow (Appendix). Using this low rate of heat flow as a constant value through time failed to create a maturation profile similar to that in the calibrated Yowalga area, so two models with elevated palaeoheat flows were run. The first model has a heat spike in the Neoproterozoic that is twice the value of the present heat flow of 67 milliwatt per square metre (mW/m^2) and gradually reduces to the present-day heat flow of 33.7 mW/m^2 (Appendix). The second model has a constant moderate heat flow (49 mW/m^2) from the Neoproterozoic to the Early Tertiary (60 Ma) and gradually reduces from that time to the present-day heat flow of 33.7 mW/m^2. Although there is virtually no difference in the present-day maturity levels between the two models, in the high initial heat-flow model the oil window is entered earlier and passed more rapidly than in the second model (Appendix).

The kinetic modelling assumes a source rock identical to that modelled in the Yowalga area (Apak and Moors, 2000b), which is a type II kerogen with a total organic carbon (TOC) of 1%. The generation of petroleum was most significantly influenced by deposition of the McFadden Formation equivalent (Appendix). The lower part of the Neoproterozoic succession (Townsend Quartzite – Lefroy Formation and lowest Browne Formation) entered mid-maturity for oil generation before deposition of the McFadden Formation equivalent, but without substantial generation (Appendix). However, stratigraphically higher units (Hussar and Kanpa Formations) generated the bulk of their petroleum, dominantly oil with some gas, after the loading effect of the McFadden Formation equivalent (Appendix). A small amount of generation also followed the deposition of the Lennis Sandstone, and is relatively more significant in the model that maintained a lower but constant heat flow through to the Tertiary. In comparison to the total petroleum generated, this phase of generation is volumetrically minor. The remainder of the post-Neoproterozoic section is immature for oil and gas generation.

Reservoir potential

The presence of both carbonate and siliciclastic sedimentary rocks in the Officer Basin has produced many opportunities for reservoir development. Potential siliciclastic reservoirs are present in the Lennis Sandstone, McFadden Formation equivalent, Wahlgu and Lefroy Formations, and the Townsend Quartzite, whereas the Steptoe, Kanpa, Hussar, and Browne Formations potentially contain hydrocarbon reservoirs in both quartzose and carbonate lithologies.

In the Yowalga area, the continuous core from GSWA Empress 1 and 1A has allowed detailed measurement of both porosity and permeability of the Neoproterozoic sandstones. Values in excess of 20% porosity and 1 darcy (D) permeability were recorded (Stevens and Apak, 1999, appendix 10). The availability of core data and a full suite of electric logs has enabled the comparison of measured and log-derived porosity and demonstrated that log-derived values are reliable (Stevens and Apak, 1999, plate 1). Most of the carbonate beds are dolomite, although they were originally calcite. There is no porosity associated with the transformation from calcite to dolomite because the replacement is mimetic and complete down to the finest detail. Other opportunities for the creation of porosity exist in the evaporitic facies, where the dissolution of halite or other evaporites may result in leached secondary porosity.

Townsend Quartzite

Because of its diagenetic history due to its low stratigraphic position and consequent deep burial, the Townsend Quartzite is not regarded as a primary reservoir target unless depositional porosity has been preserved.

Lefroy Formation

Apart from an outcrop south of the Musgrave Complex, this formation has only been intersected in the Empress 1A well, where its lithology consists of siltstone and claystone. The Lefroy Formation is not regarded as a reservoir objective.

Browne Formation

The Browne Formation consists primarily of mixed carbonate – siliciclastic strata and a few thin-bedded sandstones. The carbonate is dolomite, which may have mimetically replaced the original calcite down to the finest detail. Most of the carbonate has been deposited in shallow water and subjected to frequent periods of emergence. Unfortunately, all the initial depositional porosity has been occluded at an early stage by cement-grain rims, equant cement-cavity fillings, and anhydrite or halite cements, thus resulting in a tight non-reservoir rock. The porosity is low, with most log-derived values being around 2%. However, log-calculated values up to 15% have been determined for Yowalga 3 (Shell Company of Australia, 1981) and measured porosities of up to 9.5% were recorded from some cores.

The abundance of halite and other evaporite minerals, which are easily dissolved, could result in the development of secondary solution porosity in this formation. Potential exploration targets include unconformity traps with reservoirs enhanced by karstification. Any migration path containing fluids capable of dissolving dolomite, anhydrite, or halite may result in secondary leached porosity. No means of predicting such porosity is known at this time.

Hussar Formation

In wells drilled in the Yowalga area, the Hussar Formation is a mixed siliciclastic – carbonate succession. Because there is more sandstone than carbonate in the formation, sandstone is the main reservoir objective. Although individual sandstone beds are present, they are generally stacked into thicker sandy intervals up to 50 m in thickness. Maximum log porosities of 15–17% were derived for sandstones in Yowalga 3, Kanpa 1A, and Lungkarta 1 (Townson, 1985). Log-derived porosities were similar in the fully cored Empress 1A and reached 20%. Permeabilities were greater than 1 D, but plug and minipermeameter values were approximately 100 millidarcies (md).

The Hussar Formation contains less carbonate than the Browne Formation. In this formation, the carbonate is not present as thick sections, but it contains the same shallow-water to emergent facies, lithotypes, and evaporites as the Browne Formation. Although halite is absent, anhydrite is common. As in the Browne Formation, the carbonate consists of dolomite that has stoichiometrically replaced calcite, with no resultant porosity. Log-derived porosity is approximately 1–2% and has been confirmed by plug measurements. Permeabilities are virtually zero.

The creation of porosity by the dissolution of anhydrite is a possibility, but the most likely areas for such secondary porosity development would be associated with unconformities, where karsting may have taken place.

Kanpa Formation

In the western Officer Basin, the Kanpa Formation has only been completely penetrated in Kanpa 1A and Empress 1A, where it is a mixed siliciclastic – carbonate sequence. In Kanpa 1A, the formation contains 30% carbonate rocks and 28% sandstone, whereas in Empress 1A it contains 37% carbonate rocks and 17% sandstone. Siltstone and claystone make up the remaining lithologies.

As in the older formations, the carbonate is a shallow-water facies with evidence of emergence, desiccation, and erosion. The formation does not contain halite, although anhydritic zones are present. The dolomitization is again stoichiometric, with no porosity formed during the transformation from limestone. During log evaluation, a 6.5 m interval of dolomite with 14.9% porosity was recognized in Lungkarta 1, but typically log porosity is less than 5% (Shell Company of Australia Ltd and Schlumberger, 1985). This low carbonate porosity has been confirmed by plug measurements in Empress 1A. Permeability measurements for plugs in Empress 1A were virtually zero. The carbonate rocks can generally be regarded as non-reservoir rocks; however, substantial leached secondary porosity may be found in unconformity traps.

Within the Kanpa Formation, sandstone is only a small proportion of the formation and is present in thicknesses of less than 10 m. Consequently, it is not an attractive reservoir target. In Empress 1A, log-derived porosities for sandstone reach up to 15% and are supported by plug measurements, although plug permeabilities are only in the order of 1 md.

Steptoe Formation

As with the Kanpa Formation, the Steptoe Formation has only been penetrated in Kanpa 1A and Empress 1 and 1A. In both cases, the formation is truncated by an unconformity. The composition of the full section is unknown, but in these wells the Steptoe Formation is a mixed siliciclastic – carbonate sequence with a basal argillaceous unit overlain by interbedded sandstone and carbonate deposits. In Kanpa 1A, the formation contained 30% sandstone and 39% carbonate rocks, whereas in Empress 1 and 1A it contained more sandstone (40%) than carbonate rocks (28%).

In Kanpa 1A, 128 m of sandstone showing porosity in excess of 15% was recognized from electric logs (Shell Company of Australia Ltd, 1983a,b,c). Appropriate log coverage is absent in Empress 1 and 1A, but a single measured porosity was in excess of 22%, with a permeability of approximately 30 md. Sandstone in the Steptoe Formation is an attractive reservoir target, particulary as it can be reached at depths of less than 600 m in the crests of many anticlinal structures and unconformity traps.

As in the older formations, the carbonates are of shallow-water origin, with evidence of emergence, desiccation, and erosion. The dolomitization is again mimetic, with no porosity formed during the transformation. Only a single plug was cut in the Steptoe Formation carbonate, which gave a low porosity and virtually zero permeability when tested. Numerous permeameter readings indicate a permeability of about 0.1 md. These carbonates are not an exploration target unless secondary porosity, such as that near an unconformity, can be found. Significant vuggy porosity and karsting was observed in Empress 1 and 1A, although in this drillhole all the large karst cavities were filled with sediment from the overlying Wahlgu Formation.

Wahlgu Formation

The Wahlgu Formation consists of a siliciclastic glacigene succession dominated by mass-flow sands. Substantial lithological changes have been observed at various locations, but commonly the dominant lithology is sandy. The 200 m-thick section in Empress 1 and 1A consists mainly of sandstone, with a number of mudstone beds about 5 m thick. Measured core-plug porosity ranges between 10.9 and 32%, with an average for the five values of 23.5%. Permeability ranges between 0.04 and 831 md. Additional minipermeameter values were between 200 and 2000 md (Stevens and Apak, 1999). The formation is much thicker in the Lennis area than in the areas where the formation is known from outcrop or well penetration, and the lithologies of the Wahlgu Formation in the Lennis area could be substantially different from these other areas.

McFadden Formation equivalent

Near the Lennis area, this unit has only been intersected in Kanpa 1A and Lungkarta 1 to the west and the oil-shale bores Mason 2 and NRH 3 to the southeast. From seismic data, this unit has been estimated to reach a thickness of 1200 m (Townson, 1985), so the thin intersections observed in wells may not be representative of the bulk of the formation. In Kanpa 1A, 18.9% log porosity has been calculated for thin sandstone beds within the

McFadden Formation equivalent (Shell Company of Australia Ltd, 1983a,b,c). However, the McFadden Formation equivalent in the Lennis area may contain substantially different lithologies, as may also be the case for the Wahlgu Formation.

Seals

Seals in the Officer Basin need to be considered from a number of perspectives. Local seals can be effective in four-way dip-closed traps or fault-controlled traps and as lateral seals in stratigraphic traps, but regional seals are necessary to control the migration paths of petroleum, especially for long-range migration. The effectiveness of a seal over time is also important, as thermal-maturation modelling shows that a petroleum charge has been available in the Officer Basin since the Neoprotozoic and would need to have been contained for more than 500 million years (see **Petroleum generation**).

Within the Officer Basin, most of the formations contain lithologies that would make effective seals at all scales. All formations contain both carbonate and shale that are suitable for seals. Thinner intervals act as local seals, and thicker packages have a more regional effect.

The carbonate rocks are dolomitic and have no porosity (see **Reservoir potential**). They could form an effective seal, but their brittle nature increases the risk of them losing integrity in a fault trap. Similarly, in a fault-seal trap their brittle nature results in a higher risk of carbonate losing seal potential from the point of view of both cross-fault sealing and fault-plane gouge sealing.

The best shale seals were deposited on flooding surfaces and form the bases of the Kanpa, Hussar, and Steptoe Formations. These shale units reach thicknesses of over 100 m in the Hussar Formation in Kanpa 1A and can be correlated between wells and picked on seismic lines for hundreds of kilometres across the basin and into the Lennis area. These could form effective seals to individual traps, but more importantly they could act as a control on migration paths for fluids migrating updip.

In the Yowalga area, the Browne Formation contains massive units of halite, but individual salinas may have had a more local distribution because not all the salt packages can be correlated between all of the wells. This is probably a depositional constraint rather than a result of salt flow. Based on seismic data, a similar distribution of salt is predicted for the Lennis area. The lateral extent of the salt is adequate for sealing all the structural traps, and such an excellent seal would control petroleum migration paths over a large portion of the region.

Salt walls penetrate from the lower part of the Browne Formation through most of the overlying section, and even reach the surface. Seismic mapping shows that they extend laterally for over 100 km (Plate 1). Salt walls provide effective barriers to petroleum migrating from structural deeps, thus causing a migration shadow updip behind them. The timing of these walls with respect to the generation of petroleum is important.

Traps

Because of the geographic isolation, lack of infrastructure, and harsh climatic conditions, petroleum accumulations within the Officer Basin need to be substantial in order to be commercially viable. The current availability of low-cost alternative gas supplies to the surrounding markets also indicates that oil would be the favoured petroleum product. It was proposed to carry out a study to identify what would be the minimum size of a commercial accumulation. However, the swift obsolescence of a similar study for the South Australian portion of the Officer Basin (Alexander and McDonough, 1997) proved that each company would need to use the currently prevailing parameters in a 'just-in-time' evaluation to reach a meaningful conclusion. Alexander and McDonough (1997) concluded that oil reserves of 20 million barrels would be commercially attractive under their constraints.

The presence of salt within the Officer Basin has resulted in a wide range of possible trapping configurations. Warren (1989) defined 22 possible salt-related trap styles, based on structure and porosity development, or occlusion. Many of these could apply to the Lennis area. In petroleum-rich Oman, the Ara Salt is the principal seal for nearly all of the accumulations, and is considered a critical parameter for petroleum entrapment (Gorin et al., 1982). Salt is expected to have the same significance within the sedimentary section of a similar age in the Officer Basin. Many other conventional structural and stratigraphic plays are also present and provide attractive targets for petroleum exploration.

No effort has been made to quantify the trap sizes within the Lennis area as seismic control is inadequate, but there is the potential for some to be very large. The main play types are summarized in Figure 18 and a brief outline for each type is presented below.

Fault traps

Few faults have been observed in the Lennis area. Although their low frequency can be attributed, at least in part, to the poor seismic control, there appears to have been little extension in this very stable area. With less basin uplift along the northern margin of the Lennis area, the compressive listric, salt-mobilized thrusts that are characteristic of the Yowalga area to the west are not common, but some minor examples of such thrusts may be present, such as on seismic line 80-3B (SP 310) in Figure 13.

Normal faults

Because of the paucity of seismic control, normal faults are drawn with a short lateral extent in the report by Durrant and Associates (1998; Plate 1). Fault orientation cannot be determined from one-line intersections, but has been shown with a northwesterly strike that is parallel to the general structural grain. The size of structures associated with such faults is generally too small to be of commercial interest at present. If proven to have a greater

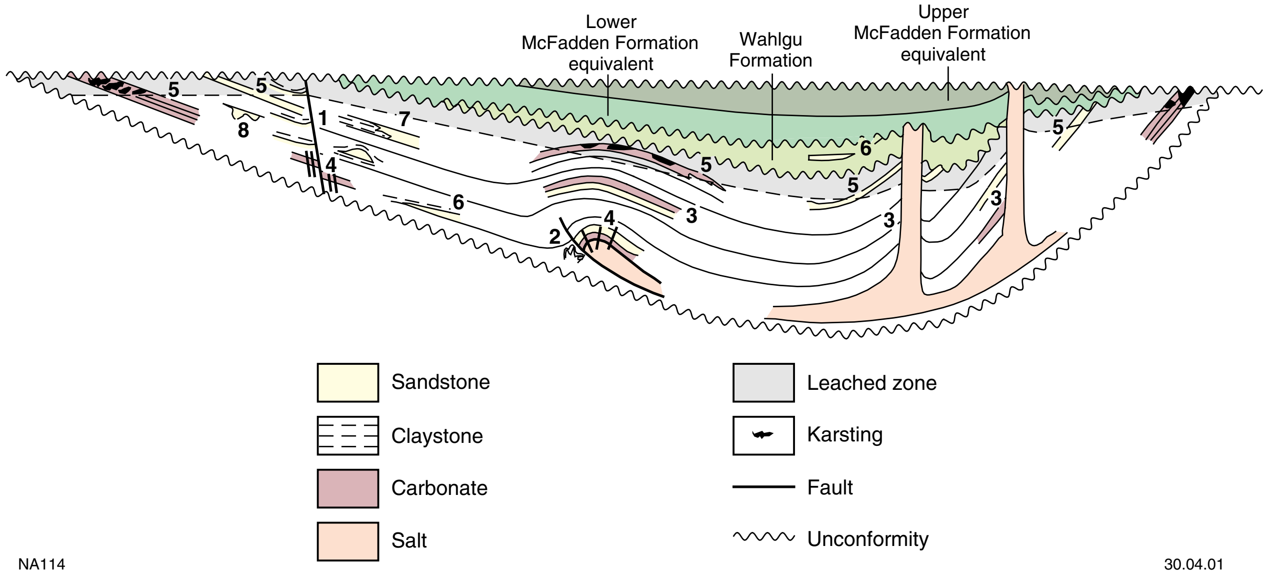


Figure 18. Schematic section of petroleum play types present in the Lennis area: 1) normal fault trap; 2) drape over salt high; 3) lateral salt seal; 4) fractured reservoir; 5) leach-enhanced porosity; 6) pinchout trap; 7) lateral facies change; 8) erosive channel or valley

lateral extent, such structures could be attractive drilling targets even though fault displacement is generally less than 100 m (Top Browne Formation, Fig. 12). With many shale intervals thicker than 100 m in the Hussar Formation, cross-fault sealing would not be a problem. Fault-gouge sealing is also possible, thereby improving sealing quality and also extending the petroleum column. Substantial vertical closure and the possibility of stacked pays may also increase the size of potential normal fault traps. Thick salt beds in the Browne Formation could make excellent seals. Tight dolomite intervals could be effective as cross-fault seals, but their brittleness is more likely to result in a fault-fracture system that would leak.

Fault traps related to the Areyonga Movement have favourable aspects with respect to charge timing, but reactivation of these faults during later tectonic phases could reduce their sealing potential.

Drape folding

Salt movement within the Browne Formation by solution, withdrawal, or injection has resulted in irregularities in the shape of the overlying strata (Plate 1). These gentle folds can be of substantial size (over 250 km^2). The possibility of multiple pays is very likely, but the prospect of tensional crestal faults in the overlying sedimentary beds may be a risk. As much of the salt flow appears to have taken place during the Areyonga Movement, the timing of the formation of such structures is favourable with respect to charge. The salt walls in the north of the study area have been remobilized and penetrate some of the younger strata, but the upper part of overlying strata that were not penetrated should still retain their integrity (e.g. Base McFadden Formation equivalent, Fig. 14).

Lateral salt seals

In the Lennis area, salt injection is shown along the northern edge of seismic control as three salt walls controlled by faulting (Plate 1). The forcible injection of the salt has upturned the adjacent strata, thus creating large structures (over 250 km^2) with considerable relief (over 200 msec). Multiple pays could further enlarge the total trap configuration. Highs abutting the salt make excellent traps. The salt, which is able to maintain its integrity over a long period, is an effective seal. Timing of the diapiric phase with respect to petroleum charge is good, as these structures were available before petroleum expulsion. Figure 10 shows the salt abutment of Supersequence 1 successions between two salt walls.

Fractured reservoirs

In the Zagros Basin in the Middle East, the main control on porosity is fold-related fracturing of carbonates (Beydoun et al., 1992). Without this fracturing, the porosity of the carbonates is typically less than 5% and their permeability is about 1 md. Wells that do not intersect fractures are dry. In the Zagros Basin, reservoir capacity and performance have been sufficiently enhanced by fractures to result in the production of up to 80 000 barrels of oil per day. Similar fracture systems may be present within carbonates in the western Officer Basin because these carbonates are sometimes tightly folded. Fracture zones that have developed during the thrusting associated with these folds are also possible. Although the carbonates here are not as thick as the Asmari Limestone of the Zagros Basin, the possibility of stacked pays increases the potential reserves.

Fracture zones associated with any of the other faults also have the potential to create reservoirs; however, their extent is probably limited.

Stratigraphic traps

Stratigraphic traps may represent significant opportunities for the discovery of petroleum in the Officer Basin. A number of such traps are discussed below.

Unconformity truncations

There are large areas adjacent to salt-injection features (Fig. 10) and along basin margins where the sedimentary successions have been tilted and severely eroded. During erosive periods, a vertical leached profile may develop and result in increased porosity (Fig. 18). Leaching out of the more soluble components such as halite, anhydrite, and carbonate from the sandstone and carbonate, and the development of karst within carbonates, may create extensive porosity. Evaporite cements and nodules are common within all the Supersequence 1 formations. An erosional unconformity also exists between the McFadden Formation equivalent and Wahlgu Formation that could create or enhance porosity in the eroded Wahlgu Formation. Similar erosion of the intra-McFadden Formation equivalent over salt intrusions has also been observed (Fig. 10), which may possibly have had a similar effect.

Another strength of the unconformity play is the fact that unconformities are commonly regional migration paths for fluids being expelled from compacting basins. These fluids could enhance porosity by dissolving soluble components and could also transport petroleum into the newly created trap.

A weakness of unconformity trap configurations below the Wahlgu Formation is that the Wahlgu Formation may be an ineffective seal. The principal lithology is sandstone that, although of glacigene provenance, appears to be an inadequate seal. In Empress 1 and 1A, porosity of the basal sandstone was in excess of 25% and permeabilities ranged between 100 and 1000 md, which would result in an ineffective seal. In the Lennis area, the formation is much thicker and the untested basal strata may make adequate seals. More work needs to be done to establish the distribution of the Wahlgu Formation, but in areas where it is absent, especially over diapiric structures, the McFadden Formation equivalent may provide an adequate seal. In Kanpa 1A, the bottom 29 m of the McFadden Formation equivalent contain porous massive sandstone. The next 70 m above this section contain massive shale that would be an effective seal. The lithology of the McFadden Formation equivalent in the Lennis area is unknown. Seismic control is still inadequate, and our understanding of charge timing, and potential reservoir and seal distribution for this play is uncertain. However, such traps could contain large petroleum accumulations.

Pinchout traps

As the authors' understanding of the evolution of the western Officer Basin has improved from studies in the Yowalga area, it has become clear that differential subsidence has resulted in the depositional pinching out of units within Supersequence 1 (Fig. 18). For example, the bottom two parasequences of the Browne Formation in Yowalga 3 and Kanpa 1A are not present in Empress 1A, and the lowest Steptoe Formation parasequence in Kanpa 1A is absent in Empress 1 and 1A (Apak and Moors, 2000b). Other examples are present in the Wahlgu Formation and McFadden Formation equivalent in the salt rims adjacent to salt walls. Figures 9 and 10 clearly show sedimentary units onlapping against the sides of the salt rims, thus creating numerous potential pinchout traps. The key component for an effective trap of this type is a reservoir pinching out between a top seal and a basal seal. From the point of view of charge, the timing of such traps is excellent, and there is a good chance that such a configuration could be maintained over a long period of time, thus preserving any petroleum accumulation.

Facies changes

An improved understanding of the Neoproterozoic stratigraphy has shown that lateral facies changes are present in the successions (Fig. 18). For example, Apak and Moors (2000b) showed that the dolomitic zone in the H 1 succession present in Kanpa 1A (2260–2400 m) is absent in the equivalent intersection in Empress 1A. In Kanpa 1A, this succession is overlain by shaly strata that would make good top seals. In Empress 1A, the equivalent strata are sandy. Sandy intervals may also terminate against suitable shale or carbonate seals. Deposition of isolated shoreface sands within fine-grained facies such as an offshore bar may also develop into possible stratigraphic traps (Fig. 18). The early timing of such traps is excellent with respect to charge and the stable, low-angled ramp configuration of the area should enable the maintenance of trap integrity over long periods of time.

A possible variant of this type of trap is the occlusion of porosity by evaporites in more marginal settings. There are numerous horizons where halite and anhydrite have been formed in desiccation zones, thus plugging the porosity of the sediments either during or just after deposition. Such traps are also early with respect to charge and could be expected to retain any accumulation over a long period.

Erosive channels or valleys

Frequent emergence is well documented in much of the Supersequence 1 strata, and any channels could later be filled with high-energy, reservoir-quality sediments and sealed by the subsequent transgressive shale (Fig. 18). Again the timing with respect to charge is excellent, and the retention of petroleum in this very stable area is likely to be good.

Prospectivity

The potential for the discovery of substantial petroleum reserves in the western Officer Basin is good. The application of modern depositional, geochemical, and sequence-stratigraphy concepts has refined the prediction of the distribution of the various components required to define petroleum systems that may be present in the Officer Basin. Because there have been so few exploration wells drilled, and they are typically poorly located structurally and commonly have not reached key objectives, the lack of past success is not surprising. However, the minor shows encountered prove that petroleum systems do exist. Key wells, such as the continuously cored Empress 1 and 1A, have provided information previously unavailable from conventional oil exploration. The following comments made on the prospectivity of the Lennis area use the Yowalga area as a model.

The lack of source rocks was seen as a negative factor in earlier assessments of the petroleum potential of the western Officer Basin (Phillips et al., 1985). However, the presence of source rocks has now been confirmed in most of the Supersequence 1 formations (Apak and Moors, 2000b). Although the intervals with identified potential are thin, they prove that favourable conditions for source-rock accumulation were present. The lateral persistence of these intervals indicates that the conditions controlling their deposition were regional, rather than local in character. Greater development of source rocks is possible in untested parts of the basin such as the Lennis area. All of the source rocks are very similar in nature and contain type II kerogen, which has both oil- and gas-generating potential.

Geochemical modelling has suggested that the timing of oil generation was very early, and hence retention of this charge is considered a problem. However, in the Lennis area generation and expulsion probably took place after the main tectonic phases of the Areyonga Movement and Petermann Ranges Orogeny, therefore suitable structures were available to trap the migrating petroleum. Later salt movements have modified some of the halokinetic traps, and there is a suggestion of repeated movements up to the present day. This may have resulted in some petroleum loss, but the salt seal itself may not have been breached. In the basin deep, as represented by the Top Browne to Hussar Formation in the pseudowell location, almost all the petroleum was generated during the Cambrian. In shallower parts of the basin, as represented by the Top Kanpa Formation in the pseudowell location, the later generation phase during deposition of the Carboniferous Lennis Formation could have been significant. Unfortunately, maturation at such shallow depths of burial is not high and only a small portion of the potential source-rock yield has been achieved.

As indicated in the **Petroleum generation** section, the heat flow in the Lennis area, at present and in the past, is poorly constrained. As in the Yowalga area, heat flow is likely to have been variable across the study area. Thus if the temperature reached in the basin was higher than that in the modelled pseudowell location, the amount of petroleum generated would have been larger. However, the timing (dominantly Cambrian with secondary generations during the Carboniferous) would not change, so charge and trap relationship for both structural and stratigraphic traps would remain very favourable.

Although many uncertainties exist, a number of generalizations about petroleum generation for any part of the Lennis area can still be made. For plays in specific areas, models can be proposed with ranges of parameters to define their sensitivities to generation and to select the most favourable traps for testing.

Reservoir presence and quality have not been considered a problem in the Officer Basin. However, by analogy with lithologies found in the Yowalga area, the presence of carbonate rocks as well as siliciclastic units within the sedimentary succession in the Lennis area opens up the possibility of a very large range of porosity types.

Assuming that the formations in the Yowalga area continue throughout the Lennis area, the Townsend Quartzite is not regarded as a reservoir target, since all the sandstone beds appear not to be of reservoir quality. The Lefroy Formation is lacking in sand and hence is not a reservoir target. Sandstone is also thin and uncommon in the Browne Formation, but carbonates and evaporites are present in significant quantities and have some potential for reservoir development. The carbonates have been dolomitized without any porosity formation, but secondary porosity could have developed as a result of fracturing during flexure or by solution during erosion (karsting). The evaporites (halite and sulfates) are prone to solution, which may result in leached porosity. The Browne Formation, where such secondary porosity has developed, is the oldest potential reservoir target.

The Hussar, Kanpa, and Steptoe Formations are predicted to contain sandstone with reservoir potential. The best reservoir-quality sandstone present in the Yowalga area is within the Hussar Formation, which contains stacked beds of sandstone over 50 m thick. In that area, good porosities, and permeabilities in the range of 100 md – 1 D, have been measured. This formation is also expected to be the most sand-prone interval in the Lennis area, but the availability of a sand source for this region has not yet been proven. Carbonate content should be more predictable and these three formations should contain significant carbonate similar to that in the Browne Formation, with minor primary porosity but a potential to develop secondary porosity. In all three formations, multiple pays are likely. In the Yowalga area, the Wahlgu Formation is an entirely siliciclastic sequence containing sandstone units with porosity up to 30% and permeability in excess of 1 D. This unit should be a target in the Lennis area, where the formation is thicker than in the Yowalga area, but where the detailed lithology is unknown. The McFadden Formation equivalent is not well represented in drillholes and to date only thin sandstone beds have been identified. These sandstones have reservoir potential and would be a target in thicker sections, such as in the Lennis area.

Because of their thickness and lithology, seals in the Officer Basin have a high potential for petroleum accumulation and should be present at all stratigraphic levels in the Lennis area. The best seal is salt, which because of its plasticity has excellent retention properties. Substantial thicknesses of salt are present in the Browne Formation, as proven on seismic sections, and salt walls may form lateral seals to substantial structures. Thick shale is present in most supersequence units, and may be over 100 m thick at the base of parasequence sets. These shales would be excellent as both top and lateral seals. In fault traps, these shales have the potential to form fault-gouge or cross-fault seals wherever the fault throw is less than their thickness. Carbonate can be an effective seal, but it is prone to fracturing in structured areas. Salt, shale, and carbonate units have a large lateral extent in the Officer Basin, and also need to be considered as significant controls on the migration of petroleum. Other local seals that could result in petroleum accumulations are diagenetic barriers, dolomitized carbonates, and evaporites.

A wide range of trap configurations is present in the Lennis area, including depositional stratigraphic traps, folds, faults, and unconformity traps. The presence of salt further enhances the potential of the area, as it is associated with large accumulations elsewhere in the world. There have been no valid tests to date in the Lennis area. The ultimate petroleum potential of the Officer Basin is unproven, but it may be very significant.

References

ALEXANDER, E. M., and McDONOUGH, R. C., 1997, Exploration and production economics, *in* The petroleum geology of South Australia, volume 3, Officer Basin *edited by* J. G. G. MORTON and J. F. DREXEL: South Australian Department of Mines and Energy Resources, Report Book 97/19, p. 141–145.

ALSHARAN, A. S., and NAIRN, A. E. M., 1997, Sedimentary basins and petroleum geology of the Middle East: Amsterdam, The Netherlands, Elsevier Science BV, 843p.

APAK, S. N., and MOORS, H. T., 2000a, A sequence stratigraphic model of Neoproterozoic strata, Yowalga area, Officer Basin, Western Australia: APPEA Journal, v. 40 (1), p. 15–25.

APAK, S. N., and MOORS, H. T., 2000b, Basin development and petroleum exploration potential of the Yowalga area, Officer Basin, Western Australia: Western Australia Geological Survey, Report 76, 61p.

APAK, S. N., MOORS, H. T., and STEVENS, M. K., in prep., GSWA Vines 1 well completion report, Waigen area, Officer Basin, Western Australia: Western Australia Geological Survey, Record.

BAGAS, L., GREY, K., HOCKING, R. M., and WILLIAMS, I. R., 1999, Neoproterozoic successions of the northwestern Officer Basin: a reappraisal: Western Australia Geological Survey, Annual Review 1998–99, p. 39–44.

BEARD, J. S., 1974, The vegetation of the Great Victoria Desert, 1:1 000 000 Vegetation Series, Explanatory Notes to Sheet 3, Great Victoria Desert: Perth, University of Western Australia Press.

BEYDOUN, Z. R., HUGHES CLARK, M. W., and STONELEY, R., 1992, Petroleum in the Zagros Basin: a Late Tertiary foreland basin overprinted onto the outer edge of a vast hydrocarbon-rich Palaeozoic–Mesozoic passive-margin shelf: American Association of Petroleum Geologists, Memoir, v. 55, p. 309–340.

BUNTING J. A., JACKSON, M. J., and CHIN R. J., 1978, Throssell, W.A.: Western Australia Geological Survey, 1:250 000 Geological Series Explanatory Notes, 17p.

CARLSEN, G. M., APAK, S. N., GHORI, K. A. R., GREY, K., and STEVENS, M. K., 1999, Petroleum potential of the Neoproterozoic Western Officer Basin, Western Australia, based on a source-rock model from Empress-1A: APPEA Journal, v. 39 (1), p. 322–341.

COCKBAIN, A. E., and HOCKING, R. M., 1989, Revised stratigraphic nomenclature in Western Australian Phanerozoic basins: Western Australia Geological Survey, Record 1989/15, 11p.

COMPSTON, W., 1974, The Table Hill Volcanics of the Officer Basin — Precambrian or Paleozoic?: Geological Society of Australia, Journal, v. 21, p. 403-412.

COTTER, K. L., 1999, Microfossils from Neoproterozoic Supersequence 1 of the Officer Basin, Western Australia: Alcheringa, v. 23, p. 63–86.

DANIELS, J. L., 1970, Bentley, W.A.: Western Australia Geological Survey, 1:250 000 Geological Series Explanatory Notes, 20p.

DANIELS, J. L., 1971, Talbot, W.A.: Western Australia Geological Survey, 1:250 000 Geological Series Explanatory Notes, 28p.

DANIELS, J. L., 1974, The geology of the Blackstone Region, Western Australia: Western Australia Geological Survey, Bulletin 123, 257p.

DURRANT and ASSOCIATES, 1998, Officer Basin regional interpretation project, Lennis and Gibson Sub-Basins: Western Australia Geological Survey, Statutory petroleum exploration report, S31319 A4 (unpublished).

GHORI, K.A. R., 1998a, Petroleum generating potential and thermal history of the Neoproterozoic Officer Basin, *in* The sedimentary basins of Western Australia 2 *edited by* P. G. PURCELL and R. R. PURCELL: Petroleum Exploration Society of Australia; Sedimentary Basins of West Australia Symposium, Perth, W.A., 1998, Proceedings, p. 717–730.

GHORI, K. A. R., 1998b, Petroleum source-rock potential and thermal history of the Officer Basin, Western Australia: Western Australia Geological Survey, Record 1998/3, 52p.

GHORI, K. A. R., 2000, Appendix — Petroleum source-rock potential and maturation history of the Yowalga area, *in* Basin development and petroleum exploration potential of the Yowalga area, Officer Basin, Western Australia, by S. N. APAK and H. T. MOORS: Western Australia Geological Survey, Report 76, 61p.

GORIN, G. E., RACZ, L. G., and WALTER, M. R., 1982, Late PreCambrian–Cambrian sediments of Huqf Group, Sultanate of Oman: American Association of Petroleum Geologists, Bulletin, v. 66, p. 2609–2627.

GREY, K., 1999, Appendix 8 — Proterozoic stromatolite biostratigraphy of Empress 1A, *in* GSWA Empress 1 and 1A well completion report, Yowalga Sub-basin, Officer Basin, Western Australia *compiled by* M. K. STEVENS and S. N. APAK: Western Australia Geological Survey, Record 1999/4, p. 40–44.

GREY, K., APAK, S. N., EYLES, C., EYLES, N., STEVENS, M. K., and CARLSEN, G. M., 1999, Neoproterozoic glacigene successions, western Officer Basin, W.A.: Western Australia Geological Survey, Annual Review 1998–99, p. 74–80.

GREY, K., and COTTER, K. L., 1996, Palynology in the search for Proterozoic hydrocarbons: Western Australia Geological Survey, Annual Review 1995–96, p. 70–80.

GREY, K., and STEVENS, M. K., 1997, Neoproterozoic palynomorphs from the Savory Sub-basin, Western Australia and their relevance to petroleum and mineral exploration: Western Australia Geological Survey, Annual Review 1996–97, p. 49–54.

GREY, K. G., STEVENS, M. K., APAK, S. N., CARLSEN, G. M., and MOORS, H. T., in prep., Stratigraphic revision of Neoproterozoic rocks of the western Officer Basin: Western Australia Geological Survey, Record.

GRIGSON, M. W., 1982, Sedimentology of the Townsend Quartzite, Officer Basin, Western Australia: University of Western Australia, Hons thesis (unpublished).

HILL, A. C., COTTER, K. L., and GREY, K., 2000, Mid-Neoproterozoic biostratigraphy and isotope stratigraphy in Australia: Precambrian Research, v. 100, p. 283–300.

HILL, A. C., and WALTER, M. R., 2000, Mid-Neoproterozoic (~830–750 Ma) isotope stratigraphy of Australia and global correlation: Precambrian Research, v. 100, p. 181–211.

HOCKING, R.M., 1994, Subdivisions of Western Australian Neoproterozoic and Phanerozoic sedimentary basins: Western Australia Geological Survey, Record 1994/4, 83p.

HUNT OIL COMPANY, 1965, Yowalga 1, Lennis 1, Browne 1 and 2 prints: Western Australia Geological Survey, Statutory petroleum exploration report, S234 (unpublished).

JACKSON, M. J., 1976, Browne, W.A.: Australia BMR, 1:250 000 Geological Series Explanatory Notes, 16p.

JACKSON M. J., 1978, Robert, W.A.: Western Australia Geological Survey, 1:250 000 Geological Series Explanatory Notes, 20p.

JACKSON, M. J., and van de GRAAFF, W. J. E., 1981, Geology of the Officer Basin, Western Australia: Australia BMR, Bulletin 206, 102p.

JAPAN NATIONAL OIL CORPORATION, 1997, Geological and geophysical survey in the western Officer Basin, Western Australia — Integrated geological interpretation study: Western Australia Geological Survey, Statutory petroleum exploration report, S10276 (unpublished).

KENNEWELL, P. J., 1977a, Westwood, W.A.: Western Australia Geological Survey, 1:250 000 Geological Series Explanatory Notes, 14p.

KENNEWELL, P. J., 1977b, Yowalga, W.A.: Western Australia Geological Survey, 1:250 000 Geological Series Explanatory Notes, 15p.

KONTOROVICH, A. E., MANDEL 'BAUM, M. M., SURKOV, V. S., TROFIMUK, A. A., and ZOLOTOV, A. N., 1990, Lena-Tunguska Upper Proterozoic–Palaeozoic petroleum superprovince, *in* Classic petroleum provinces *edited by* J. BROOKS: Geological Society of London, Special Publication, no. 50, p. 473–489.

KUZNETSOV, K. G., 1997, Riphean hydrocarbon reservoirs of the Yurubachen–Tokhom zone, Lena-Tunguska province, NE Russia: Journal of Petroleum Geology, v. 20 (4), p. 459–474.

LAMBECK, K., 1984, Structure and evolution of the Amadeus, Officer and Ngalia Basins of central Australia: Australian Journal of Earth Sciences, v. 31, p. 25–48.

MOUSSAVI-HARAMI, R., and GRAVESTOCK, D. I., 1995, Burial history of the eastern Officer Basin, South Australia: APEA Journal, v. 35 (1), p. 307–320.

MYERS, J. S., SHAW, R. D., and TYLER, I. M., 1996, Tectonic evolution of Proterozoic Australia: Tectonics, v. 15, p. 1431–1446.

PERINCEK, D., 1996, The age of Neoproterozoic–Palaeozoic sediments within the Officer Basin of the Centralian Super-Basin can be constrained by major sequence-bounding unconformities: APPEA Journal, v. 36 (1), p. 61–79.

PERINCEK, D., 1997, The stratigraphic and structural development of the Officer Basin, Western Australia — a review: Western Australia Geological Survey, Annual Review 1995–96, p. 135–148.

PERINCEK, D., 1998, A compilation and review of data pertaining to the hydrocarbon prospectivity of the Officer Basin: Western Australia Geological Survey, Record 1997/6, 209p.

PHILLIPS, B. J., JAMES, A. W., and PHILIP, G. M., 1985, The geology and hydrocarbon potential of the northwestern Officer Basin: APEA Journal, v. 25 (1), p. 52–61.

PREISS, W. V., WALTER, M. W., COATS, R. P., and WELLS, A. T., 1978, Lithological correlations of Adelaidean glaciogenic rocks in parts of the Amadeus, Ngalia, and Georgina Basins: Australia BMR, Journal of Australian Geology and Geophysics, v. 3, p. 45–53.

SHELL COMPANY OF AUSTRALIA, LTD, 1981, Yowalga 3 well completion report: Western Australia Geological Survey, Statutory petroleum exploration report, W1709 A5/V1, V2 (unpublished).

SHELL COMPANY OF AUSTRALIA LTD, 1983a, Kanpa 1/1A well completion report: Western Australia Geological Survey, Statutory petroleum exploration report, W2281 V1/A2/V1 (unpublished).

SHELL COMPANY OF AUSTRALIA LTD, 1983b, Kanpa 1/1A well completion report: Western Australia Geological Survey, Statutory petroleum exploration report, W2281 V1/A2/V2 (unpublished).

SHELL COMPANY OF AUSTRALIA LTD, 1983c, Kanpa 1/1A well completion report (Officer Basin, EP 178): Western Australia Geological Survey, Statutory petroleum exploration report, W2281 V1/A2/V3 (unpublished).

SHELL COMPANY OF AUSTRALIA LTD and SCHLUMBERGER, 1985, Lungkarta 1 and Lungkarta 1, Sidetrack 1 well completion report (enclosures): Western Australia Geological Survey, Statutory petroleum exploration report, W2667 A4/V1 (unpublished).

SHEVCHENKO, S. I., and IASKY, R. P., 1997, Calculating depth to basement from magnetic and gravity data, with an example from the western Officer Basin: Western Australia Geological Survey, Annual Review 1996–97, p. 69–75.

STEVENS, M. K., and ADAMIDES, S. N., 1998, GSWA Trainor 1 well completion report, Savory Sub-basin, Officer Basin, Western Australia, with notes on petroleum and mineral potential: Western Australia Geological Survey, Record 1996/12, 69p.

STEVENS, M. K., and APAK, S. N., 1999, GSWA Empress 1 and 1A well completion report, Yowalga Sub-basin, Officer Basin, Western Australia: Western Australia Geological Survey, Record 1999/4, 110p.

STEVENS, M. K., and CARLSEN, G. M., 1998, A review of data pertaining to the hydrocarbon prospectivity of the Savory Sub-basin, Officer Basin, Western Australia: Western Australia Geological Survey, Record 1998/5, 65p.

TOWNSON, W. G., 1985, The subsurface geology of the western Officer Basin—results of Shell's 1980–1984 petroleum exploration campaign: APEA Journal, v. 25 (1), p. 34–51.

VAN WAGONER, J. C., MITCHUM, R. M., CAMPION, K. M., and RAHMANIAN, V. D., 1990, Siliciclastic sequence stratigraphy in well logs, cores, and outcrops: AAPG Methods in Exploration Series, no. 7, 55p.

WALTER, M. R., and GORTER, J., 1994, The Neoproterozoic Centralian Superbasin in Western Australia: the Savory and Officer Basins, *in* The sedimentary basins of Western Australia *edited by* P. G. PURCELL and R. R. PURCELL: Petroleum Exploration Society of Australia; Sedimentary Basins of West Australia Symposium, Perth, W.A., 1994, Proceedings, p. 851–864.

WALTER, M. R., KRYLOV, I. N., and PREISS, W. V., 1979, Stromatolites from Adelaidean (Late Proterozoic) sequences in central and South Australia: Alcheringa, v. 3, p. 287–305.

WARREN, J. K., 1989, Evaporite sedimentology — its importance in hydrocarbon accumulations: Englewood Cliffs, New Jersey, Prentice-Hall Scientific Publications, 285p.

WATTS, K. J., 1982, The geology of the Townsend Quartzite — Upper Proterozoic shallow water deposit of the northern Officer Basin, Western Australia: University of Western Australia, Hons thesis (unpublished).

WILLIAMS, I. R., 1992, Geology of the Savory Basin, Western Australia: Western Australia Geological Survey, Bulletin 141, 115p.

WILLIAMS, I. R., 1994, The Neoproterozoic Savory Basin, Western Australia, *in* The sedimentary basins of Western Australia *edited by* P. G. PURCELL and R. R. PURCELL: Petroleum Exploration Society of Australia; Sedimentary Basins of West Australia Symposium, Perth, W.A.,1994, p. 841–850.

ZHAO, J.-X., McCULLOCH, M. T., and KORSCH, R. J., 1994, Characterisation of a plume-related ~800 Ma magmatic event and its implications for basin formation in central-southern Australia: Earth and Planetary Science Letters, v. 121, p. 349–367.

Appendix

Thermal history of the Lennis area

(by K. A. R. Ghori)

Introduction

The only well drilled in the Lennis area (Lennis 1) was terminated in the Table Hill Volcanics at a total depth of 614.5 m and therefore no direct subsurface information on Neoproterozoic rocks is available for this part of the Officer Basin. It is critical for the prospectivity of this area to estimate its thermal history during the Neoproterozoic. A location in the deepest part of the geological section was selected from the available seismic data for this study.

For this modelling it was assumed that the geological evolution of the Lennis and Yowalga areas was similar and that subsurface information available from the Yowalga area (Ghori, 2000) can be used to model the thermal and hydrocarbon-generation history of the Lennis area.

The geographic location of the pseudowell used in this study is latitude 27°01'08"S and longitude 126°44'06"E, corresponding to shotpoint 4500 on seismic line T82-138. Software version 7.06 of BasinMod 1-D (Platte River Associates) was used to model the timing of petroleum generation in the area.

Basin modelling

Basin modelling is a very powerful tool used to test and analyse various geological concepts for an unexplored area. A one-dimensional burial history was reconstructed from the stratigraphic thicknesses of the formations as estimated from seismic section T82-138, and their lithology as encountered in Empress 1 and 1A, Kanpa 1A, Lungkarta 1, and Yowalga 3. The thermal history was reconstructed using estimated heat flow and erosional history, and by adjusting thermal conductivities and transient heat flow to constrain the maturity model against the measured maturity of the Yowalga area. The bottom-hole temperatures, equivalent vitrinite reflectance (%Ro), Rock-Eval parameter T_{max}, and information from apatite fission-track analysis from the Yowalga area were used to constrain the present-day temperatures and palaeo-temperatures.

For the pseudowell, four alternative models were developed because the present-day maturity of the formations is higher than expected for their current depth of burial. Their higher degree of maturity may be due to either a higher palaeoheat flow or to deeper burial. In the first two models, higher palaeoheat flow was used to constrain the models, whereas in the third and fourth models deeper burial and erosion were used to constrain the models, while keeping the heat flow constant.

To constrain the first model, a high heat-flow value of 67 milliwatts per square metre (mW/m^2) was required for the base of the section at 840 Ma. The heat flow was then reduced at a constant rate to the level of the present-day heat flow of 33.7 mW/m^2. Figures A1a and A2a illustrate the calibration of measured versus calculated temperature and maturity for this model respectively. For the second model, a constant heat flow of 49 mW/m^2 was used for the section from 840 to 60 Ma (early Tertiary), and then the heat flow was reduced at a constant rate to the level of the present-day heat flow of 33.7 mW/m^2. Figures A1b and A2b illustrate the calibration of measured versus calculated temperature and maturity for this model respectively.

For the third and fourth models, a constant present-day heat-flow value of 36.3 mW/m^2 was used, with two different scenarios for the erosional history. To constrain the third model, a 1400 m-thick section was eroded during the Alice Springs Orogeny. Figures A1c and A2c illustrate the calibration of measured versus calculated temperature and maturity respectively, assuming that major erosion occurred during the Alice Springs Orogeny. In the fourth model, a 1050 m-thick section was eroded during the Late Jurassic break-up orogeny. Figures A1d and A2d illustrate the calibration of measured versus calculated temperature and maturity respectively, assuming that major erosion occurred during the Late Jurassic break-up orogeny.

Figure A3 illustrates the burial and maturation histories of the above models based on: a) high heat flow at 840 Ma; b) high heat flow up to the early Tertiary; c) major erosion during the Alice Springs Orogeny; and d) major erosion during the Late Jurassic break-up orogeny. Table A1 summarizes the time-stratigraphy used in developing these models.

Finally, the maturity models were used to perform kinetic modelling of petroleum generation as a function of geothermal history, and type and amount of kerogen to determine the timing of hydrocarbon generation, using

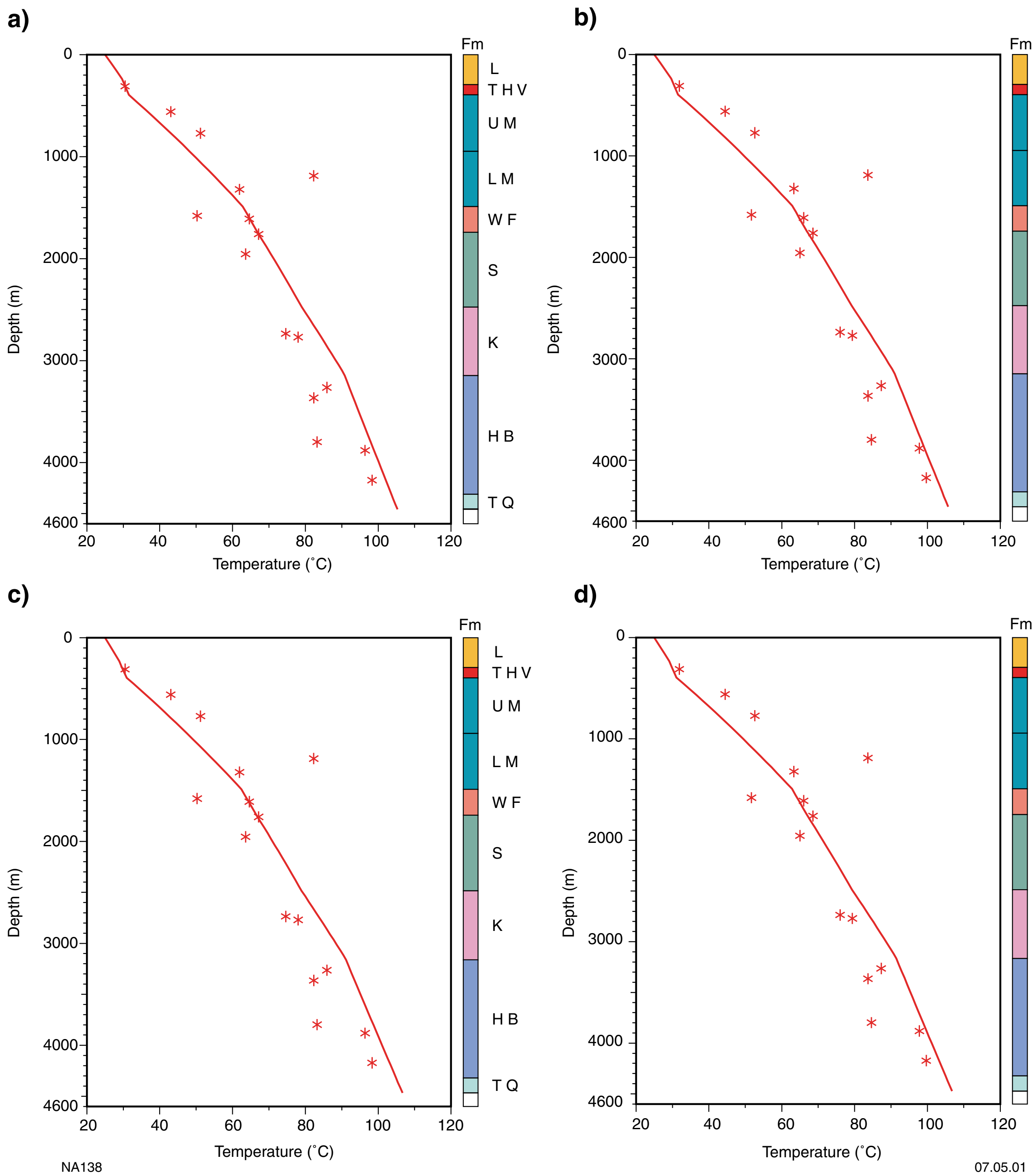


Figure A1. Calibration of measured versus calculated temperatures based on: a) high palaeoheat flow at 840 Ma; b) high palaeoheat flow during 840–60 Ma; c) major erosion during the Alice Springs Orogeny; d) major erosion during the Late Jurassic break-up orogeny. The sedimentary sequences indicated on these figures are the Lennis Sandstone (L), Table Hill Volcanics (THV), Upper McFadden Formation equivalent (UM), Lower McFadden Formation equivalent (LM), Wahlgu Formation (WF), Steptoe Formation (S), Kanpa Formation (K), Hussar and Browne Formations (HB), and the Townsend Quartzite (TQ)

one-percent organic richness of type II kerogen. Figures A4, A5, and A6 are plots of hydrocarbon-generation rate versus time at the top of the Browne and Hussar, Kanpa, and Steptoe Formations respectively. In these figures, different scales for hydrocarbon-generation rate were required to illustrate the generation rate reached in the various formations at the modelled location.

Discussion

The burial, thermal, and erosional histories of the Lennis area are poorly understood because no direct information on the Neoproterozoic rocks is available. Basin modelling has been applied to analyse the deepest Neoproterozoic sequence in the Lennis area as interpreted from the

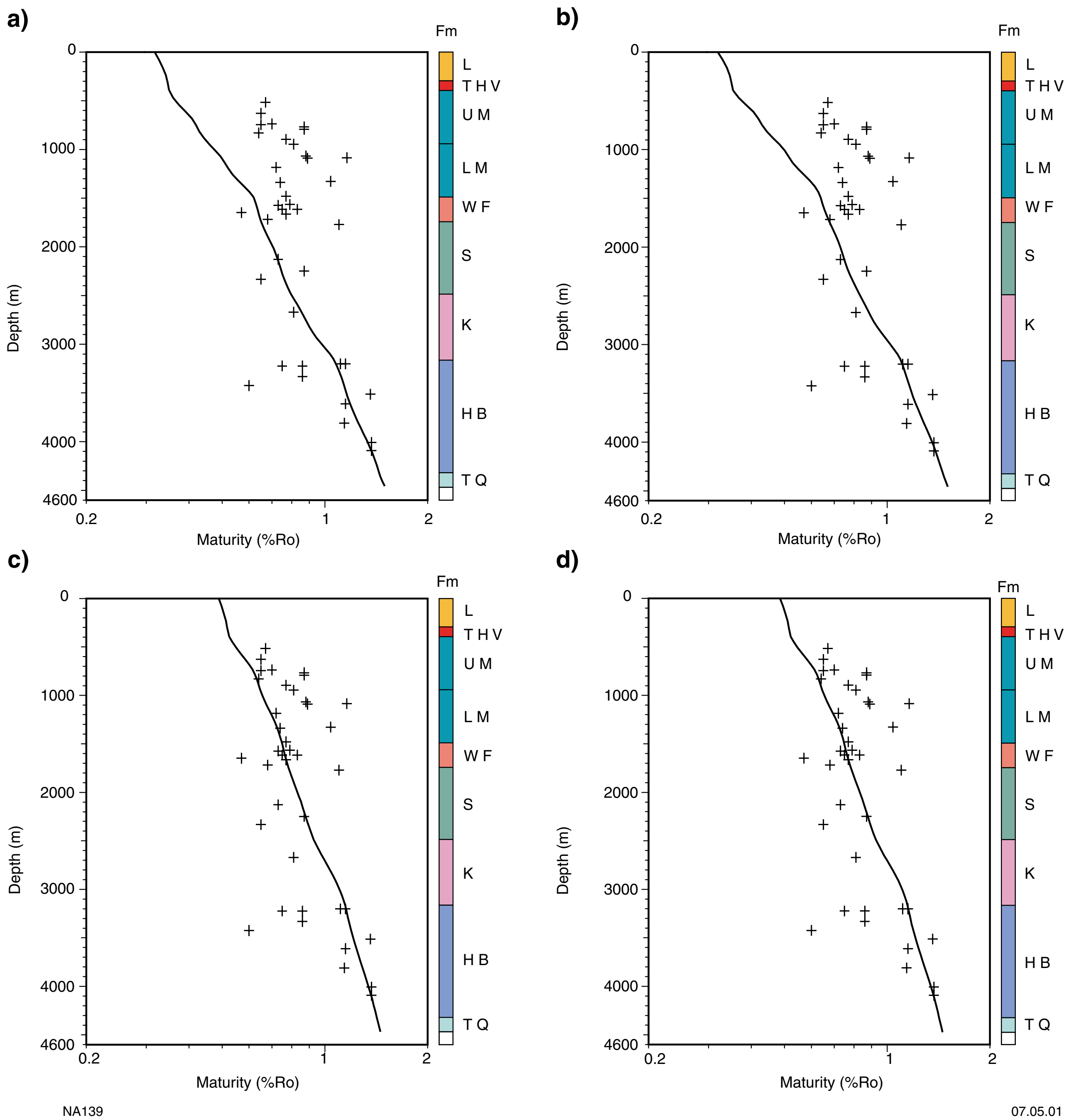


Figure A2. Calibration of measured versus calculated maturity based on: a) high palaeoheat flow at 840 Ma; b) high palaeoheat flow during 840–60 Ma; c) major erosion during the Alice Springs Orogeny; d) major erosion during the Late Jurassic break-up orogeny. The sedimentary sequences indicated on these figures are the Lennis Sandstone (L), Table Hill Volcanics (THV), Upper McFadden Formation equivalent (UM), Lower McFadden Formation equivalent (LM), Wahlgu Formation (WF), Steptoe Formation (S), Kanpa Formation (K), Hussar and Browne Formations (HB), and the Townsend Quartzite (TQ)

available seismic data. Four maturation and hydrocarbon generation models were developed to analyse different geological scenarios for the evolution of the Officer Basin.

In the geological section modelled, it is inferred that there was no significant erosion and that the higher than expected maturity is mainly due to high heat flow. The first two models developed are based on different heat-flow histories. Because the geological history of the area is poorly understood and other explanations for the higher maturity could include deeper burial than is evident at present, two other models based on deeper burial were also developed.

The optimization of calculated versus measured temperature is similar for the various models based on different heat flows and erosional histories (Fig. A1). However, the models based on deeper burial and erosion

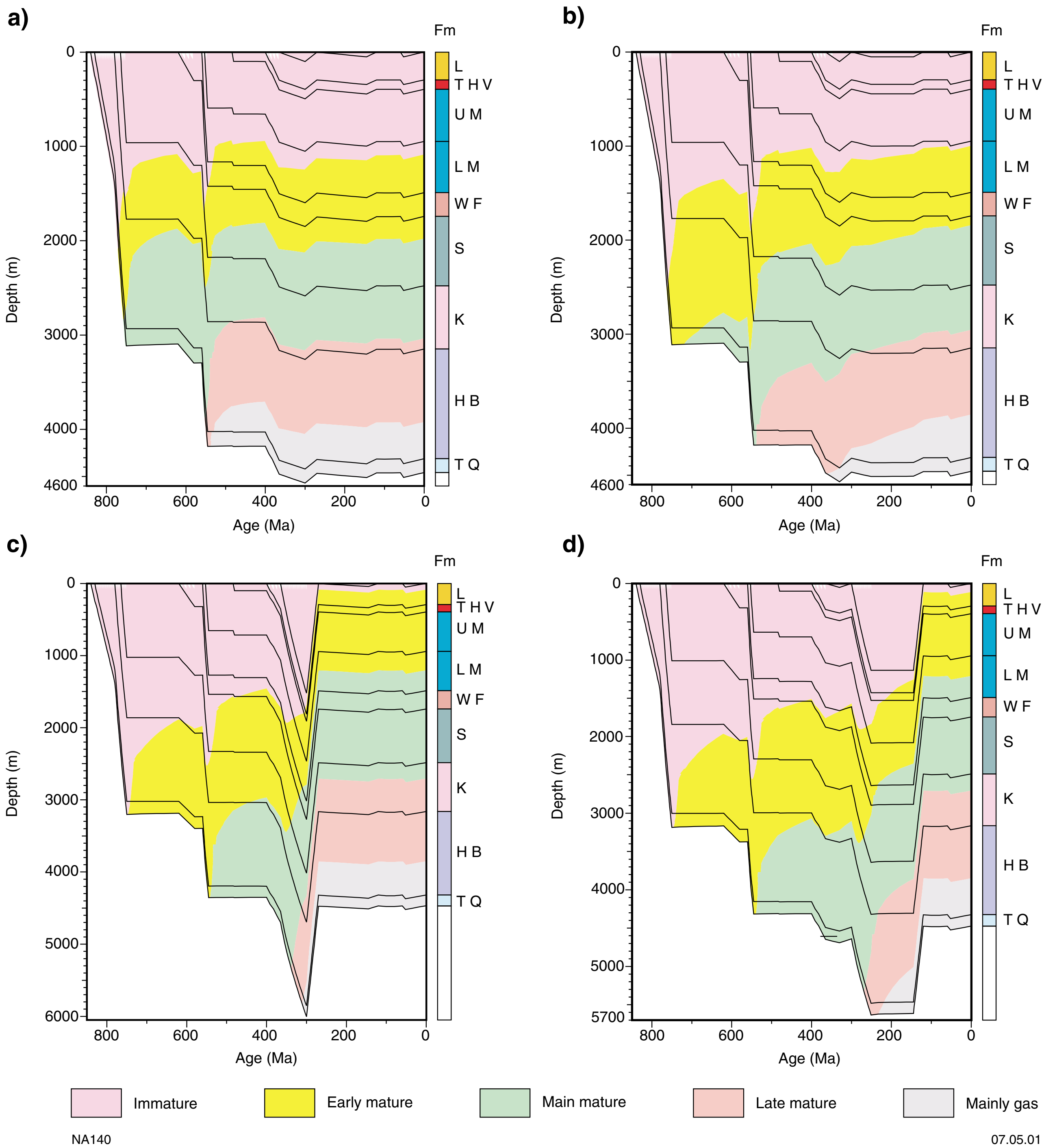


Figure A3. Burial and maturation histories for models based on: a) high palaeoheat flow at 840 Ma; b) high palaeoheat flow during 840–60 Ma; c) major erosion during the Alice Springs Orogeny; d) major erosion during the Late Jurassic break-up orogeny. The sedimentary sequences indicated on these figures are the Lennis Sandstone (L), Table Hill Volcanics (THV), Upper McFadden Formation equivalent (UM), Lower McFadden Formation equivalent (LM), Wahlgu Formation (WF), Steptoe Formation (S), Kanpa Formation (K), Hussar and Browne Formations (HB), and the Townsend Quartzite (TQ)

provide a better fit between calculated and measured maturity (Figs A2c and d) when compared with the models based on higher heat flow (Figs A2a and b). The relatively high maturity measurements at shallow depths are mostly from Neoproterozoic rocks in Empress 1 and 1A, and Lungkarta 1. During optimization, a better fit was obtained for calculated maturity with the maturity measured in Kanpa 1A and Yowalga 3. This is due to the fact that the geology of the model location appears to be similar to that of the Kanpa 1A and Yowalga 3 locations.

The maturation history varies with changes in palaeoheat flow and erosional history, as illustrated in Figure A3. If a high palaeoheat flow was the main reason

Table A1. Time-stratigraphy used in maturity models

Formation or event	Base age (Ma)	Formation top (m)	Formation thickness (m)	Missing thickness (m) Model 1	Model 2	Model 3	Model 4
Tertiary unconformity	52	–	–	50	50	50	50
Cretaceous	120	absent	–	–	–	–	–
Mesozoic unconformity	145	–	–	50	50	50	1050
Paterson Formation	300	absent	–	–	–	–	–
Alice Springs Orogeny	365	–	–	50	50	1400	50
Lennis Sandstone	400	0	293	–	–	–	–
Rodingan Movement	480	nd	–	–	–	–	–
Table Hill Volcanics	484	293	100	–	–	–	–
Delamerian Orogeny	545	nd	–	–	–	–	–
Upper McFadden Formation equivalent	553	393	552	–	–	–	–
Lower McFadden Formation equivalent	560	945	535	–	–	–	–
Petermann Ranges Orogeny	580	nd	–	–	–	–	–
Wahlgu Formation	620	1480	248	–	–	–	–
Areyonga Movement	750	nd	–	–	–	–	–
Steptoe Formation	765	1728	719	–	–	–	–
Kanpa Formation	780	2447	661	–	–	–	–
Browne–Hussar Formations	830	3108	1142	–	–	–	–
Townsend Quartzite	840	4250	150	–	–	–	–

NOTE: nd no deposition

for the higher than expected present-day maturity, then the rocks matured at an early stage of the basin's evolution, and if the heat flow was very high then they matured at the start of deposition. At present, the maturity of the Browne and Hussar Formations ranges from over mature to late mature for oil, the Kanpa Formation ranges from late mature to main mature, and the Steptoe Formation ranges from main mature to early mature (Figs A3a and b).

Alternatively, if palaeoburial was the main reason for the present-day higher than expected maturity, then the timing of maturation depends on the timing of burial and erosion. The models based on the two erosional scenarios suggest that the Neoproterozoic rocks matured at later stages of the basin's evolution compared to the models based on the high heat flow, and much later if the major erosion was during the Late Jurassic break-up orogeny. At present, the maturity of the Browne and Hussar Formations ranges from over mature to late mature for oil generation, the Kanpa Formation ranges from late mature to main mature, and the Steptoe Formation is at the main mature stage for oil generation (Figs A3c and d).

The emphasis of this study was to determine the timing of hydrocarbon generation and how sensitive the modelling is to variations in thermal and erosional history. The high palaeoheat-flow models suggest that the rate of hydrocarbon generation peaked during the Cambrian for the top of the Browne and Hussar Formations (Figs A4a and b) and the Kanpa Formation (Figs A5a and b). As the estimated thickness of the Browne and Hussar Formations is 1142 m, and the base of the Browne Formation is over mature for oil generation, the generation rate must have peaked during the Neoproterozoic for the base of the Browne Formation. The top of the Steptoe Formation is at an early mature stage, and consequently the rate of hydrocarbon generation has been very low for this formation (Figs A6a and b).

Models with a deeper palaeoburial suggest that the rate of hydrocarbon generation peaked during the Carboniferous for the top of the Browne and Hussar (Fig. A4c), Kanpa (Fig. A5c), and Steptoe (Fig. A6c) Formations if the major erosion was during the Alice Springs Orogeny. If the major erosion was during the Late Jurassic break-up orogeny, then peak generation would have been during the Permian (Figs A4d, 5d, and 6d).

The modelling clearly demonstrates that the timing and level of hydrocarbon generation attained in the Browne and Hussar, Kanpa, and Steptoe Formations changes with predicted variations in the poorly understood thermal and burial history of the Lennis area. The hydrocarbon-generation history of the Officer Basin has been affected by its burial and erosional histories, which were interrupted by at least seven unconformities. The base of the Browne Formation was deeply buried and attained optimum maturity for hydrocarbon generation during the early stages of evolution of the basin, when most of the generative potential of the base of the formation was exhausted. The timing of hydrocarbon generation for the younger Hussar, Kanpa, and Steptoe Formations could be during the Palaeozoic to Mesozoic, but it is not possible to be more specific due to poorly constrained model parameters such as palaeoheat flow and major erosional events.

Conclusions

Hydrocarbon-generation modelling of the Lennis area is based on variations in the amount and timing of heat flow, burial, uplift, and erosion. The models suggest that:

- If the higher than expected maturity of formations in the Lennis area is due mainly to high heat flow rather than deep burial, then the rate of hydrocarbon

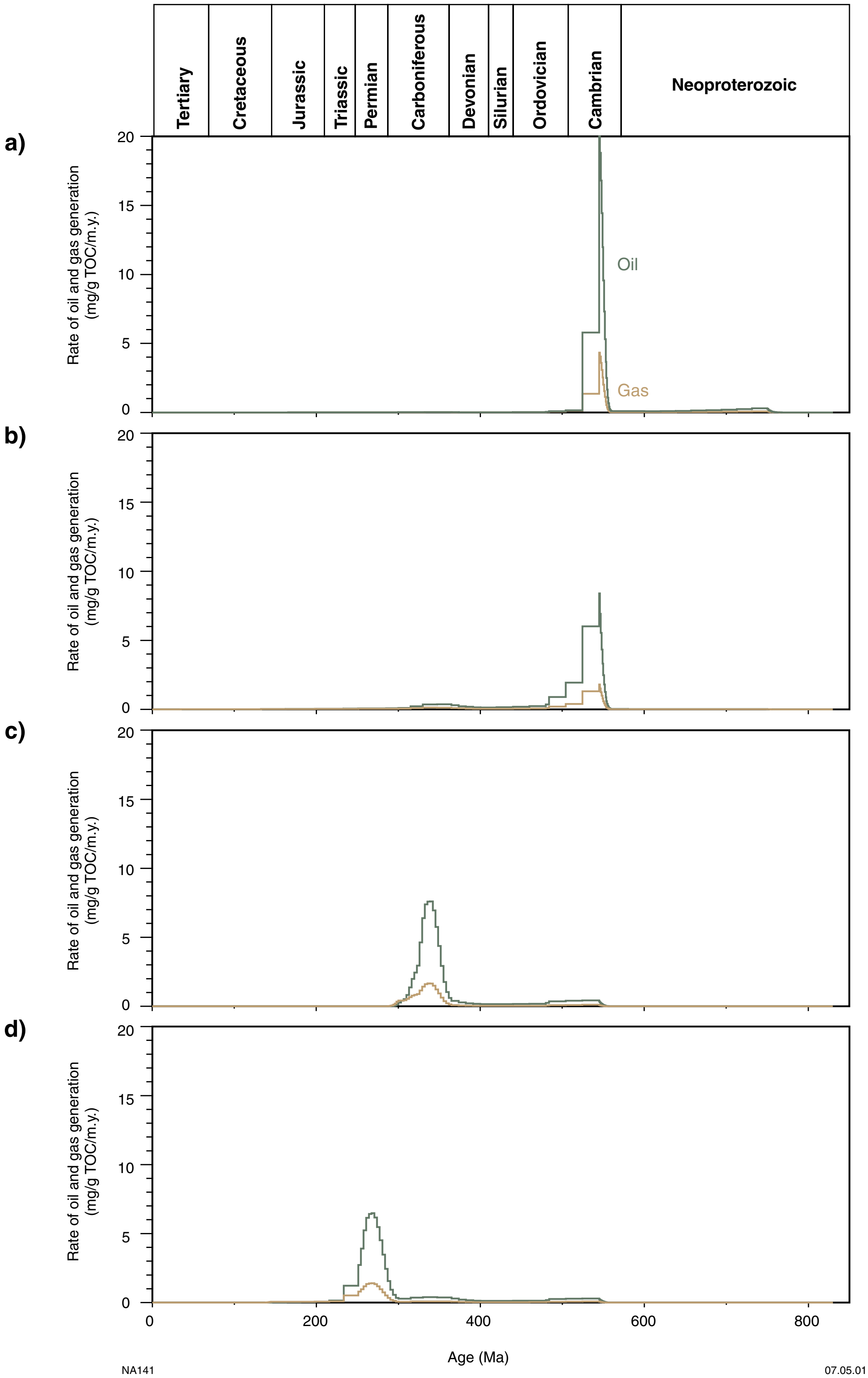


Figure A4. Rate of hydrocarbon generation for the top of the Browne and Hussar Formations for models based on: a) high palaeoheat flow at 840 Ma; b) high palaeoheat flow during 840–60 Ma; c) major erosion during the Alice Springs Orogeny; d) major erosion during the Late Jurassic break-up orogeny

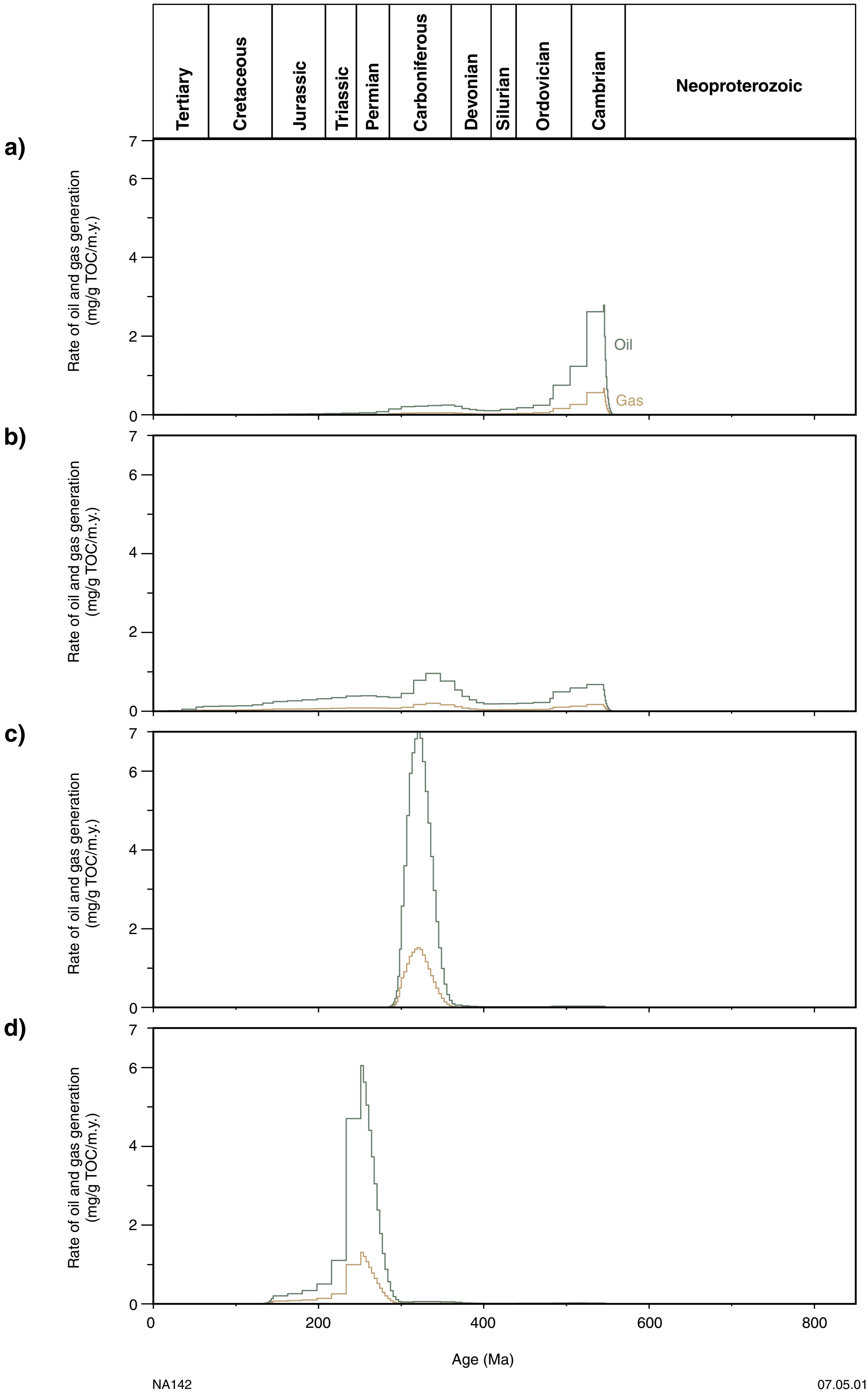


Figure A5. Rate of hydrocarbon generation for the top of Kanpa Formation for models based on: a) high palaeoheat flow at 840 Ma; b) high palaeoheat flow during 840–60 Ma; c) major erosion during the Alice Springs Orogeny; d) major erosion during the Late Jurassic break-up orogeny

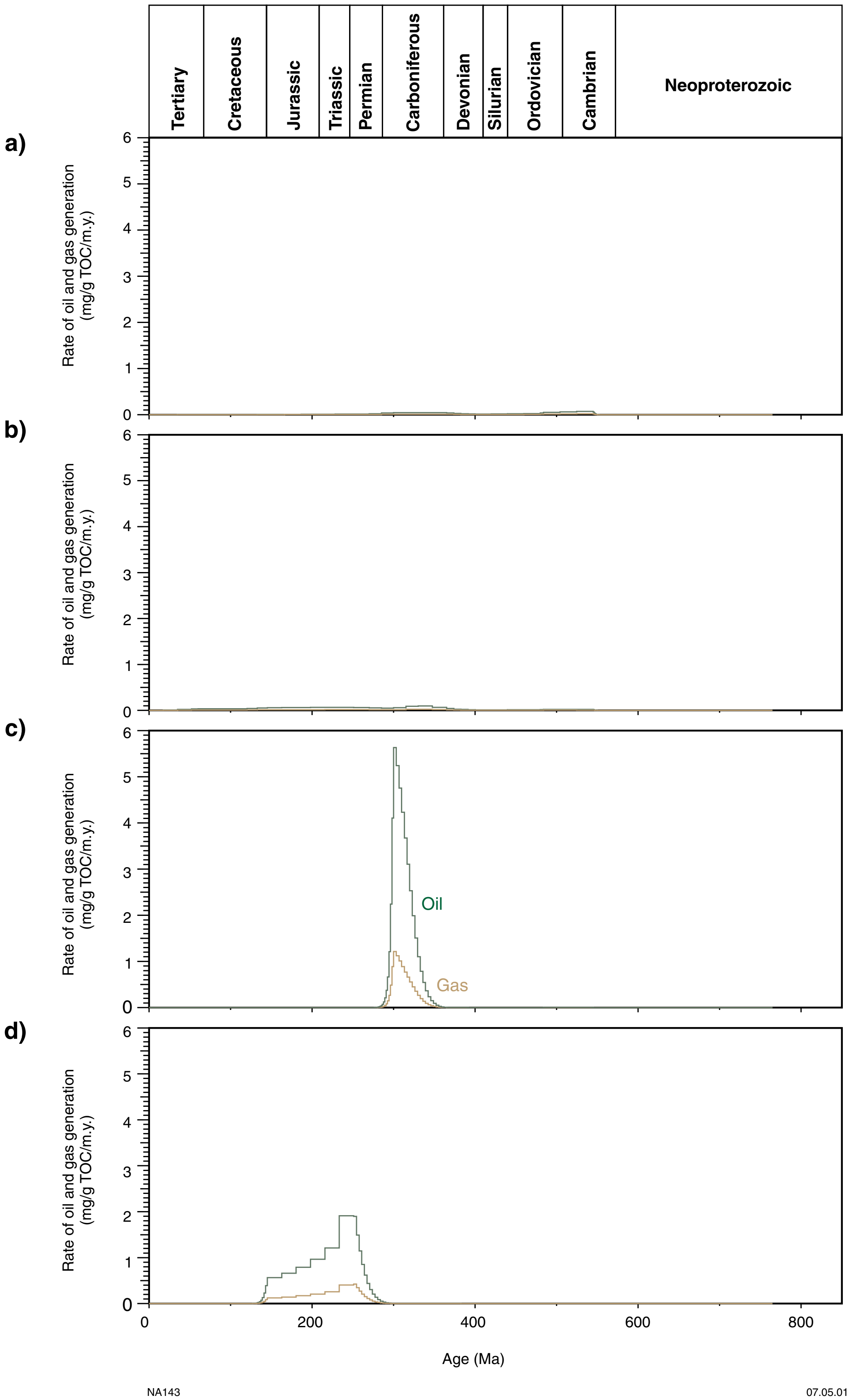


Figure A6. Rate of hydrocarbon generation for the top of Steptoe Formation for models based on: a) high palaeoheat flow at 840 Ma; b) high palaeoheat flow during 840–60 Ma; c) major erosion during the Alice Springs Orogeny; d) major erosion during the Late Jurassic break-up orogeny

generation peaked during the Cambrian for the top of the Browne and Hussar Formations, and the Kanpa Formation. Currently, the basal part of the Browne Formation would be over mature for oil generation and the top of Steptoe Formation is at an early mature stage.

- If the higher degree of maturity is due to deeper than expected burial, then the rate of hydrocarbon generation peaked during the Carboniferous or Permian for the top of the Browne and Hussar Formations, the Kanpa Formation, and the Steptoe Formation. The timing would have depended on whether major erosion occurred during the Alice Springs Orogeny or the Late Jurassic break-up orogeny.
- The modelling predicts that the Browne and Hussar Formations, the Kanpa Formation, and the Steptoe Formation are presently within the oil window and provides encouragement for further exploration.

References

COOK, A. C., 1995, Report on source rock type, maturation levels, thermal history and hydrocarbon occurrence in suites of samples from four wells in the Officer Basin, W.A.: Western Australia Geological Survey, Statutory petroleum exploration report, S31319 A1, (unpublished).

GHORI, K. A. R., 1998a, Petroleum generating potential and thermal history of the Neoproterozoic Officer Basin, *in* The sedimentary basins of Western Australia 2 *edited by* P. G. PURCELL and R. R. PURCELL: Proceeding of West Australian Basins Symposium, Perth, Western Australia, 1998, p. 717–730.

GHORI, K. A. R., 1998b, Petroleum source-rock potential and thermal history of the Officer Basin, Western Australia: Western Australia Geological Survey, Record 1998/3, 52p.

GHORI, K. A. R., 1999, Appendix 9 — Geochemistry, *in* GSWA Empress 1 and 1A well completion report, Yowalga Sub-basin, Officer Basin, Western Australia *compiled by* M. K. STEVENS and S. N. APAK: Western Australia Geological Survey, Record 1999/4, 110p.

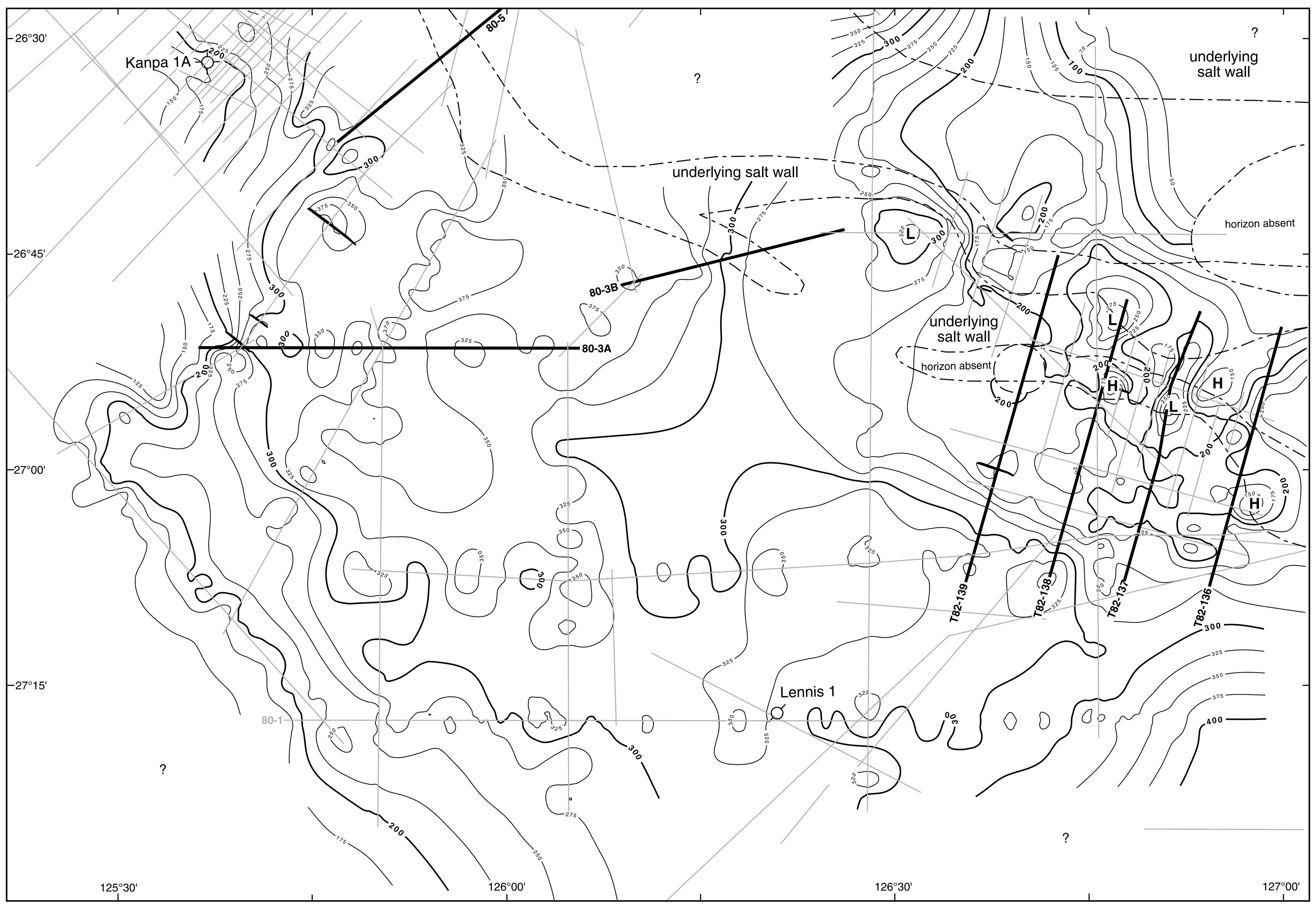
GHORI, K. A. R., 2000, Appendix — Petroleum source-rock potential and maturation history of the Yowalga area, *in* Basin development and petroleum exploration potential of the Yowalga area, Officer Basin, Western Australia *by* S. N. APAK and H. T. MOORS: Western Australia Geological Survey, Report 76, p. 49–61.

HEGARTY, K. A., O'BRIEN, C., and WATSON, P. G. F., 1988, Thermal history reconstruction for the Empress 1A well (Officer Basin) using apatite fission track analysis and reflectance: Western Australia Geological Survey, Statutory petroleum exploration report, S20424 A2 (unpublished).

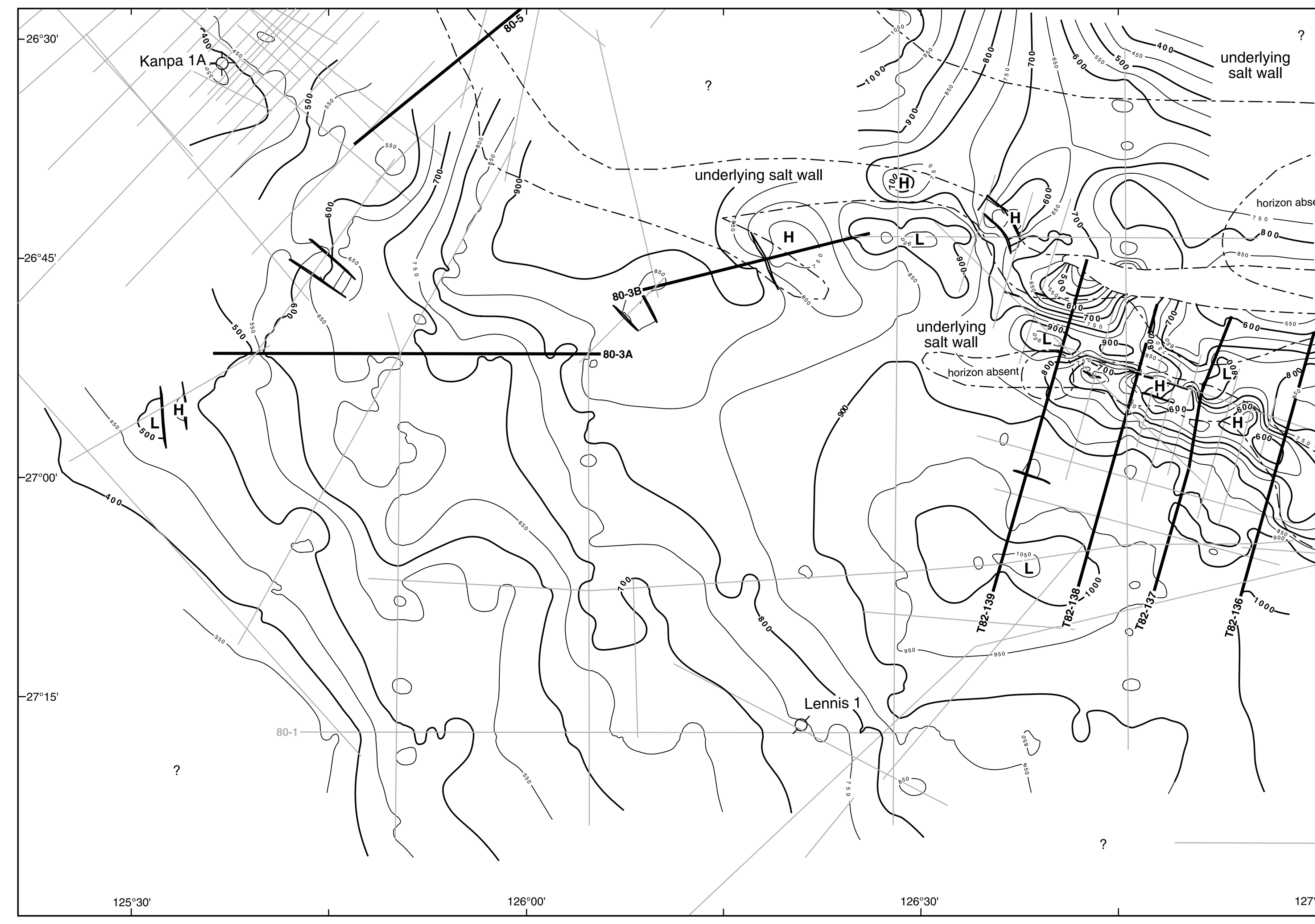
LARTER, S.R., 1985, Integrated kerogen typing and quantitative assessment of petroleum source rocks, *in* Petroleum geochemistry in exploration of the Norwegian Shelf *edited by* B. M. THOMAS: London, Norwegian Petroleum Society, p. 269–286.

PERINCEK, D., 1998, A compilation and review of data pertaining to the hydrocarbon prospectivity of the Officer Basin: Western Australia Geological Survey, Record 1997/6, 209p.

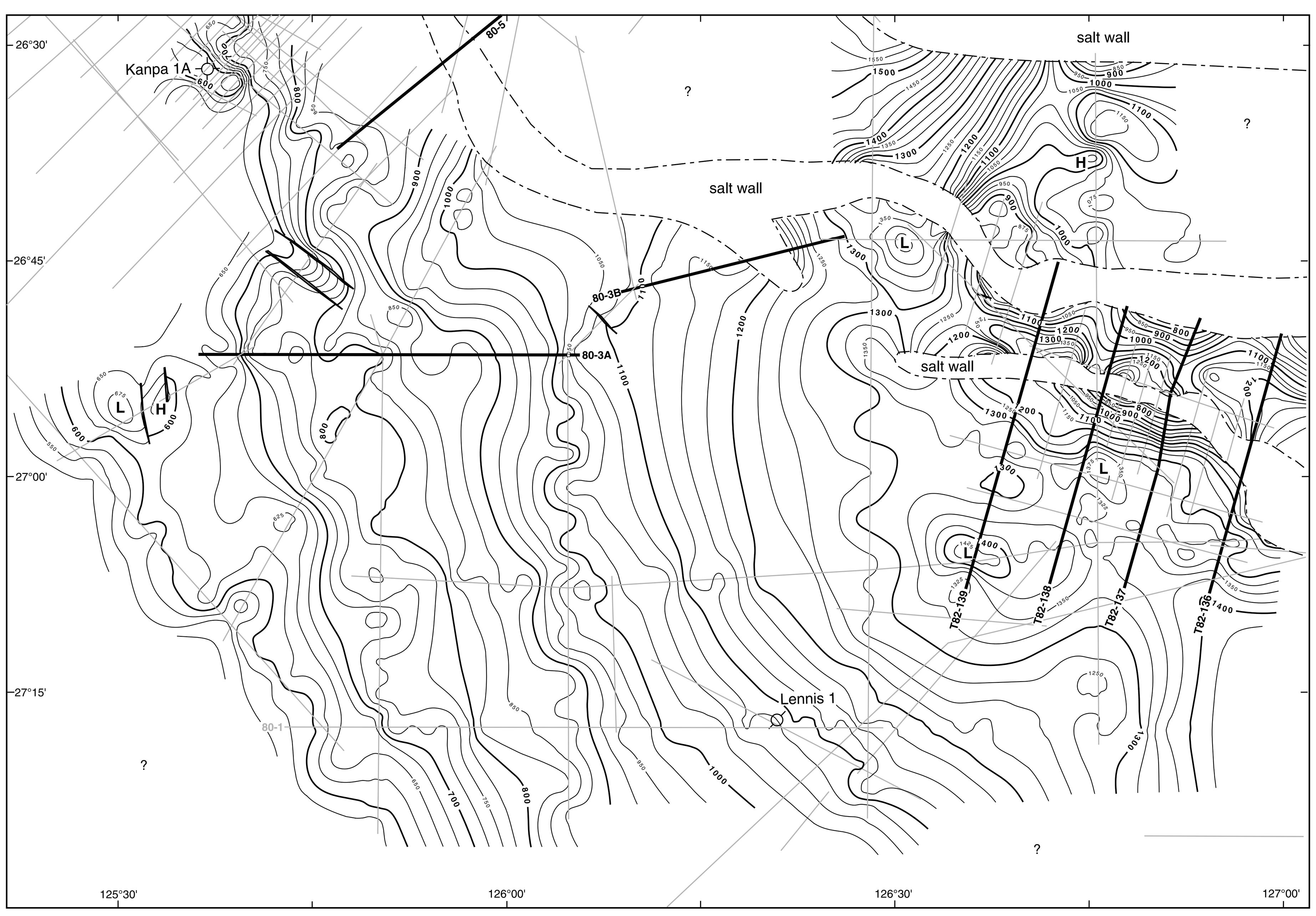
A. TOP TABLE HILL VOLCANICS



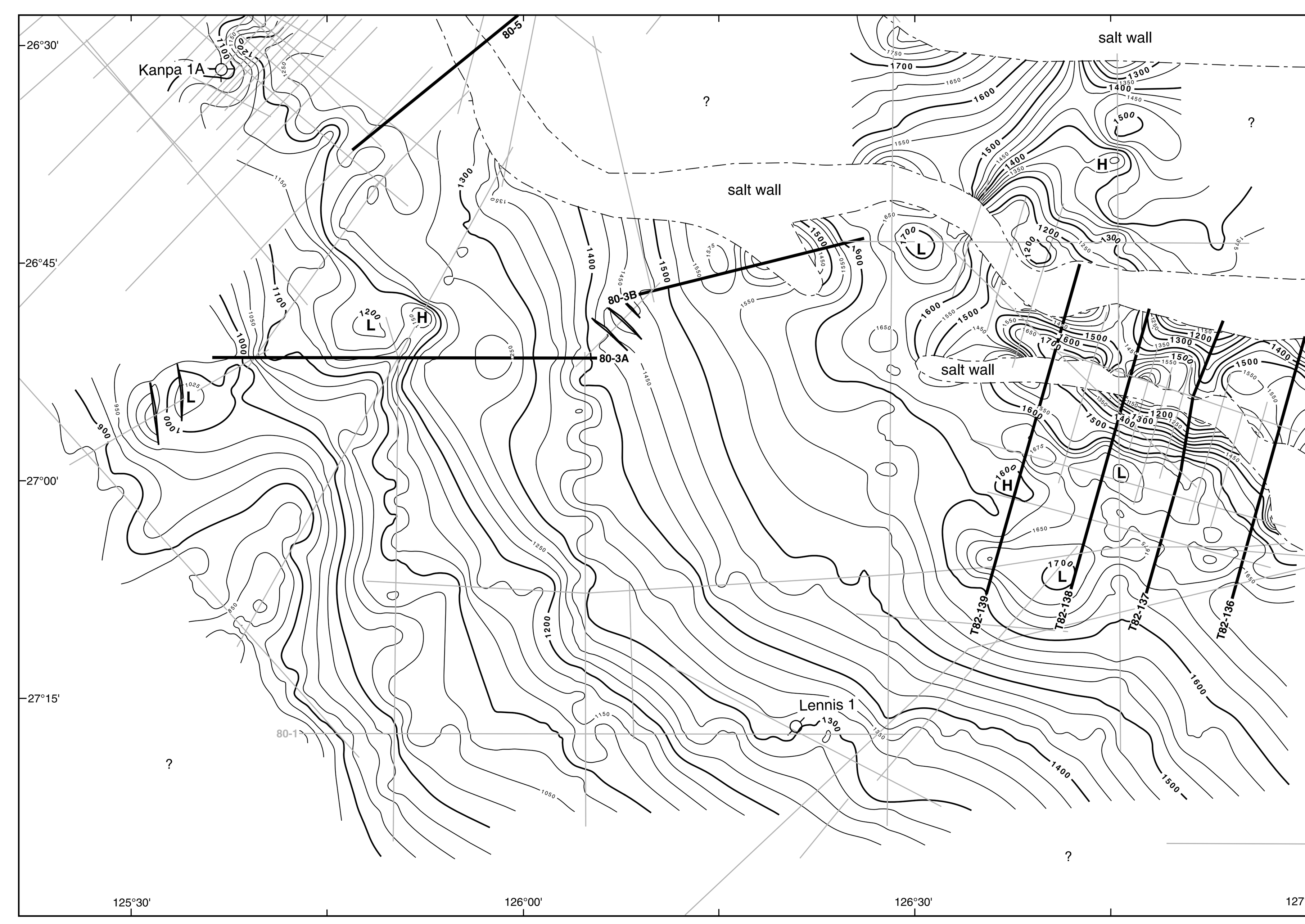
B. BASE McFADDEN FORMATION EQUIVALENT



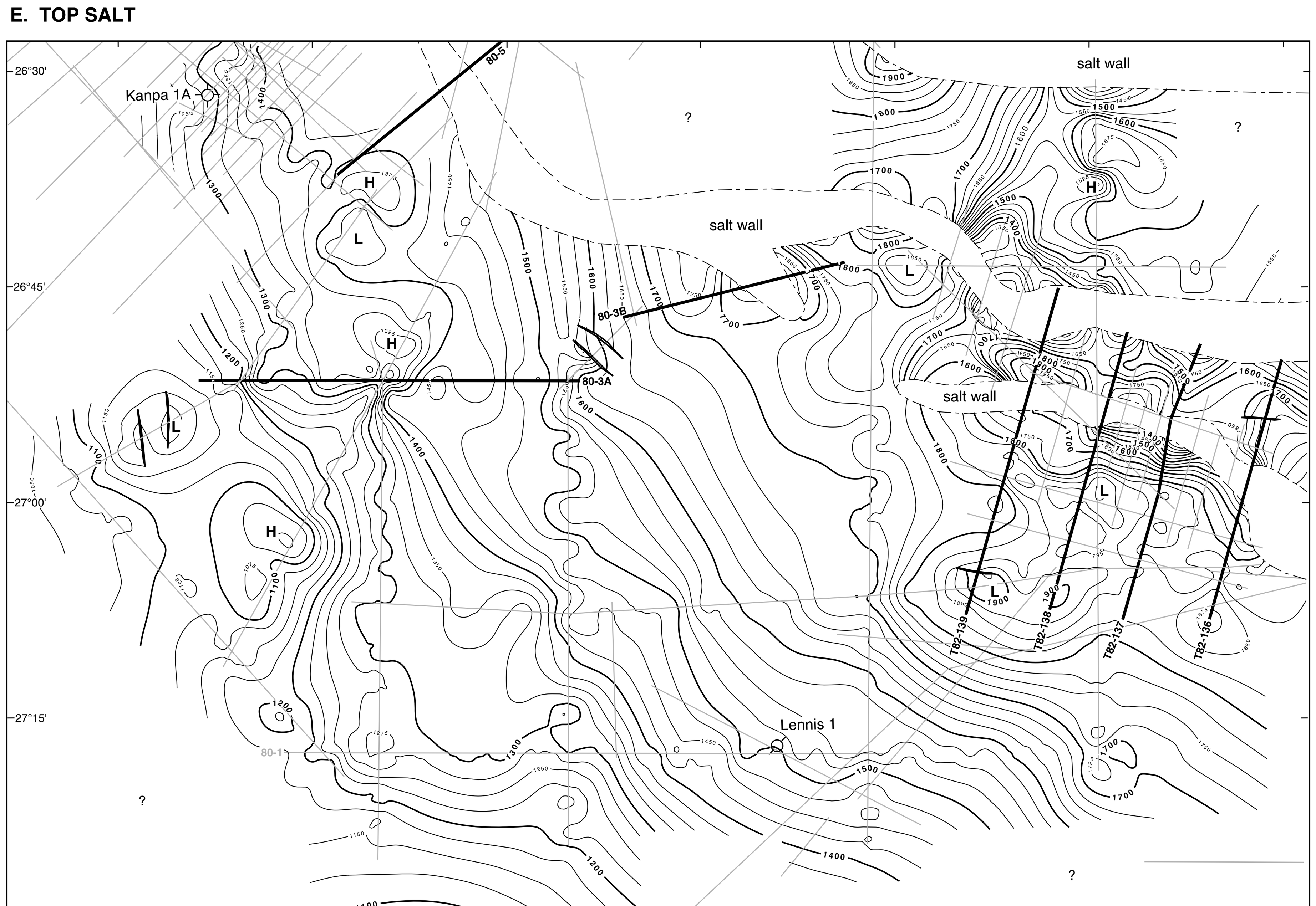
C. TOP KANPA FORMATION



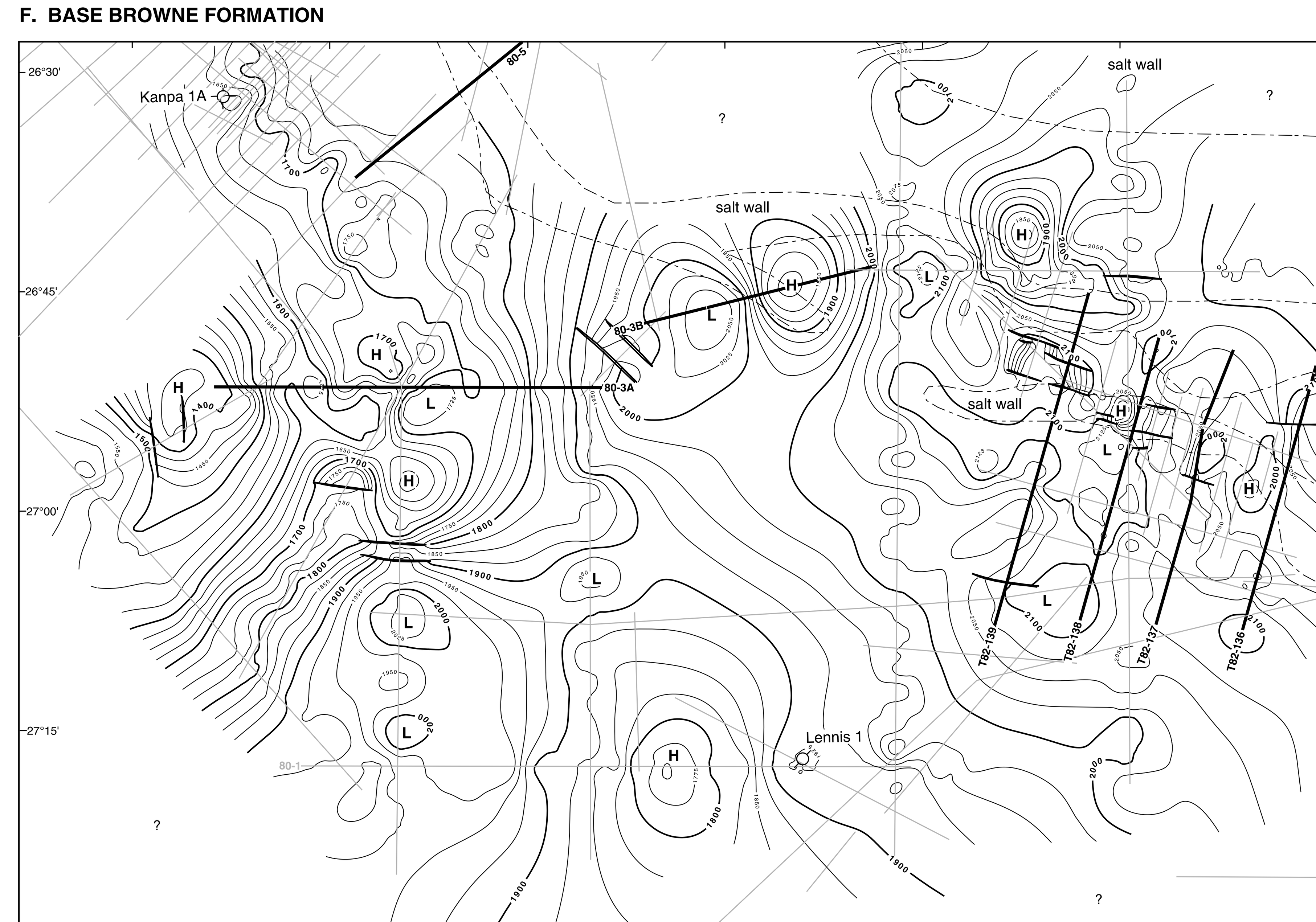
D. TOP BROWNE FORMATION



E. TOP SALT



F. BASE BROWNE FORMATION



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REPORT 77 PLATE 1

KEY SEISMIC HORIZON MAPS
LENNIS AREA, OFFICER BASIN

Compiled by S. N. Apak and H. T. Moors

Edited by L. Day and G. Loan
Cartography by L. J. Cosgrove
CAD file: NA115 (08.05.01)

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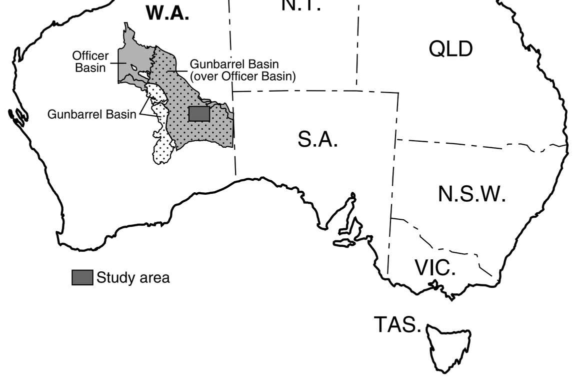
- Seismic section (in Report)
- Seismic section (not in Report)
- Exploration well
- Stratigaphic well
- Contours in milliseconds
- Fault
- **H** High areas
- **L** Low areas
- ? Contours terminate due to uncertainty in interpretation
- Approximate extent of salt wall



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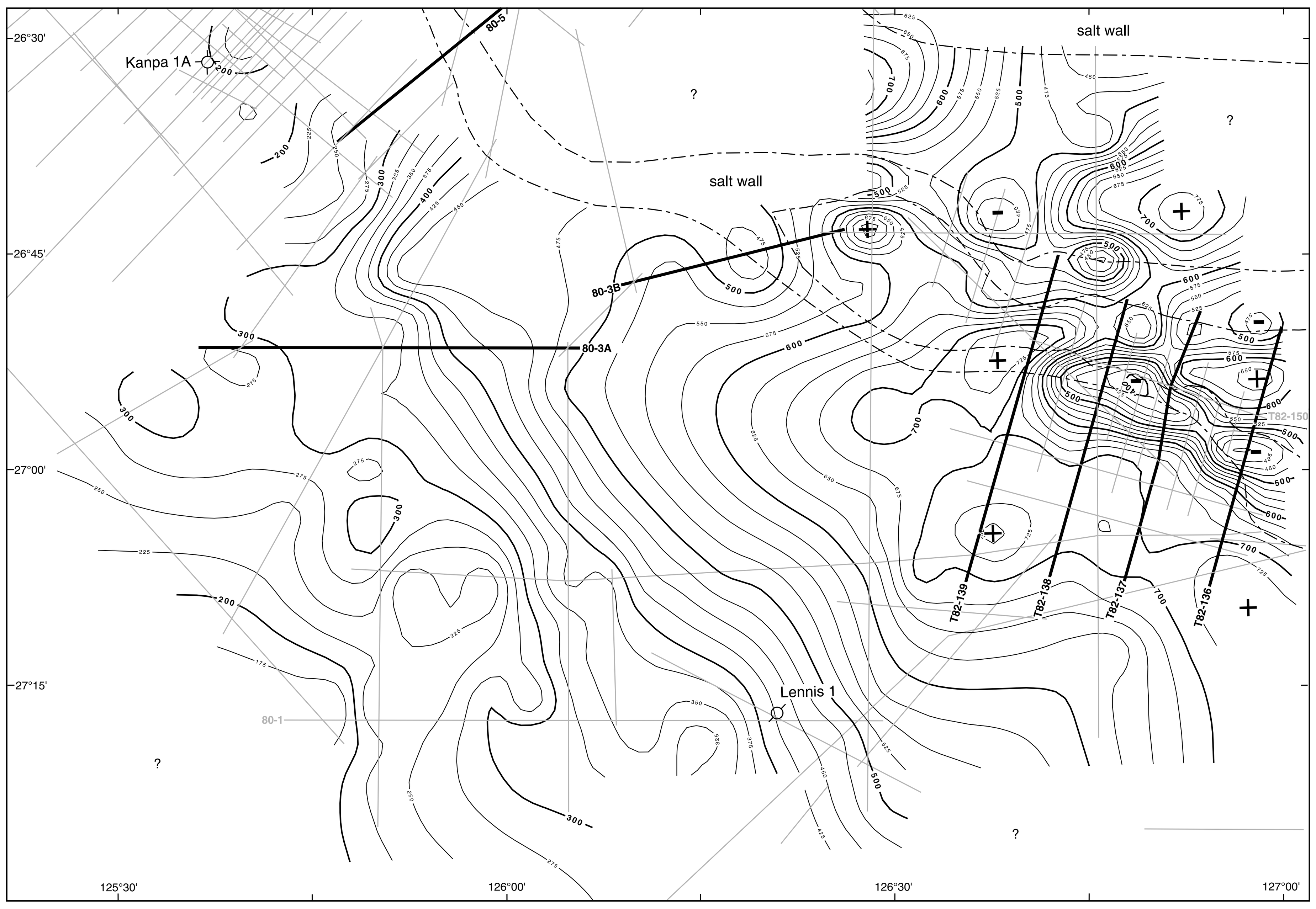
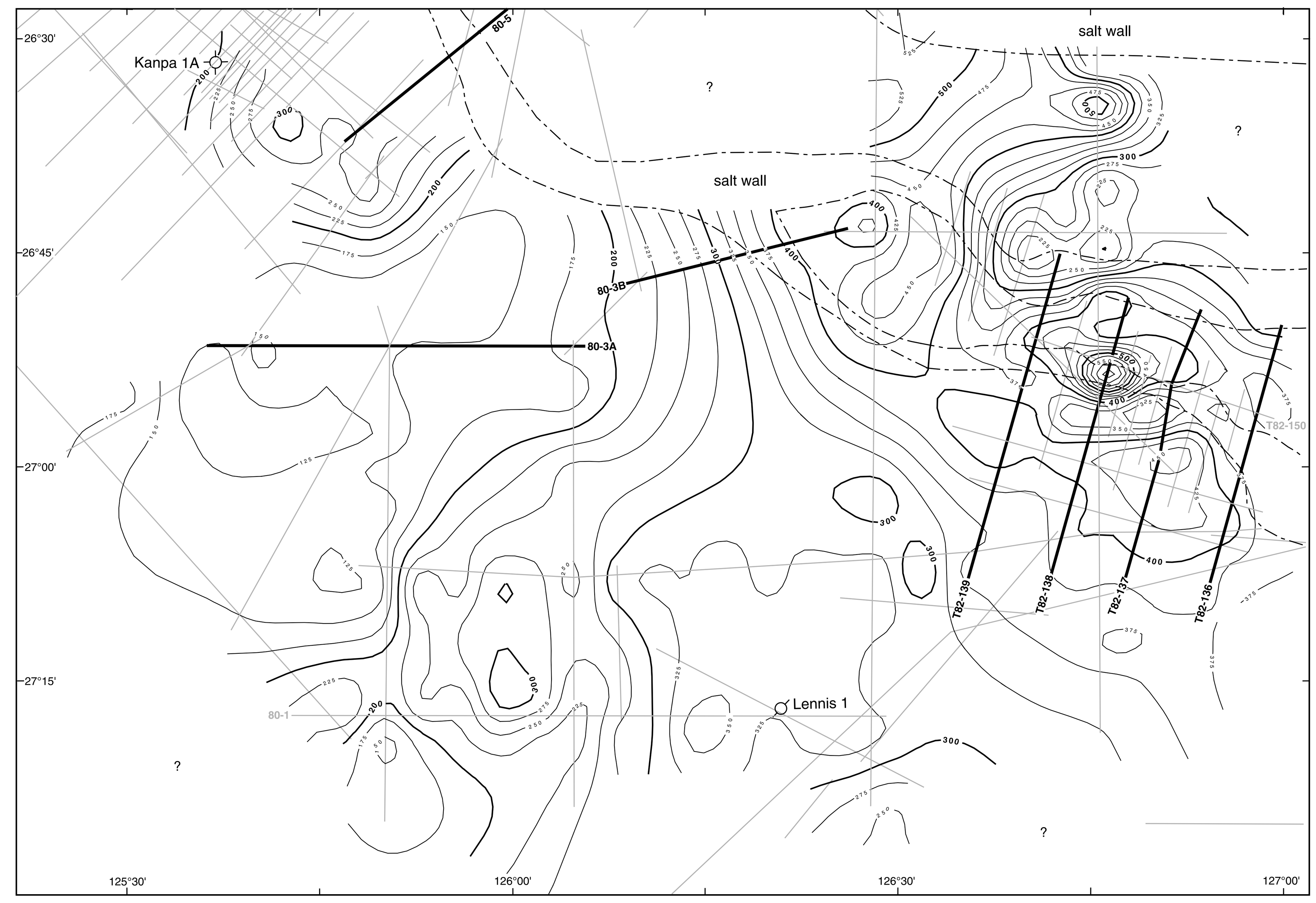
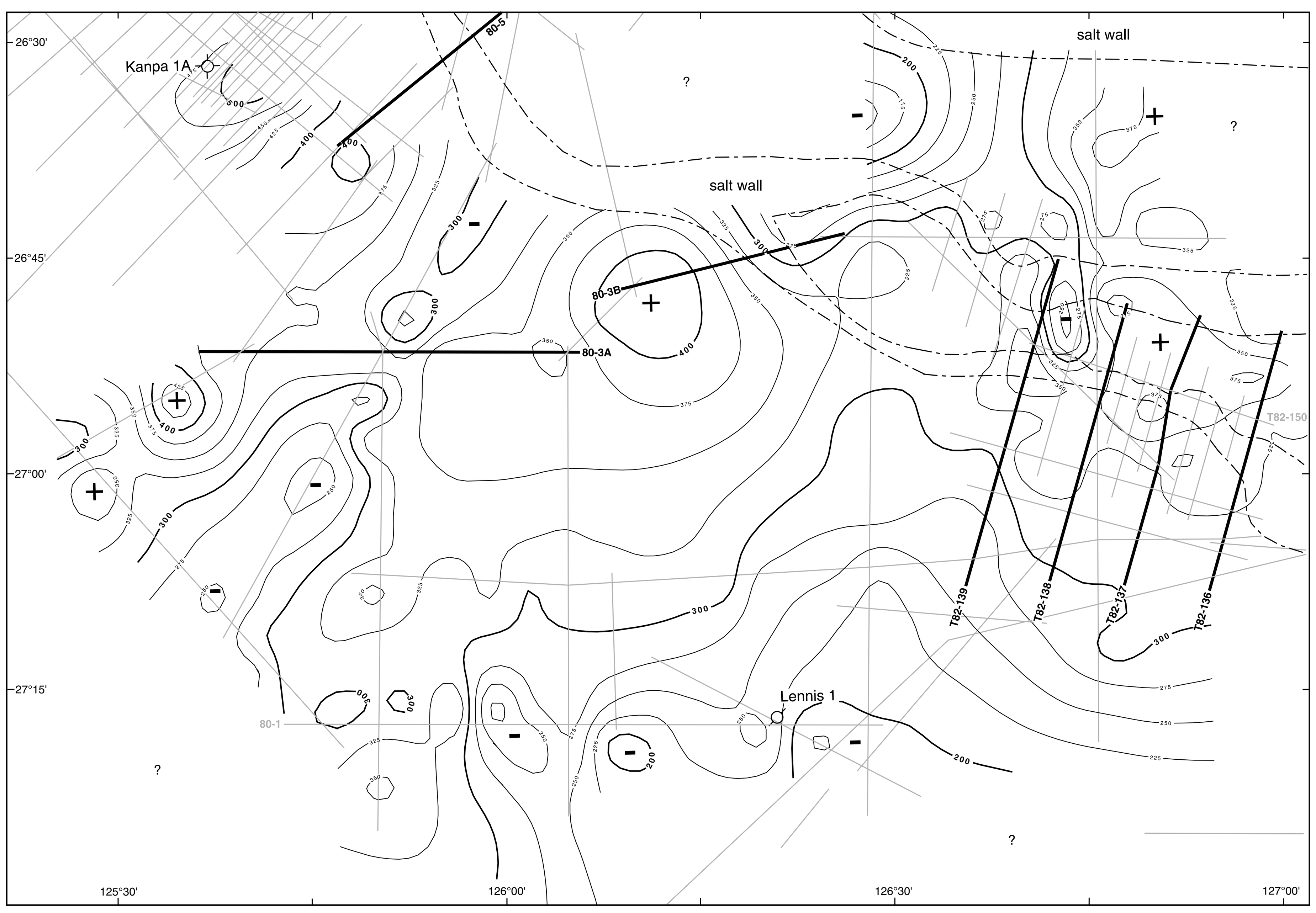
A. TOP TABLE HILL VOLCANICS TO BASE McFADDEN FORMATION EQUIVALENT



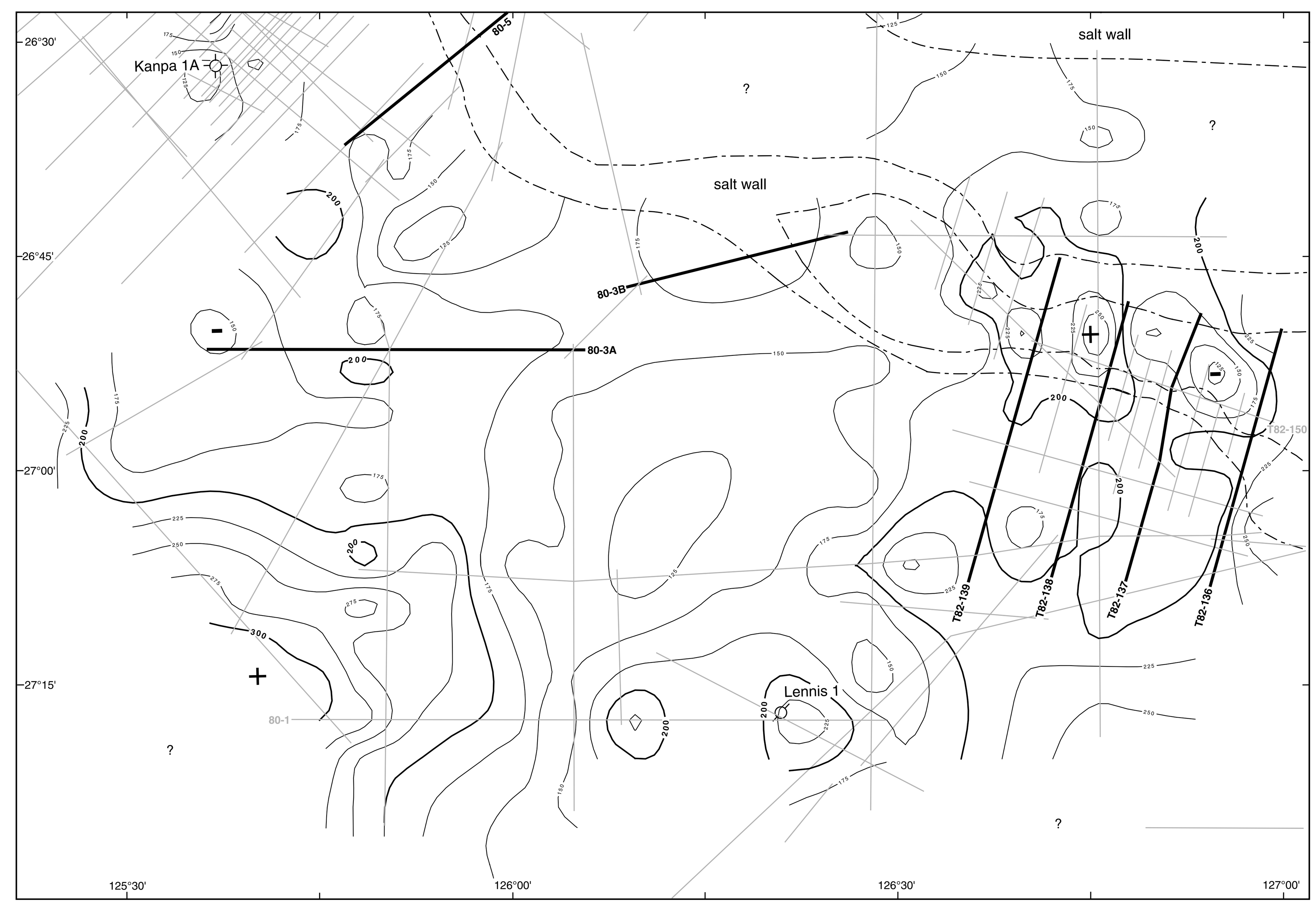
B. BASE McFADDEN FORMATION EQUIVALENT TO TOP KANPA FORMATION



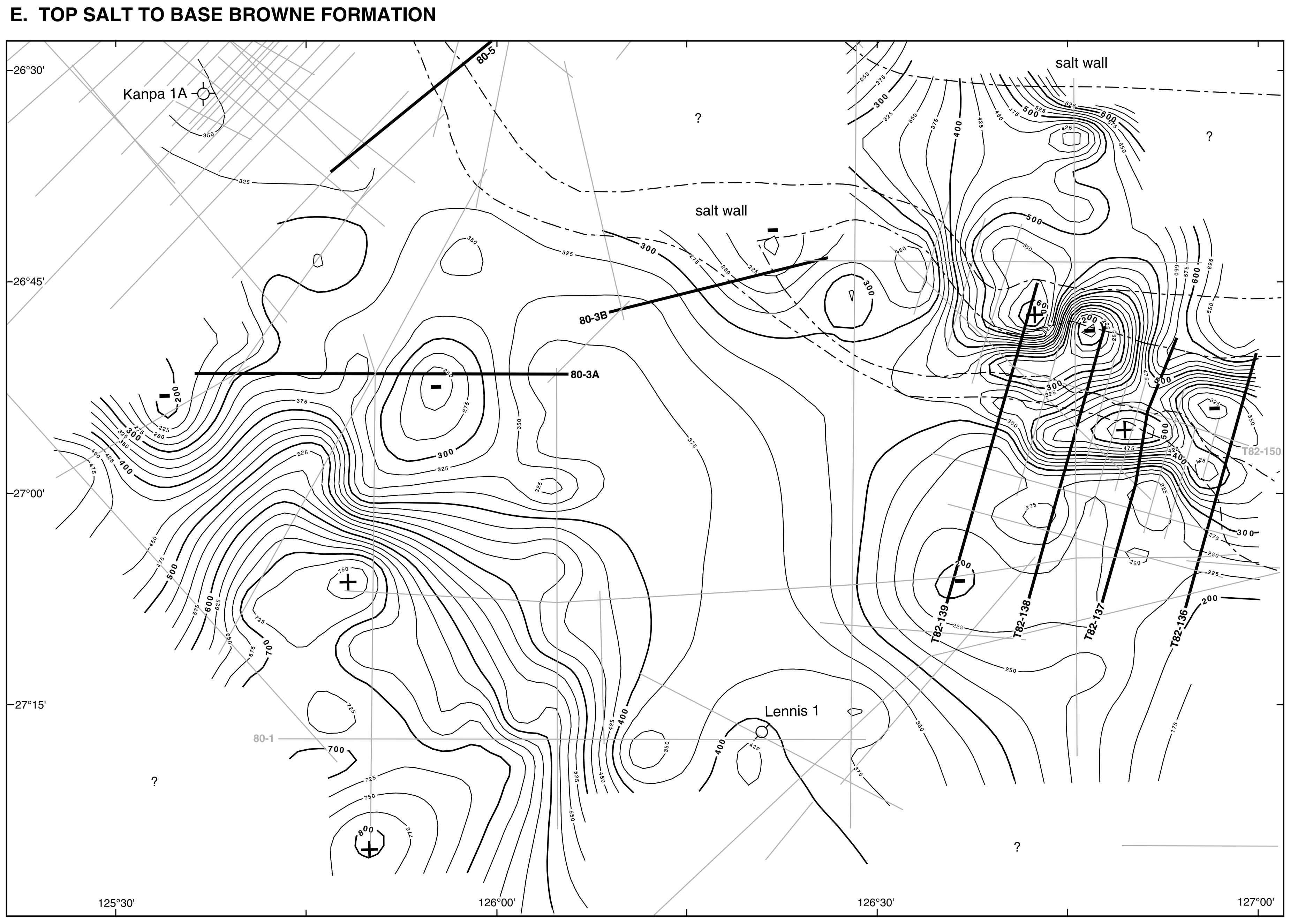
C. TOP KANPA FORMATION TO TOP BROWNE FORMATION



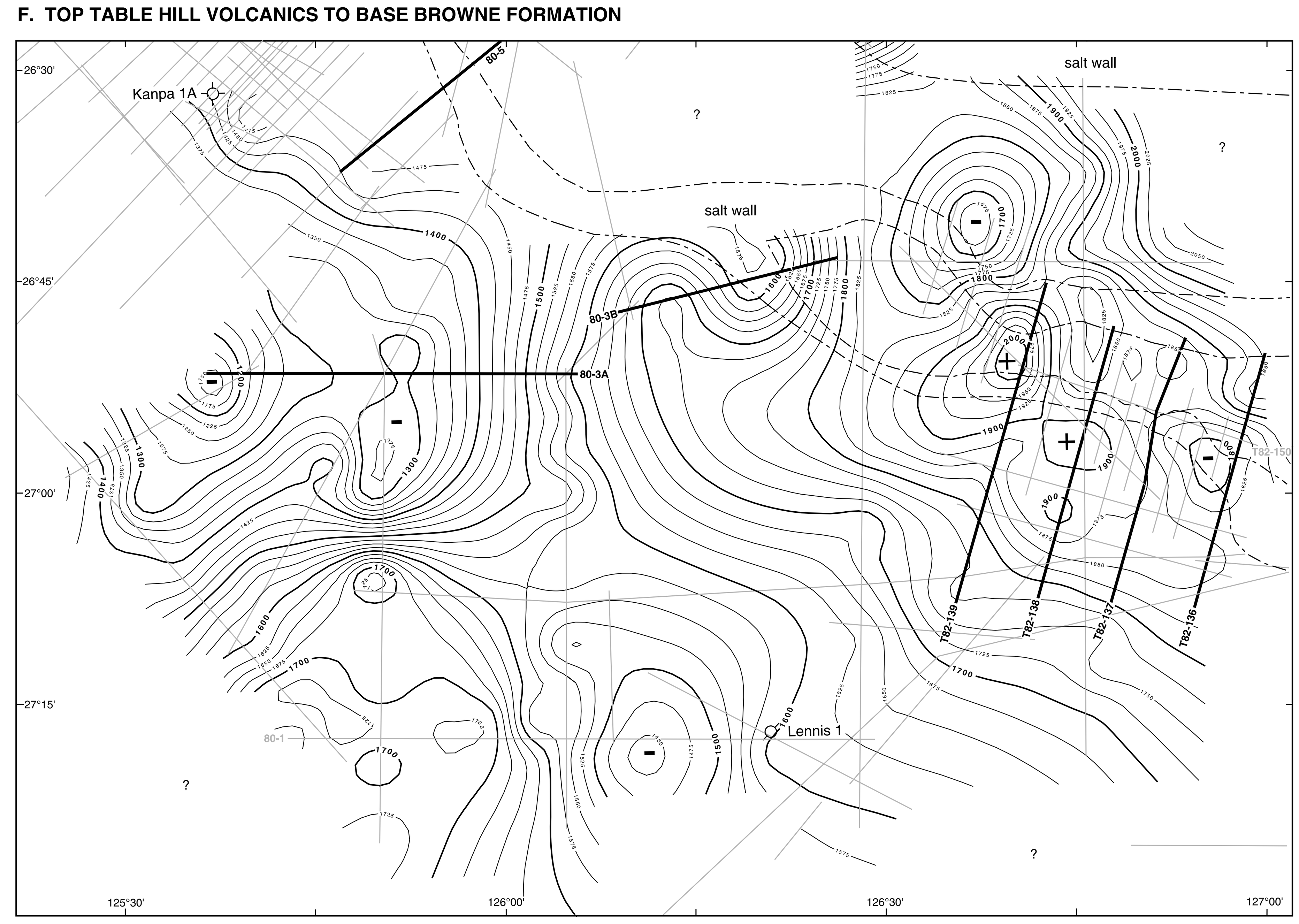
D. TOP BROWNE FORMATION TO TOP SALT



E. TOP SALT TO BASE BROWNE FORMATION



F. TOP TABLE HILL VOLCANICS TO BASE BROWNE FORMATION



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REPORT 77 PLATE 2

SEISMIC ISOCHRON MAPS
LENNIS AREA, OFFICER BASIN

Compiled by S. N. Apak and H. T. Moors

Edited by L. Day and G. Loan
Cartography by L. J. Cosgrove
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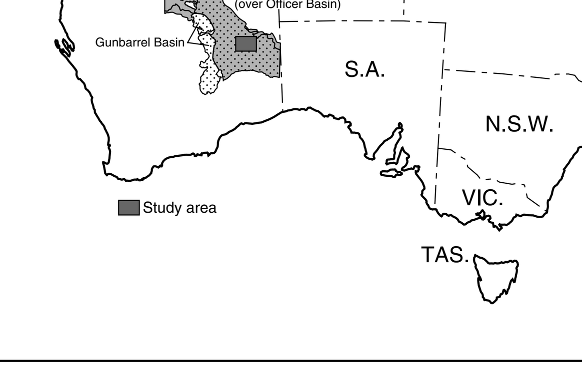

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