BURIAL HISTORY

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Chapter 9

INTRODUCTION

The Eromanga Basin was formed by crustal downwarping of central Australia during the Early Jurassic (Veevers, 1984; Veevers and Li, 1991; Veevers *et al.*, 1991). Sediments of the Eromanga Basin are Early Jurassic to early Late Cretaceous in age; they unconformably overlie the Cooper Basin or older strata and are themselves unconformably overlain by Tertiary sediments of the Lake Eyre Basin. Thickness of Jurassic–Cretaceous sediments in the Cooper region ranges from <1200 m in the Tinga Tingana area in the south to >2200 m in the Patchawarra and Nappamerri Troughs in the north.

Deposition ceased by the end of the early Late Cretaceous and the Eromanga Basin became a site of erosion and non-deposition until the Late Paleocene. The Tertiary Lake Eyre Basin unconformably covers the Eromanga succession and consists of three unconformity-bounded sequences.

Knowledge gained from burial history analysis of the Eromanga Basin in northeast South Australia includes: variation in sedimentation and subsidence rates which may be related to tectonic reactivation; timing of structural episodes and erosion patterns; and constraints on timing of hydrocarbon generation and migration, which will aid future petroleum discoveries.

METHOD

The subsurface information comprises stratigraphic data from 1020 petroleum and stratigraphic drillholes, as well as the Eromanga Basin 'Z', 'P' and 'C' horizons' depth structure contour maps. Detailed information used in this study is given in Moussavi-Harami (1996).

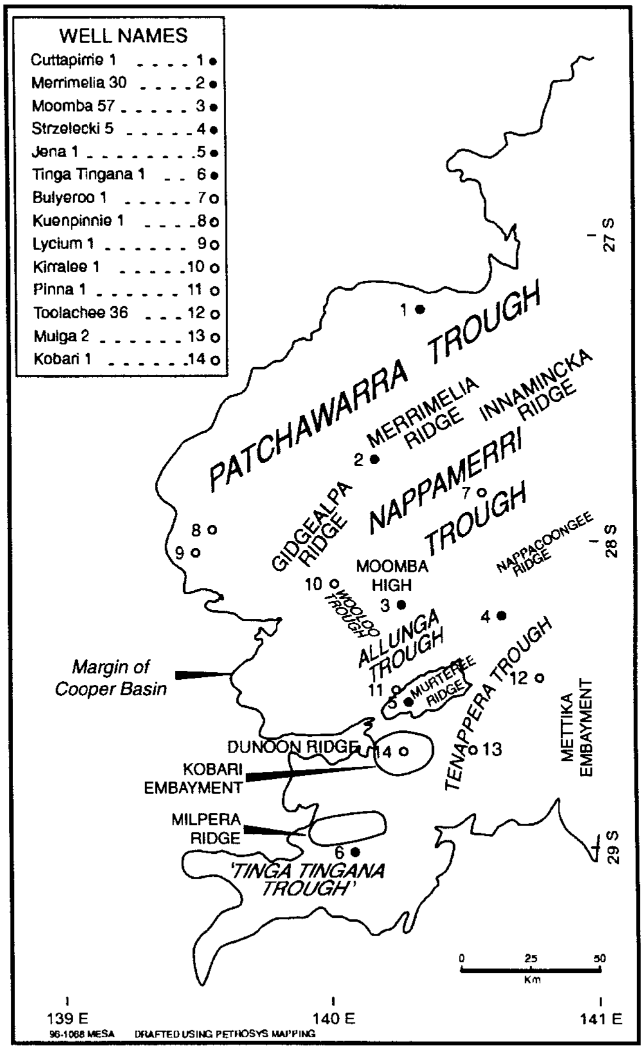

Fig. 9.1 Location of the study area and 14 drillholes selected for burial history analysis.

Burial history diagrams were constructed for 14 drillholes, whose locations were selected to represent the principal tectonic and stratigraphic elements of the Cooper region (Fig. 9.1). These diagrams start from the basal unit in the Eromanga Basin. Ages used for the construction of these diagrams were determined by calibrating the palynological work of Price *et al.* (1985) for the Mesozoic of the Eromanga Basin and other stratigraphic information (Wopfner, 1974; Wopfner and Cornish, 1967; Wopfner *et al.*, 1970, 1974; Callen, 1981, 1990; Moore and Pitt, 1984, 1985; Moore, Pitt *et al.*, 1986; Burger, 1986; Wiltshire, 1989; Krieg *et al.*, 1990, 1991, 1995; Alexander and Frears, 1995; Gravestock *et al.*, 1995) to the geological time scale (Haq *et al.*, 1987 and 1988; Harland *et al.*, 1990; Struckmeyer and Totterdell, 1992; Drexel *et al.*, 1993). Calculations were carried out using BasinMod® version 4.2, a 1D basin modelling commercial software package of Platte River Associates Inc. The model of Sclater and Christie (1980) was used for the computation of decompacted sediment thickness, because it has been assumed that the rate of sedimentation was relatively high in the Eromanga Basin and this model is more accurate for areas with rapid deposition that result in exponential porosity decrease with depth. Rock types and thickness of each stratigraphic interval were determined from drillhole logs and regional stratigraphic studies (e.g. Gravestock *et al.*, 1995; Krieg *et al.*, 1995). The only marine sediments are in the middle part of the Eromanga sequence set (or supersequence) and were deposited in a shallow-marine

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epicontinental sea with a maximum water depth of probably <100–150 m (Moore, Pitt *et al.*, 1986; Ozimic, 1986; Sherwood and Cook, 1986). Palaeobathymetry variations on a small portion of the studied interval are not likely to affect the burial history diagrams. Consequently no palaeobathymetry correction has been used for construction of these diagrams.

Missing and erosional intervals during each uplift event, are interpreted from the restored isopach maps of each sedimentary package, and published (e.g. Morton, 1987; Eadington *et al.*, 1989; Gravestock *et al.*, 1995; Krieg *et al.*, 1995) and unpublished data (e.g. well completion reports). These maps were constructed by using the interpretation of depositional environment of each unit, the present-day stratigraphic thickness and local and regional structural configuration of basins. Moussavi-Harami (1996) constructed the first regional isopachs of the study area.

STRATIGRAPHIC SEQUENCES

Four different unconformity-bounded sequences and sequence sets (or supersequences) are identified for the Eromanga and Lake Eyre Basins in northeast South Australia (Fig. 9.2). These sequences range from Early Jurassic – Recent and are summarised below in ascending order from sequence set J–K to T_3–Q. Stratigraphic variations and depositional environments of each unit are described in Chapter 5.

SEQUENCE SET J–K (EARLY JURASSIC – LATE CRETACEOUS)

This sequence set consists of a stack of three higher order sequences bounded by two major unconformities, one Late Cretaceous and the other Early Jurassic (Fig. 9.2). The lower sequence is non-marine and is overlain by marginal marine to marine rocks of the middle sequence. This part of the interval underlies the upper non-marine sequence at the top (Krieg *et al.*, 1995; Gravestock *et al.*, 1995).

The lower sequence starts with the Early–Middle Jurassic Poolowanna facies and Hutton Sandstone which unconformably overlie the Permo-Triassic rocks of the Cooper Basin. These siliciclastic sediments were deposited in a fluvial environment (Moore, 1986) with parts redistributed across the basin by aeolian and lacustrine processes (Wiltshire, 1989). A restored isopach map of these units indicates that the estimated thickness ranges from 40 m in the south (‘Tinga Tingana trough’; informal name) to >360 m in the north, where the major depocentre was in the Patchawarra Trough (Fig. 9.3). Toward the south, east and west, these units thin and are replaced (or intertongue) with the Middle–Late Jurassic Algebuckina Sandstone. The restored isopach map shows that the source points were in the south and southeast and sediments were carried by streams that were flowing from the south toward the north and northwest and redistributed across the study area.

The Birkhead Formation (Middle–Late Jurassic) is composed of interbedded siltstone, mudstone and sandstone with minor coal seams that were deposited in floodbasin lacustrine and meandering fluvial environments (Paton, 1986). The estimated thickness of the unit on the restored isopach map ranges from zero in the south to >150 m in the Patchawarra Trough and increases toward the northeast in Queensland (Fig. 9.4), as shown by Paton (1986). This trend shows that during deposition of the Birkhead Formation, the major depocentre was probably in the northeast, outside the study area (Cooper region). It thins toward the northwest to <70 m west of Charo 1, and intertongues with the Algebuckina Sandstone in the Poolowanna region. Southward, it also thins to zero thickness and possibly intertongues with the Algebuckina Sandstone.

The Late Jurassic Adori Sandstone, Westbourne Formation and Namur Sandstone are mainly composed of sandstone, siltstone and minor shale that were deposited in fluvial and lacustrine environments (Wiltshire, 1989; Gravestock *et al.*, 1995). A restored isopach map of these combined units indicates that the major depocentres were in the Nappamerri and Patchawarra Troughs and the estimated thickness in the study area ranges from 110–290 m (Fig. 9.5). Thickness of these units decreases to <140 m toward the north (Cordillo Dome) and northwest (over the Birdsville Track Ridge), beyond the Cooper region. The differences in thickness between ridges and troughs are mainly related to differential compaction, rather than tectonic sinking. Northwest-southeast thinning of this interval in the northwestern part of the study area is probably related to the beginning of structural growth of the Late Jurassic – Early Cretaceous in the west.

The youngest unit in the lower non-marine sequence is the Early Cretaceous (Neocomian) Murta Formation which is composed of interbedded siltstone, shale and very fine grained sandstone that were deposited in lacustrine environment (Ambrose et al., 1986). A restored isopach map of the Murta Formation shows that this interval has a relatively uniform thickness in the Cooper region and the difference between troughs and structural ridges are mainly related to differential compaction (Fig. 9.6). Thickening of this unit toward the northeast indicates that the depocentre was further to the northeast in Queensland. Thinning of this interval toward the northwest to 20 m, replacing or intertonguing with the Namur or Algebuckina Sandstones over the Birdsville Track Ridge, shows the structural growth during the Late Jurassic – Early Cretaceous to the west (Ambrose et al., 1986).

The middle marine sequence of the Eromanga Basin starts with the Lower Cretaceous (Neocomian–Aptian) siliciclastic sediments of the Cadna-owie Formation (sequence K1; Fig. 9.2) deposited during early transgressive and highstand systems tracts in marginal marine and high-energy shoreline environments (Wopfner et al., 1970; Moore and Pitt, 1985). A restored isopach map of this unit shows that the estimated thickness ranges from 40 to >114 m and the major depocentres were mainly in the Nappamerri and northern Patchawarra Troughs (Fig. 9.7). Estimated thickness of this unit decreases to <50 m toward the northwest over the Birdsville Track Ridge. Another depocentre was present in the Allunga Trough and Dunoon Embayment, where >90 m of sediments were deposited in contrast to <60 m over the Murteree Ridge. It is interpreted that the thickness of the Cadna-owie Formation in the Milpera Depression and Tinga Tingana trough is 65 and 70 m respectively, with the unit correspondingly thin (45 m) over the Milpera Ridge.

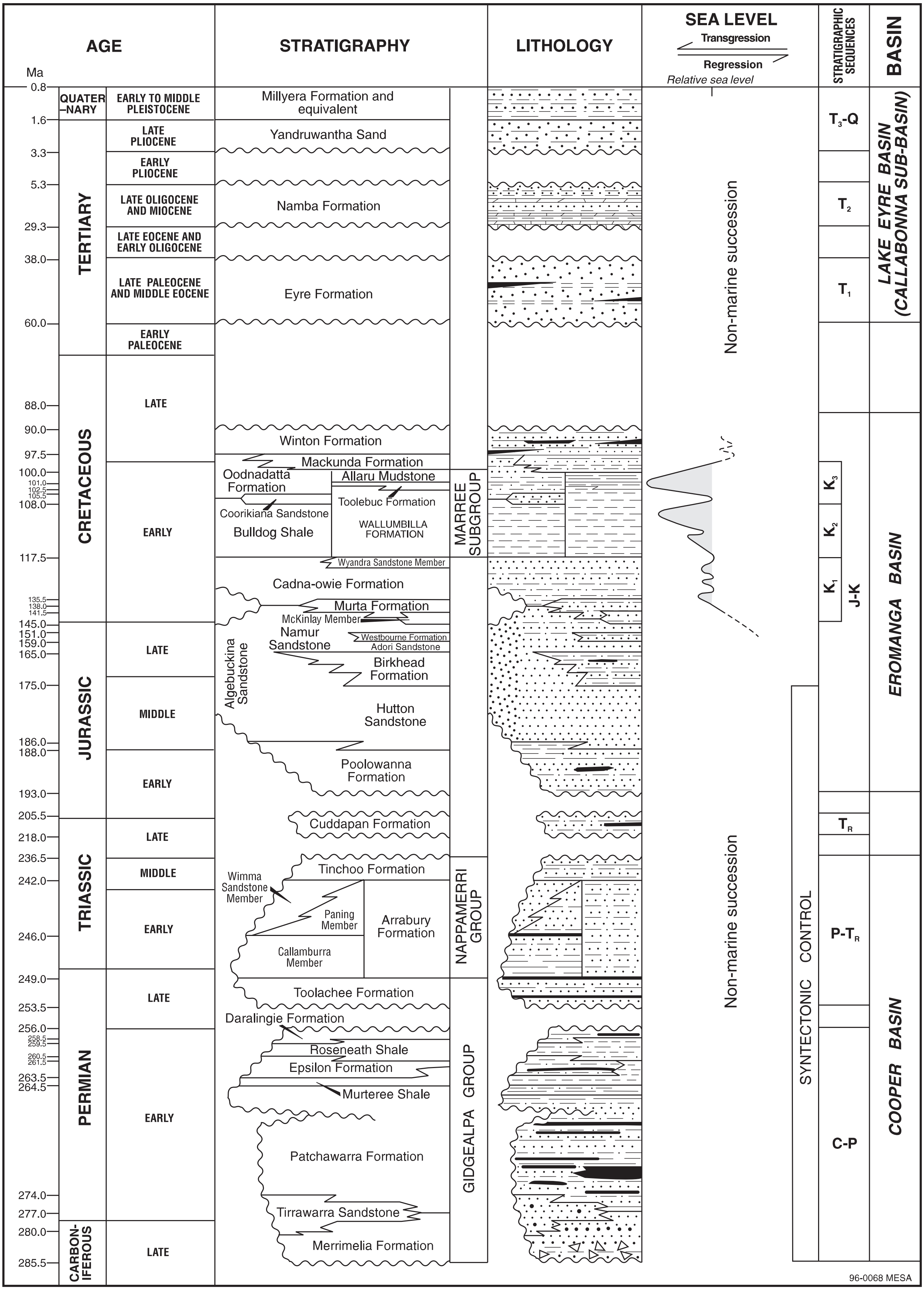

***Fig. 9.2** Generalised stratigraphic column and sequences of the Cooper, Eromanga and Lake Eyre Basins in northeast South Australia.*

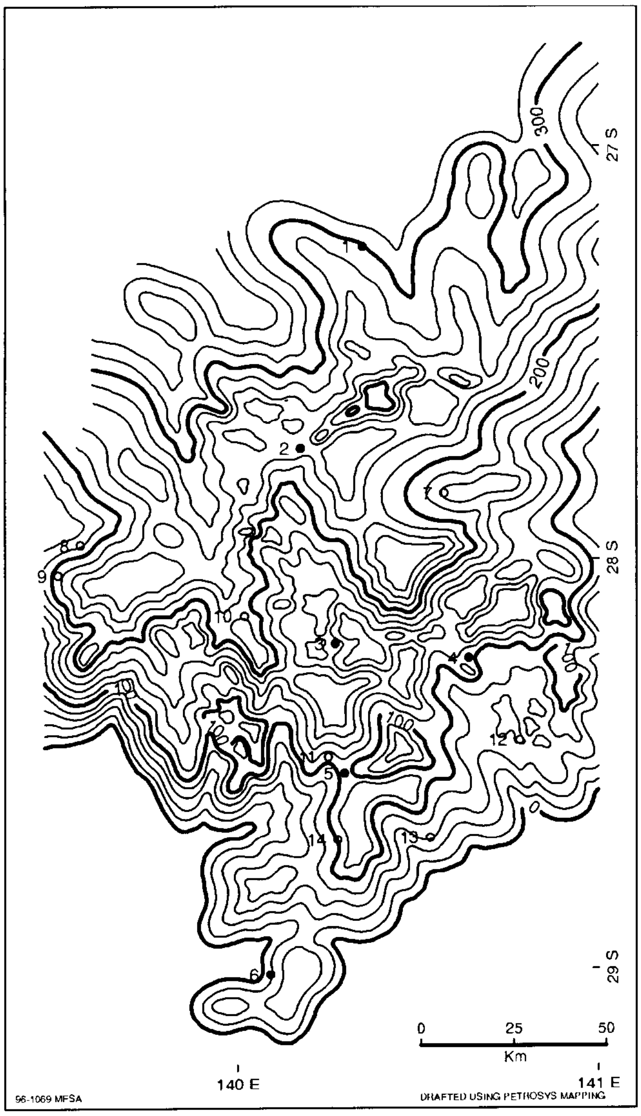

Fig. 9.3 Restored isopach map of Hutton Sandstone and Poolowanna facies (Early–Middle Jurassic; contour interval 20 m).

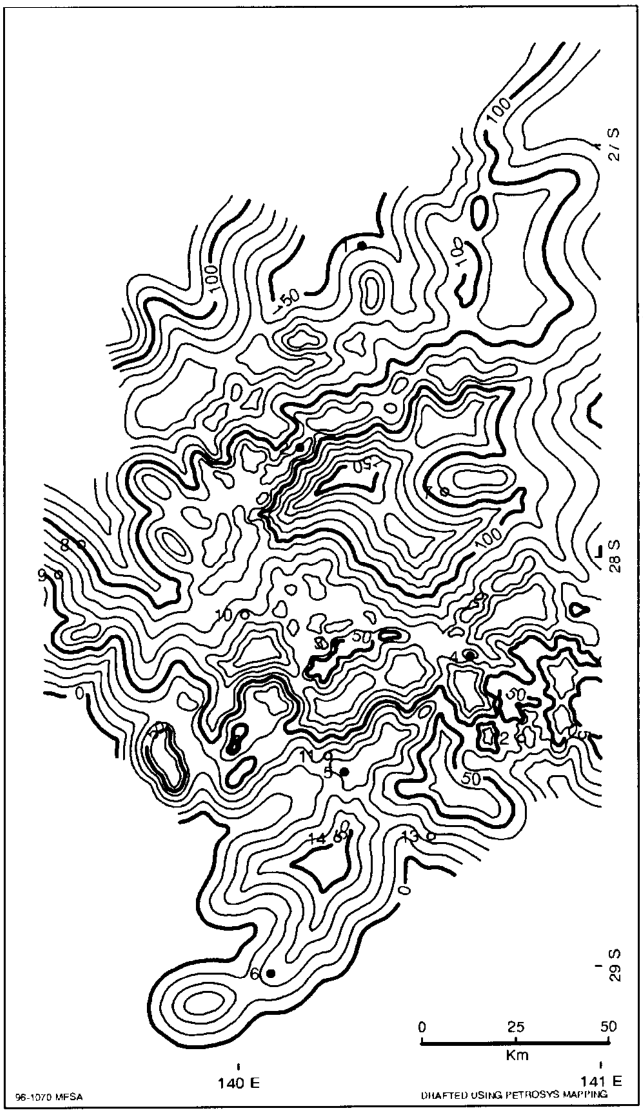

Fig. 9.4 Restored isopach map of Birkhead Formation (Middle–Late Jurassic; contour interval 10 m).

The mid to late Early Cretaceous Marree Subgroup (sequences K_2 and K_3) is mainly composed of marine shale, siltstone and sandstone. The upper part of the Bulldog Shale and Wallumbilla Formation (sequence K_2) were deposited during the first major transgression (transgressive systems tracts) in a shallow marine environment, while the Coorikiana Sandstone was deposited during eustatic fall of sea level in a shoreline environment (Morgan, 1980). The maximum transgression (maximum marine flooding surface; sequence K_3) took place during deposition of the Toolebuc Formation which is composed of black calcareous siltstone and mudstone with marine fauna, and is represented by a condensed section that can be traced for hundreds of kilometres in South Australia and southwestern Queensland (Moore, Pitt *et al.*, 1986; Ozimic, 1986). A second condensed section (possibly maximum marine flooding surface; sequence K_2) has been identified as a separate entity from the Toolebuc Formation (Ch. 5). The fine-grained sediments of the Allaru Mudstone and Oodnadatta Formation were deposited during regression in a low-energy shallow marine environment (Morgan, 1980; Moore and Pitt, 1985).

The youngest unit in the middle marine sequence is the Mackunda Formation which consists of interbedded glauconitic sandstone, siltstone and shale deposited in a marginal marine environment. The estimated thickness of the Marree Subgroup and Mackunda Formation on the restored isopach map ranges from 250 to 900 m (Fig. 9.8), where the major depocentres were in the Nappamerri and northern Patchawarra Troughs. The unit also thickens toward the northeast in Queensland. The estimated thickness over the structural ridges was <600–700 m and the differences are probably related to compaction rather than tectonic sinking. These units thin toward the northwest (<300 m) over the Birdsville Track Ridge and thicken again toward the Poolowanna Trough (Alexander and Jensen-Schmidt, 1995). This is possibly related to structural activity of the Birdsville Track Ridge that allowed more sediment to be deposited on both of its flanks.

The upper non-marine sequence of the Eromanga Basin is the Winton Formation (Late Cretaceous) which is composed of interbedded siltstone, shale and sandstone with numerous thin coal seams deposited in fluvial to lacustrine environments (Krieg *et al.*, 1995). The estimated thickness of the Winton Formation on the restored isopach map in the study area ranges from 275 m in the south to >1125 m in the northeast (northern Patchawarra Trough; Fig. 9.9). This unit

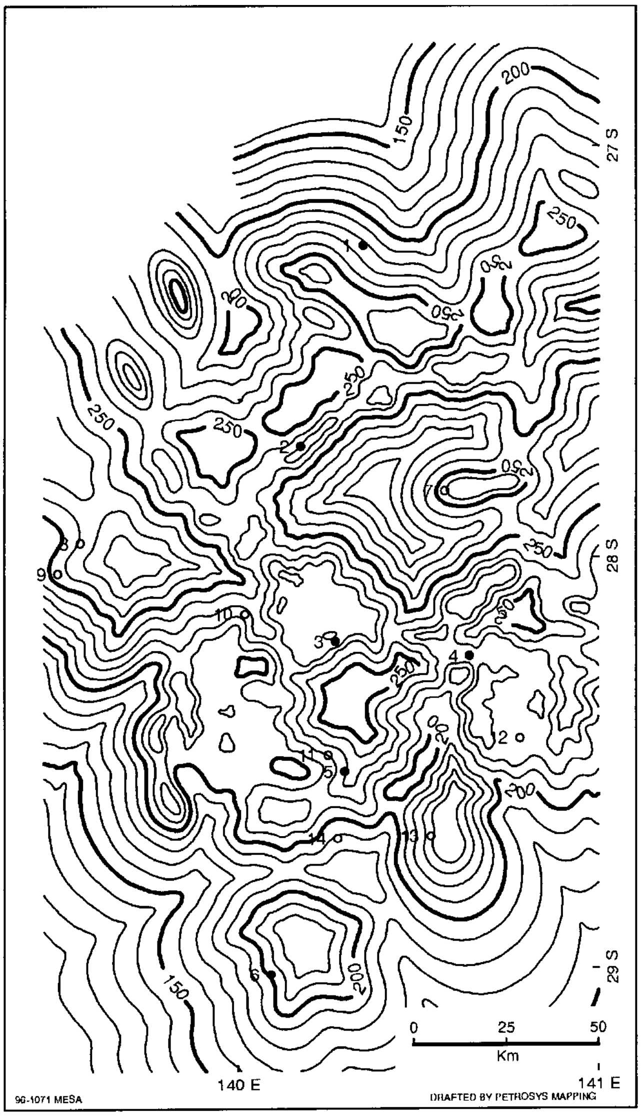

Fig. 9.5 Restored isopach map of Adori Sandstone, Westbourne Formation and Namur Sandstone (Late Jurassic; contour interval 10 m).

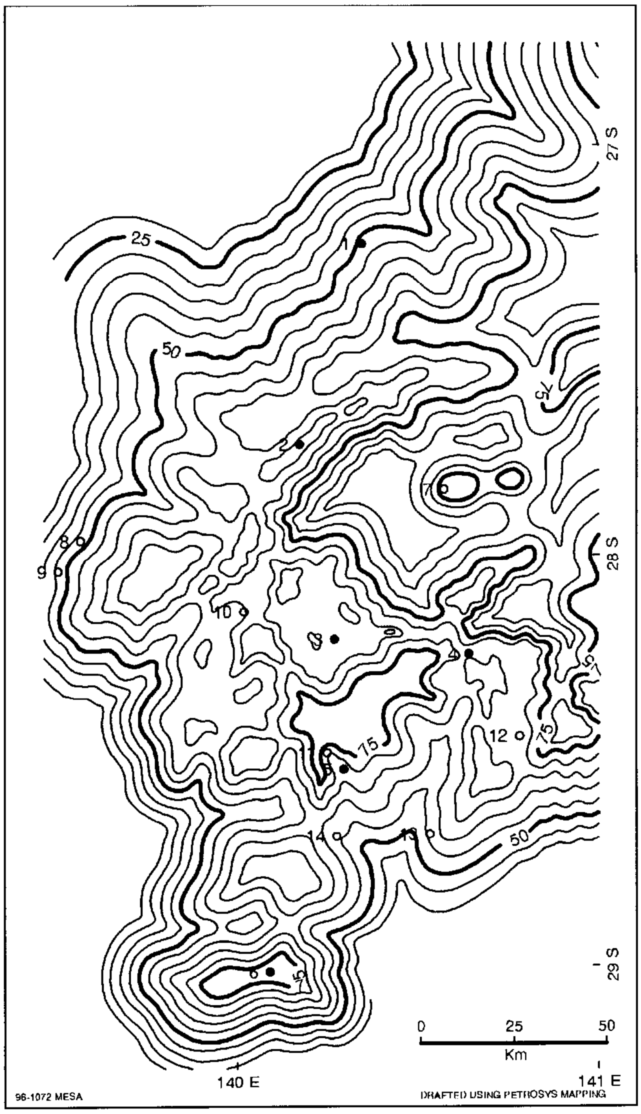

Fig. 9.6 Restored isopach map of Murta Formation (Early Cretaceous; contour interval 5 m).

thins toward the north and east (Innamincka Dome), where it is exposed at surface and the top is eroded. It is interpreted that the maximum thickness over the Innamincka Dome was ~ 800 m and >300 m of sediments have been eroded during the Late Cretaceous – early Tertiary from this area. Another depocentre was probably present in the southern Nappamerri Trough, where >950 m of sediments may have been deposited before thinning toward the south and southeast. The maximum estimated thicknesses in the Mettika Embayment and the 'Kidman embayment' (informal name) were probably 700 and 725 m respectively, and the Winton Formation gradually thins over the Toolachee Ridge. It is worth noting that the maximum thickness over the GMI and Murteree–Nappacoongee Ridges is less than in the troughs and this is also probably related to differential compaction between these areas. Southward, this unit thickens to 600 m in the Milpera Embayment and Tinga Tingana trough and thins again toward the south and east.

A restored isopach map of the entire supersequence (J–K) indicates that the thickness ranges from 1100 to 3000 m in the study area (Fig. 9.10). During deposition two major depocentres were present in the southern Nappamerri and northern Patchawarra Troughs, where it is interpreted up to 3000 m of sediments were deposited. Over the ridges (such as GMI) and structural highs (such as Moomba and Bulyeroo), the thickness varies from 1500 to 2300 m, while in the troughs, the thickness increases. These differences are mainly related to differential compaction rather than regional tectonic activity. In general, this supersequence thins towards the northwest over the Birdsville Track Ridge to <1600 m, but thickens again in the Poolowanna Trough (Alexander and Jensen-Schmidt, 1995). It should be noted that the isopach map reflects the pre-Jurassic structural elements (ridges and highs) that were reactivated during Late Triassic diastrophism in the Cooper Basin and formed the basement of the Eromanga Basin.

SEQUENCE T1 (LATE PALEOCENE – MID EOCENE)

This sequence consists of the Eyre Formation that disconformably overlies the Winton (Late Cretaceous) and underlies the Namba (middle–late Tertiary) Formations respectively (Fig. 9.2). It is mainly composed of sandstone with minor interbeds of lignite deposited in broad shallow

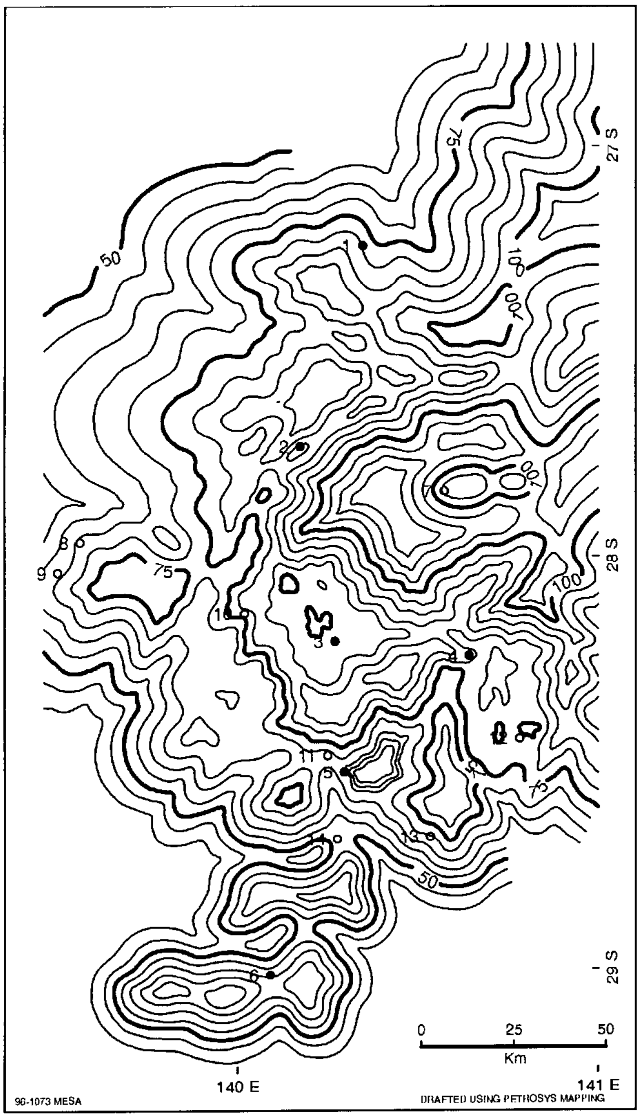

Fig. 9.7 Restored isopach map of Cadna-owie Formation (sequence K_1; Early Cretaceous; contour interval 5 m).

braided stream systems (Wopfner *et al.*, 1974; Gravestock *et al.*, 1995; Callen *et al.*, 1995). Thickness of this unit on the restored isopach map ranges from 30 to 140 m in the Callabonna Sub-basin (Fig. 9.11). It is interpreted that two major depocentres in the Cooper region were present in the southern Nappamerri and Allunga–Wooloo Troughs, separated by the Moomba high, and >140 m of sediments have been deposited in these regions. This unit thins over the Nappacoongee and Strzelecki highs, but thickens over Toolachee Field where the maximum estimated thickness was probably >120 m. In the southernmost part of the study area, the maximum interpreted thickness of the Eyre Formation is ~100 m within the Tinga Tingana trough and it thins toward the margins of the basin in the south and east.

In the Patchawarra Trough, the maximum estimated thickness was ~130 m in the central part, north of the Tirrawarra and Moorari Fields. Variation in thickness in the central Patchawarra Trough reflects the structural movement after deposition of this unit. Over the Innamincka Dome, this unit is probably eroded and the upper Eromanga sequence crops out at the surface. Over the Gidgealpa and Merrimelia Ridges, the thickness ranges from 60 to 80 m and the differences with troughs is mainly attributed to differential compaction.

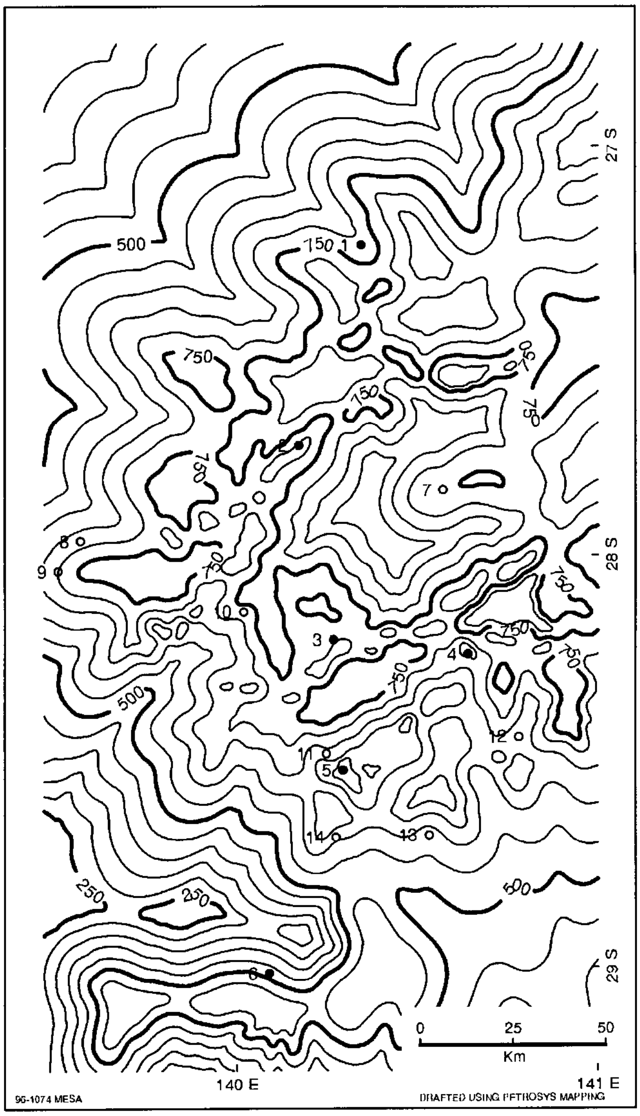

Fig. 9.8 Restored isopach map of Marree Subgroup and Mackunda Formation (sequences K_2 and K_3; Early–Late Cretaceous; contour interval 50 m).

SEQUENCE T2 (LATE OLIGOCENE – LATE MIOCENE)

This sequence is represented by the Namba Formation, composed of interbedded sandstone, siltstone, shale and dolomite locally, deposited in alkaline lake to fluvial environments (Gravestock *et al.*, 1995; Callen *et al.*, 1995). It disconformably overlies the early Tertiary and is disconformably overlain by the latest Tertiary and Quaternary sequence (Fig. 9.2). A restored isopach map of the Namba Formation shows that the estimated thickness ranges from 30 to 210 m and the major depocentre was in the western Allunga Trough (Fig. 9.12), where the thick basal dolomite of the Namba was deposited in a broad shallow lake. In the Patchawarra Trough, it is interpreted that three separate or possibly connected lakes (depocentres) were present in the Late Oligocene – Late Miocene. The central part of the Patchawarra Trough (Tirrawarra Field) received less sediment during deposition of the Namba Formation. This is mainly related to structural activity (uplift) in this area after deposition of the Eyre Formation during the Late Eocene – Early Oligocene. Based on the structural contour map at the top of the Winton Formation (Morton, 1987) another

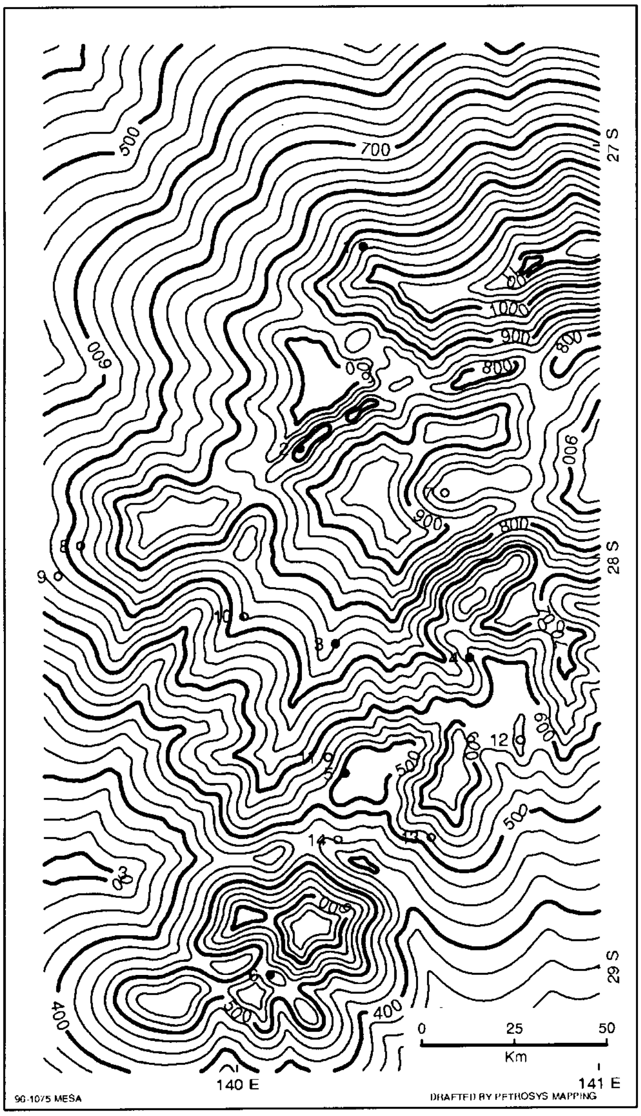

Fig. 9.9 Restored isopach map of Winton Formation (Late Cretaceous; contour interval 25 m).

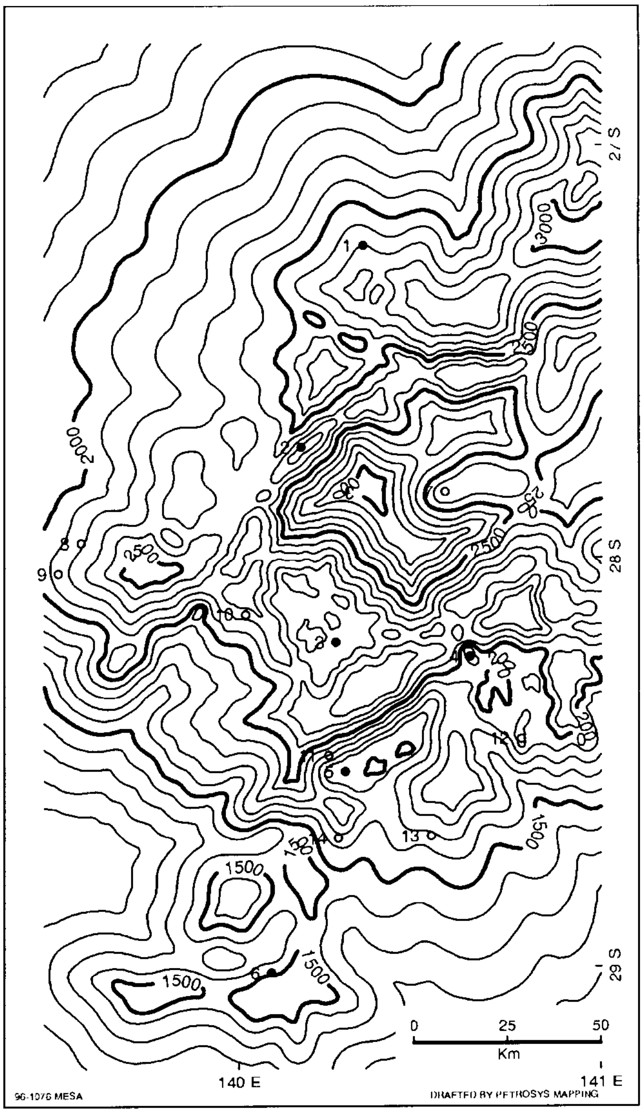

Fig. 9.10 Restored isopach map of J–K sequence (Jurassic–Cretaceous sequence set; contour interval 100 m).

depocentre may have existed south of the Merrimelia Ridge, in the southern Nappamerri Trough, where >140 m of sediments were deposited. This unit thins to <90 m towards the northwest (over the Birdsville Track Ridge).

Another depocentre was probably present west of the Pando Field, where the estimated maximum thickness of the Namba Formation was >180 m. This unit thins towards the south, over the Dunoon Ridge, but thickens again to 170 m. This indicates that a series of depressions or lakes existed in the study area as described for other parts of South Australia (Callen, 1981, 1990). Thinning of the Namba Formation in the eastern Strzelecki Field is probably related to uplift during the middle Tertiary that prevented deposition of the thick basal dolomite.

SEQUENCE T3–Q (LATE PLIOCENE – QUATERNARY)

This sequence unconformably overlies the Namba Formation and comprises sand, silt and clay units with some dense evaporite horizons in soils deposited in fluvial channel, saline lake and aeolian environments (Callen, 1992; Callen *et al.*, 1995; Gravestock *et al.*, 1995). An isopach map of surficial, post-Namba Formation units, indicates that their thickness ranges from zero to >60 m (Fig. 9.13). Northeast-southwest thinning of these units, to <20 m over ridges (GMI and Murteree–Nappacoongee) shows that structural activity of the basement (rising) caused these ridges to be sites of erosion and sediment bypass rather than deposition.

BURIAL HISTORY

Burial history analysis is very important in order to place constraints on the timing of thermal maturation of organic matter, and generation and migration of hydrocarbons in a sedimentary basin. Thermal maturity of organic matter progressively increases as sediments subside through time. The rate of total subsidence varies and depends on geological setting. For example, the subsidence rate in a tectonically active area, such as a rift basin, is much more than that in an intracratonic basin, which is mostly stable through time. The terms of comparison of relative subsidence rate used in this chapter are given in Table 9.1.

Burial history diagrams were constructed for 14 drillholes however, only those six representing the key tectonic and

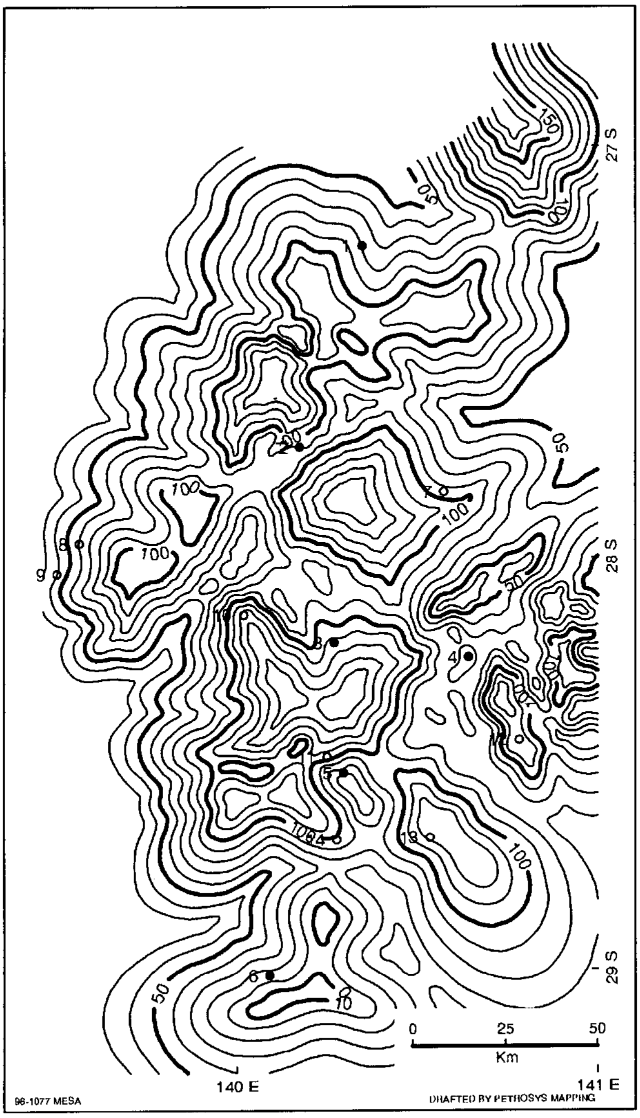

Fig. 9.11 Restored isopach map of Eyre Formation (Late Paleocene – Middle Eocene; contour interval 10 m).

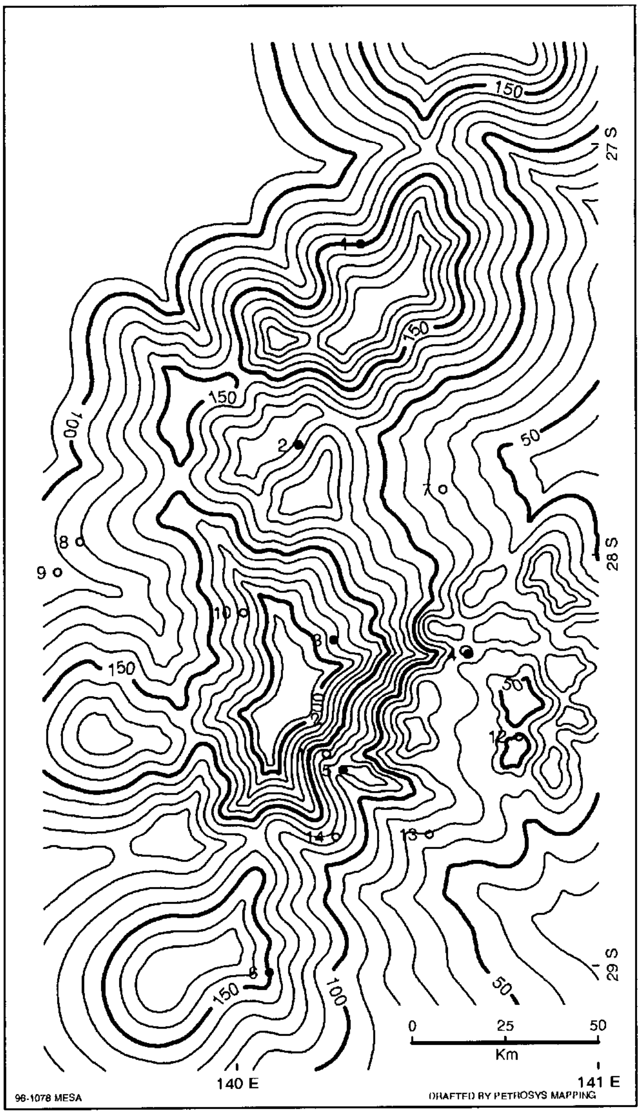

Fig. 9.12 Restored isopach map of Namba Formation (Late Oligocene – Late Miocene; contour interval 10 m).

stratigraphic elements of the Cooper region (Cuttapirrie 1, Merrimelia 30, Moomba 57, Jena 1, Strzelecki 5 and Tinga Tingana 1) are presented here (Figs 9.14–9.18). Detailed discussion of the burial history of the Cooper, Eromanga and Lake Eyre Basins in northeast South Australia are given by Moussavi-Harami (1996). Interpretation is presented below in ascending order from sequence set J–K to T–Q and mostly from the northern to southern part of the study area.

SEQUENCE SET J–K

After a long period of uplift and erosion from Late Triassic – Early Jurassic, continental downwarping within the Australian landmass created the Eromanga Basin and sedimentation continued from the Early Jurassic – Late Cretaceous (~193–90 Ma), without any major break.

Lower non-marine succession

In the Patchawarra Trough and on the Merrimelia Ridge, the subsidence rate above the basal unconformity was initially moderate (average 10.3, 14.2 and 10.9 metres per million years (m/my) in Lycium 1, Cuttapirrie 1 and Merrimelia 30 respectively) during deposition of the Poolowanna facies and Hutton Sandstone, and decreased to an average of 5.5–9.5 m/my during deposition of the Birkhead Formation (~175 Ma; Fig. 9.14). The higher subsidence rate was mostly related to rapid deposition of coarse-grained siliciclastic sediments in fluvial environments, and to tectonic subsidence. The lower rate can be attributed to reduced sedimentation and compaction rates in the Patchawarra Trough (Fig. 9.19). As seen on the restored isopach map of the Birkhead Formation (Fig. 9.4), two major depocentres were present in the Patchawarra Trough. As a result, the rate of subsidence in these areas was higher (average 8.25 and 9.1 m/my in Kuenpinnie 1 and Cuttapirrie 1 respectively) than other parts of the basin.

Due to a high rate of coarse-grained siliciclastic sedimentation (Adori Sandstone, Westbourne Formation and Namur Sandstone) in the Late Jurassic (~165–145 Ma; Fig. 9.19), the subsidence rate increased again in the northern part of the study area (average 10 and 11 m/my in Merrimelia 30 and Cuttapirrie 1 respectively; Fig. 9.14). However, during deposition of the Murta Formation (Neocomian) the subsidence rate was low to moderate (~6.5 m/my) in the Patchawarra Trough because of a low rate

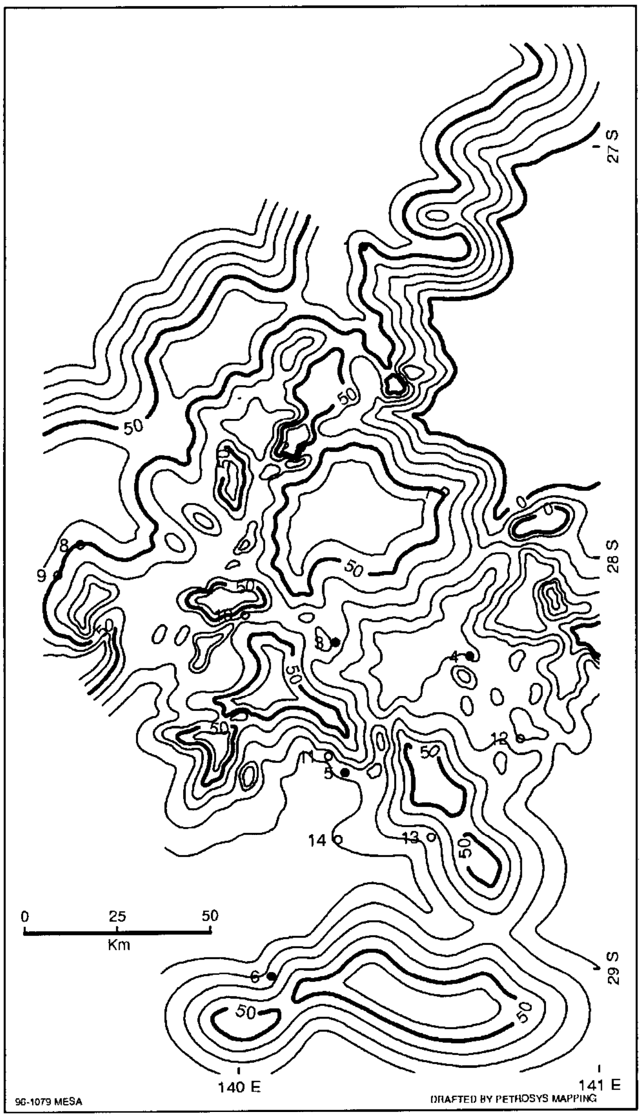

Fig. 9.13 Isopach map of Late Pliocene – Quaternary (contour interval 10 m).

of fine-grained siliciclastic sedimentation in the lacustrine environment (Fig. 9.19).

During Early–Middle Jurassic, the rate of subsidence in the Wooloo Trough (average 11 m/my in Kirralee 1) and the Moomba high (average 10.46 m/my in Moomba 57; Fig. 9.15) was relatively moderate and higher than the Nappamerri and Allunga Troughs (average 7.1 m/my in Bulyeroo 1 and 3.46 m/my in Pinna 1). This can be related to the higher rate of coarse-grained siliciclastic sedimentation in this area. During the later Jurassic (~175–165 Ma) differential compaction in the Nappamerri Trough created more accommodation for deposition of fine-grained sediments of the Birkhead Formation in a lacustrine environment. Subsequently, the rate of subsidence during this period was higher in the Nappamerri Trough (average 13.5 m/my) than over the Moomba high (~8 m/my). During the Tithonian (165–145 Ma), the subsidence rate in the central part of the study area was moderate, ranging from 13.5 m/my in Moomba 57 to 20 m/my in Bulyeroo 1. This again resulted from rapid deposition of very coarse grained siliciclastic sediments (Fig. 9.19), differential compaction between trough and high (Fig. 9.5) as well as tectonic sinking. At the beginning of the Early Cretaceous the subsidence rate decreased again resulting from a low rate of fine-grained siliciclastic sedimentation of the Murta Formation.

During deposition of the Early–Middle Jurassic sediments in the southern and southeastern portions of the study area, the subsidence rate was low, ranging from 3.08 m/my in Mulga 2 to 4.88 m in Jena 1 (Fig. 9.16) and Kobari 1. This low rate was due to onlap of sediments over the Murteree Ridge and on the margin of the Cooper region. During deposition of the Birkhead Formation (~175 Ma), the subsidence rate decreased to an average of 3–5 m/my, which resulted from a low fine-grained siliciclastic sedimentation rate. Due to rapid deposition of coarse-grained terrigenous sediments of the Adori Sandstone, Westbourne Formation and Namur Sandstone in the Late Jurassic (~165–145 Ma), the subsidence rate in the south and southeast increased to an average of 14 m/my (Fig. 9.17). This was less (~12 m/my) in Kobari 1 and Tinga Tingana 1 (Fig. 9.18).

In general, from the Early Jurassic – Early Cretaceous, the rates of subsidence decreased from the north (average 15 m/my in Cuttapirrie 1) toward the south (~6.22 m/my in Tinga Tingana 1). This can also be seen on the restored isopach map of the J–K sequence set, where the major depocentre was in the northern Patchawarra Trough and the thickness of the sequence increases toward the northeast into the Queensland, while it gradually thins toward the northwest and southeast (Fig. 9.10).

Marine succession

Due to comparatively greater downwarping of the northern part of the Australian continent in the Early Cretaceous (~135.5 Ma), the epicontinental sea transgressed from northeast toward the south and southwest into the South Australian portion of the Eromanga Basin. The oldest marine unit is the Cadna-owie Formation (sequence K_1) that was deposited as a highstand systems tract in high-energy shoreline to shallow marine environments. The rate of subsidence was relatively low during deposition of the Cadna-owie Formation (Figs 9.14–9.18), averaging 4–5 m/my in the Patchawarra Trough and the Nappamerri Trough. This rate decreased toward the south to an average of 3 m/my in the Kobari Embayment and Tinga Tingana trough. The low subsidence rate at this time is mainly due to deposition of fine to medium-grained siliciclastic sediments rather than tectonic sinking (Fig. 9.19).

The first major transgression started in the Aptian (~117.5 Ma) and lasted through early Albian time (108 Ma). This transgression created sufficient accommodation space for very rapid deposition of a thick fine-grained siliciclastic sequence of the Bulldog Shale and the Wallumbilla Formation (sequence K_2). Maximum marine transgression was reached during deposition of the upper Bulldog Shale and equivalents, which is also consistent with the global sea-level curves of Haq *et al.* (1987, 1988). During this period, the rate of subsidence was high in the northern Patchawarra and central Nappamerri Troughs, averaging 43.20 and 42.11 m/my in Cuttapirrie 1 (Fig. 9.14) and Bulyeroo 1, respectively, as a result of a higher rate of fine-grained siliciclastic sedimentation in a marine environment (Fig. 9.19), as well as basement subsidence.

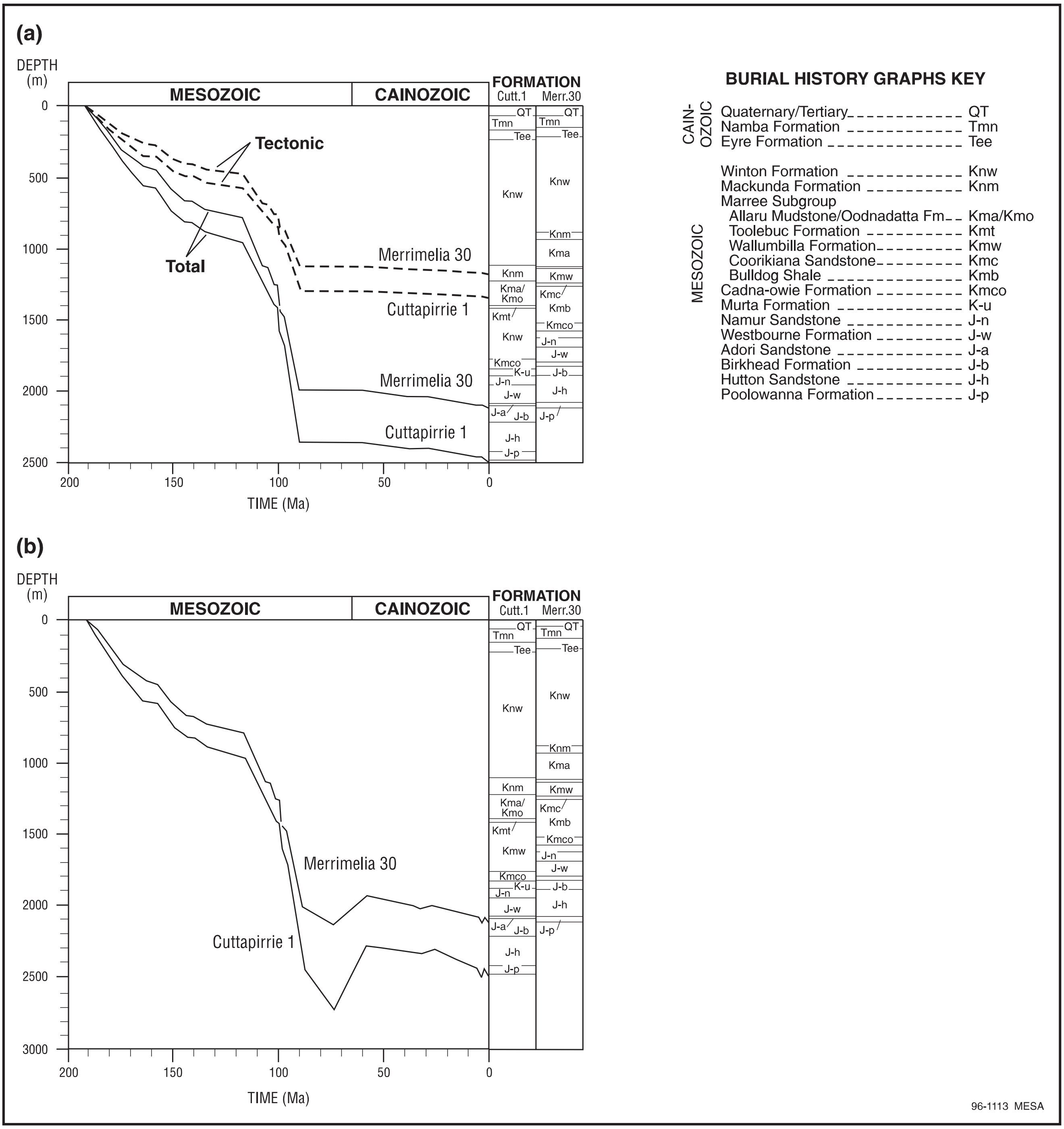

***Fig. 9.14 (a)** Burial history of Cuttapirrie 1 (trough) and Merrimelia 30 (ridge). Solid lines show total subsidence and dashed lines tectonic subsidence.* ***(b)** Interpretive burial history of Cuttapirrie 1 and Merrimelia 30. Parameters in Table 9.2 have been used for construction of the interpretive diagrams.*

This higher sedimentation rate was possibly related either to slumping and mass flow processes on a mildly unstable shelf, or to rapid deposition along reactivated major faults in these areas. However, it decreased to an average 32.63 and 26.32 m/my over ridges (Merrimelia 30 and Jena 1; Figs 9.14, 9.16). The difference between troughs and ridges can be attributed to sediment loading and compaction and possibly to minor tectonic subsidence, as suggested by Zhou (1989). A restored isopach map of the Marree Subgroup also shows that the maximum thickness of these units was >900 m in the northern Patchawarra and Nappamerri Troughs, increasing toward the northeast into the central Eromanga Basin in Queensland (Fig. 9.8). This very high subsidence rate decreases gradually toward the west and northwest to ~28.95 m/my in Lycium 1 in the southern Patchawarra Trough. By comparison, ~1000 km further west, close to the southwestern margin of the basin, the subsidence rate is 4.3 m/my in Manya 5 (Officer Basin ;Moussavi-Harami and Gravestock, 1995), and is probably related to sediment loading rather than tectonic activity. During this period, the subsidence rate in Kirralee 1 (~33.5 m/my) was less than in Moomba 57 (41.05 m/my; Fig. 9.15), because the former is located at the margin of the Wooloo Trough. Due to a lower rate of fine-grained siliciclastic sedimentation, the subsidence rate also decreased to 31.58, 27.37 and 28.11 m/my in Strzelecki 5 (Fig. 9.17), Toolachee 36 and

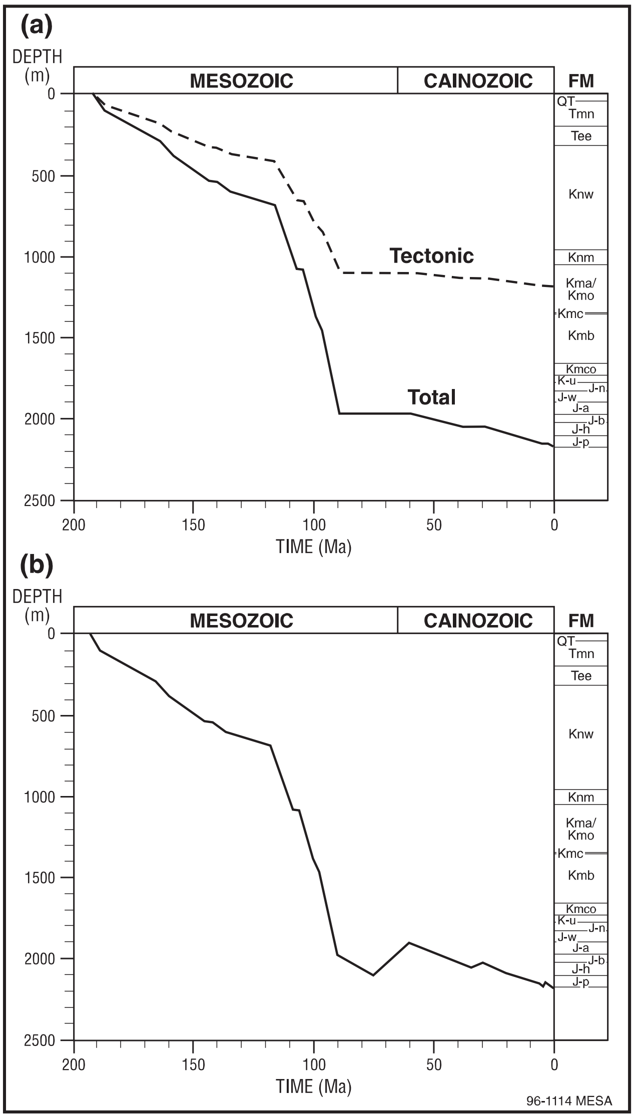

***Fig. 9.15 (a)** Burial history and **(b)** interpretive burial history of Moomba 57. Parameters in Table 9.2 have been used for construction of the interpretive diagram.*

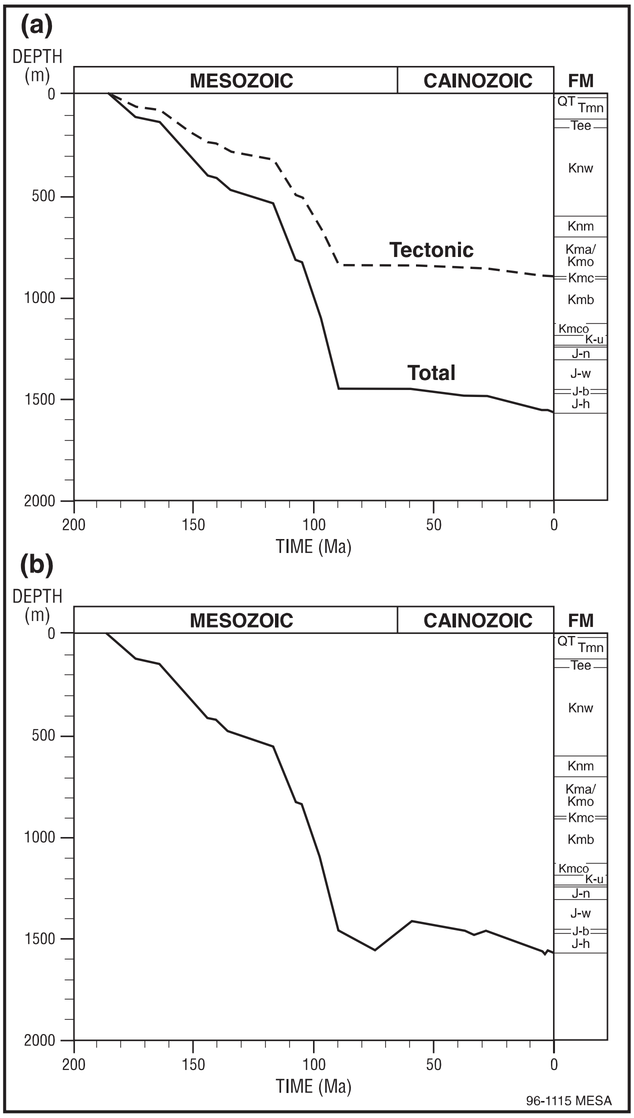

***Fig. 9.16 (a)** Burial history and **(b)** interpretive burial history of Jena 1. Parameters in Table 9.2 have been used for construction of the interpretive diagram.*

Mulga 2, respectively. Further south the subsidence rate decreased in the Kobari Embayment (~25.89 m/my in Kobari 1), and reduced to 12.57 m/my for the total Marree Subgroup in the Tinga Tingana trough (Fig. 9.18) where the sedimentation rate was relatively low (Fig. 9.19).

In middle Albian time, the sea regressed toward the east and the Coorikiana Sandstone was deposited, during a lowstand phase of sedimentation in a shoreline environment (Fig. 9.2). During the late Albian, sea level rose again rapidly worldwide, and maximum transgression took place during this period, depositing mainly marine shales and mudstones of sequence K_3 (upper Marree Subgroup; Fig. 9.2). During this period, the basin subsided at a relatively higher rate in troughs (e.g. 46.8 m/my in Bulyeroo 1) than on ridges (e.g. 27.5 m/my in Jena 1). This is interpreted to be caused in part by very high rates of fine-grained siliciclastic sediment loading and compaction rather than tectonic activity (Fig. 9.19). A restored isopach map of the Marree Subgroup and Mackunda Formation shows that a major depocentre may have been present in the southern Nappamerri Trough and the maximum rate of subsidence may have taken place in this area, but the paucity of data does not allow a better understanding in support of this interpretation (Fig. 9.8). During deposition of these units, the subsidence rate was lower in the south (average 25 and 16 m/my in Kobari 1 and Tinga Tingana 1 respectively), which resulted from a lower rate of sedimentation in this area (Figs 9.18, 9.19). Overall, the subsidence rate during late Albian – early Cenomanian Mackunda Formation deposition (Fig. 9.2) was higher in the northern Patchawarra Trough (~52 m/my in Cuttapirrie 1; Fig. 9.14) than other parts of the study area. This high subsidence rate can be related to sediment loading and compaction, as well as probably tectonic sinking. The subsidence rate decreased toward the southwest in the southern Patchawarra Trough (average 23.2 m/my in Lycium 1). This is interpreted to be related to a lower rate of sedimentation (as shown on restored isopach map, Fig. 9.8) and compaction, as Lycium 1 approaches the crest of one of the structures which comprises the Birdsville Track Ridge. Southward, subsidence also decreased to an average of 14 and 30 m/my in Kobari 1 and Tinga Tingana 1 which is mainly related to a lower sedimentation rate over relatively shallow Proterozoic basement, but with continued subsidence of the Tinga Tingana trough.

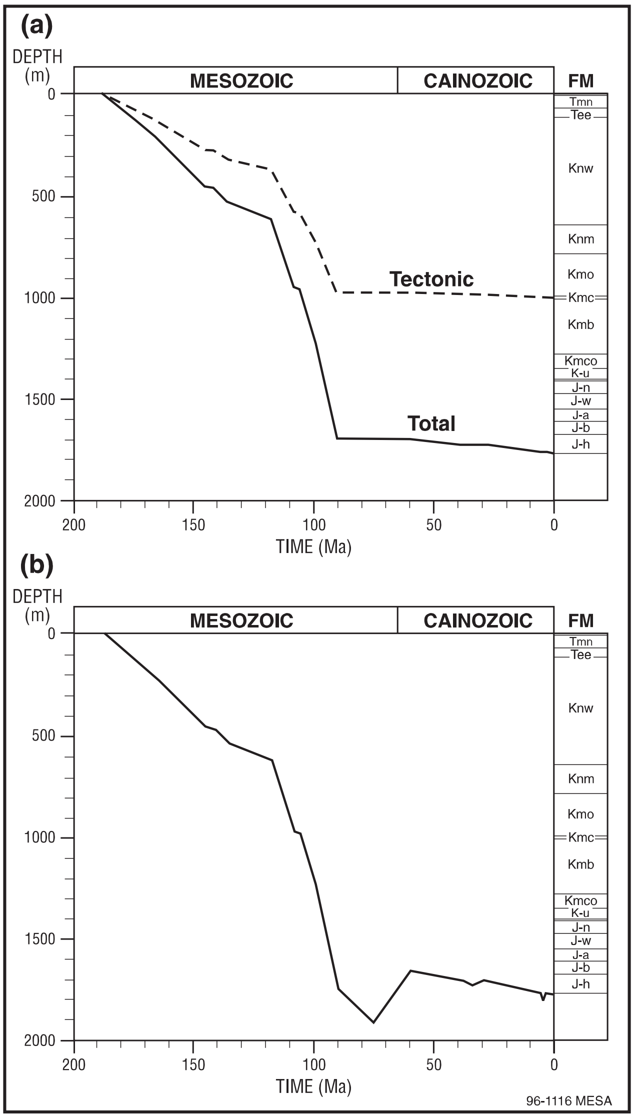

Fig. 9.17 *(**a**) Burial history and (**b**) interpretive burial history of Strzelecki 5. Parameters in Table 9.2 have been used for construction of the interpretive diagram.*

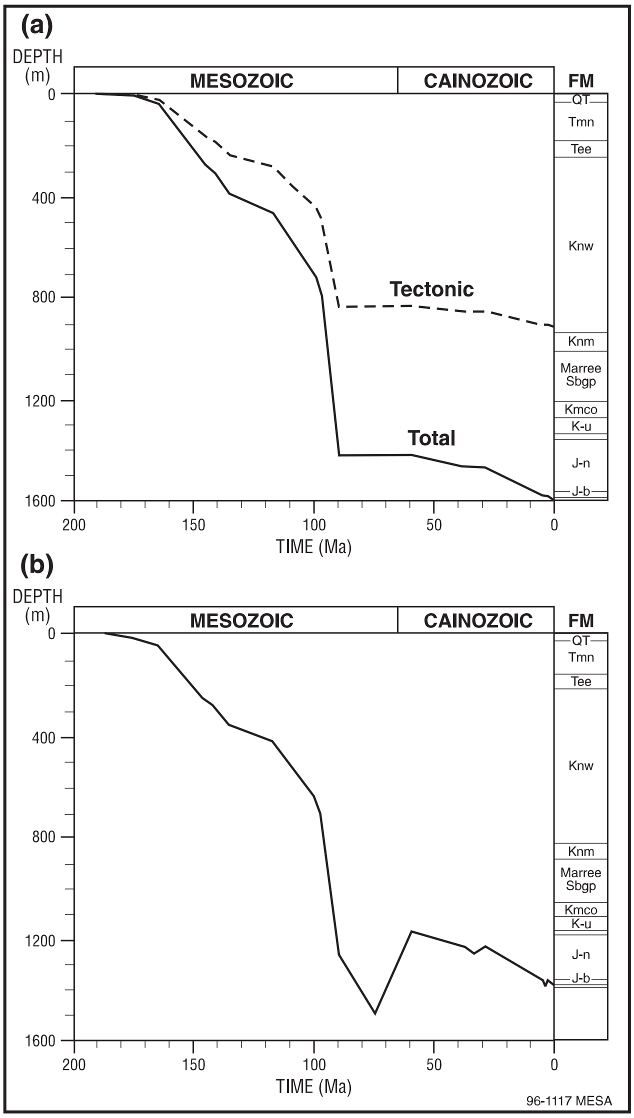

Fig. 9.18 *(**a**) Burial history and (**b**) interpretive burial history of Tinga Tingana 1. Parameters in Table 9.2 have been used for construction of the interpretive diagram.*

Upper non-marine succession

This period of subsidence, which created more accommodation space for deposition of marine sequences (K_1, K_2 and K_3) was followed by a fall of sea level and the study area became a site of continental sedimentation. During the Late Cretaceous (Cenomanian), the rate of subsidence was much higher in the northern Patchawarra Trough (average 122.67 m/my in Cuttapirrie 1) and the Nappamerri Trough (113.33 m/my in Bulyeroo 1) than over the intervening GMI Ridge (average 93.33 m/my in Merrimelia 30; Fig. 9.14). This was mainly due to differential compaction and very rapid deposition of fine to medium-grained siliciclastic sediments of the Winton Formation in fluvial and lacustrine environments, as well as tectonic sinking along the old zones of weakness, as suggested by Moore and Pitt (1984). A restored isopach map of the Winton Formation (Fig. 9.9) also shows that the major depocentre was in the northern Patchawarra Trough. More than 1125 m of sediments were deposited in this area, thickening toward the northeast into Queensland. Southward, the subsidence rate decreased to an average of 60 m/my in Kobari 1, but increased to 85.33 m/my in the Tinga Tingana trough (Fig. 9.18), resulting from sediment loading and basement subsidence in the trough. The subsidence rate in Toolachee 36 and Strzelecki 5 was much lower than in troughs to the north (~77 m/my; Fig. 9.17) and was probably related to a lower rate of sedimentation and compaction between ridges and troughs (Fig. 9.19). Thinning of the Winton Formation toward the margin of the basin is mainly related to severe erosion during Late Cretaceous – early Tertiary time (e.g. Alexander *et al.*, 1996).

In relation to a very high subsidence rate in the Early–Late Cretaceous, Gallagher and Lambeck (1989) suggested that subsidence of the Eromanga Basin in the Jurassic followed a simple thermally-based mechanism, by which subsidence rate decreases exponentially to nearly linear with time. However, from the mid-Cretaceous (~110 Ma) the rates of subsidence increased suddenly by ~5–10 times that of the earlier Jurassic and lasted for ~20 million years through the Late Cretaceous. These authors concluded that this rapid subsidence rate during deposition of marine and upper non-marine portions of the Eromanga Basin resulted from

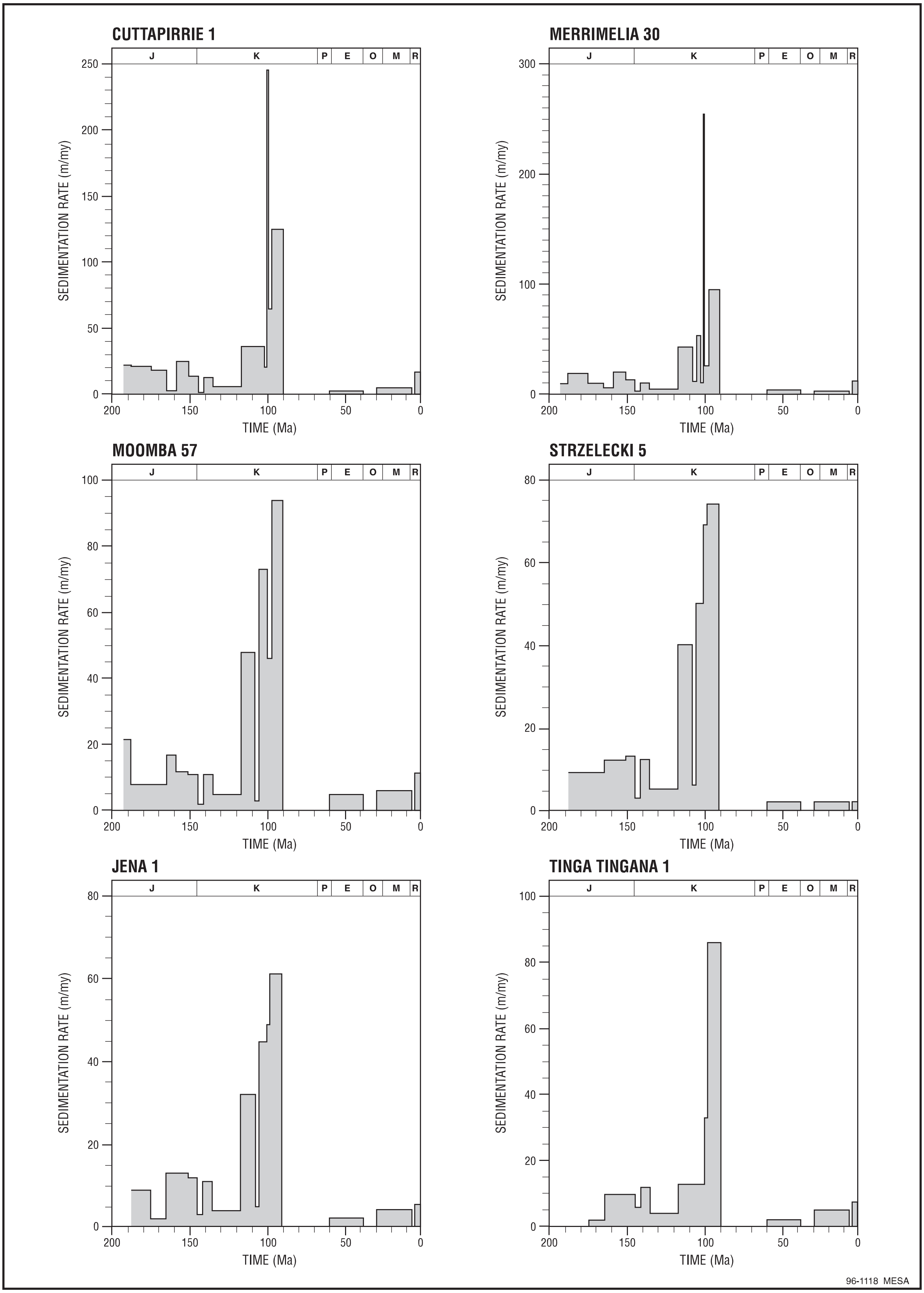

Fig. 9.19 *Sedimentation rate versus time for six wells, representing different structural elements in the Cooper region. Note the rate of sedimentation is very high during the Early–Late Cretaceous.*

variation in sediment influx, with sediment sourced from an active volcanic arc located off the east coast of the Australian continent, rather than from a primarily tectonic mechanism beneath the lithosphere of the Eromanga Basin. Zhou (1989) suggested that the abnormal subsidence during deposition of marine and upper non-marine portions of the Eromanga may be caused by: regional tectonic compression that was generated by rifting processes on the southern and eastern margin; active volcanoes along the northeast margin of the continent; and metamorphic phase transition in the deepest parts of the crust from eclogite to granulite. Based on this study, the high subsidence rate during the Early–Late Cretaceous is mainly related to rapid deposition of fine-grained siliciclastic sediments in marine and non-marine environments, as well as possibly tectonic subsidence along reactivated major faults.

WINTON UNCONFORMITY

The Winton epoch of sedimentation and subsidence was followed by a period of uplift and erosion from Turonian – Late Palaeocene (~90–60 Ma). This is attributed to east-west directed basement compression on a regional scale, starting from the eastern margin of the continent (Veevers, 1984; Shaw, 1991). This period of non-deposition is shown as a horizontal segment on the tectonic and total subsidence curves (Figs 9.14a–9.18a). A restored isopach map of the Eromanga sequence set shows that >3000 m of sediment may have been deposited in the Cooper region, within the Patchawarra and Nappamerri Troughs, increasing into southwestern Queensland (Fig. 9.10). Moore and Pitt (1984) estimated that up to 800 m of the Winton Formation were eroded from the crests of major structures in southwestern Queensland where erosion was severe; this erosion was less in South Australia. It is calculated that >350 m of sediment were eroded over the Innamincka Dome where the Winton Formation crops out at the surface; this is similar to estimates suggested by Moore and Pitt (1984). Based on a restored isopach map of the J–K sequence set, it is calculated that the amount of section lost at the top Winton unconformity ranges from 150 to 440 m (Table 9.2). The maximum estimate of section lost was in Cuttapirrie 1, close to the margin of the Cooper Basin, and is possibly related to the initiation of movement of the Cordillo Dome in the north prior to deposition of the Eyre Formation. The amount of section lost during the Late Cretaceous – early Tertiary in the drillholes studied is presented in Table 9.2. Lost section is also shown by upward movement of the curves on the interpretive burial history diagrams (Figs 9.14b–9.18b).

SEQUENCE SET T–Q

During the Late Paleocene – Middle Eocene (~60–38 Ma), sedimentation resumed in northeast South Australia and coarse-grained siliciclastic sediments of the Eyre Formation were deposited as sheet sands in braided stream systems. This sequence (T_1) subsided at a very low rate, ranging from 0.91 to 6.45 m/my. A restored isopach map of the Eyre Formation shows that the major depocentres were in the southern Nappamerri Trough, Moomba high, Wooloo Trough and Allunga Trough (Fig. 9.11), where the subsidence rate was higher than other parts of the study area (6.45, 5.45 and 4.55 m/my in Moomba 57, Kirralee 1 and Pinna 1 respectively). In general, the distribution of sediments during the Late Paleocene – Middle Eocene is mainly related to the structural highs that were formed during Permian and Triassic time, as also noted by Callen in Gravestock *et al.* (1995). The subsidence rate over the GMI and Murteree–Nappacoongee Ridges was very low (~3.41 and ~2.27 m/my in Merrimelia 30 and Jena 1 respectively). The differences in subsidence rate between troughs and ridges is mainly related to higher sediment loading and compaction rather than basement subsidence.

This period of sedimentation was followed by a prolonged period of uplift and erosion, from Late Eocene – Early Oligocene (~38–29.3 Ma), related to an epeirogenic movement. During this period, portions of the Early Tertiary (T_1) and Late Cretaceous (Winton Formation) sedimentary section were eroded from the crests of anticlines, such as the Innamincka Dome and domes comprising the Birdsville Track Ridge (Wopfner et al, 1974; Moore and Pitt, 1984). Shaw (1991), in his study of the Tertiary structures in southwestern Queensland, suggested that in addition to regional Tertiary uplift, deformation during this period may have also involved reactivation of pre-existing basement faults. Based on a restored isopach map of the Eyre Formation, it is calculated that the amount of section lost during the Late Eocene – Early Oligocene in the study area, ranges from 12 to 36 m (Table 9.2). However, the sparseness of Tertiary data does not allow confirmation of the amount of erosion, which may have been greater than that assumed here. Maximum erosion was over the Innamincka Dome (~50–60 m).

After this period of uplift and erosion, downwarping (~29.3 Ma) caused the Moomba high and the Wooloo Trough areas to subside at a relatively higher rate than other parts of the study area during the Late Oligocene – Miocene. The subsidence rate was ~7.13 and ~7.08 m/my in Moomba 57 and Kirralee 1, respectively. This moderate rate can be attributed to deposition of carbonate (dolomite) in a large shallow alkaline lake that formed during the Late Eocene and Early Oligocene. As seen on the restored isopach map for the Namba Formation (Fig. 9.12), there may have been a number of depocentres (lakes) present during the Late Oligocene – Miocene in the northern and western parts of the study area, where dolomite formed. Lower rates of subsidence occur in the east and southeast of the Cooper region (average 2.70, 2.0 and 1.88 m/my in Strzelecki 5, Toolachee 36 and Mulga 2 respectively). This is related to both the gradual uplift of the area, which prevented the formation of dolomite, and to the lower rate of sedimentation (Fig. 9.19), as shown by thinning of the Namba Formation on the restored isopach map (Fig. 9.12). A very low rate of subsidence in Bulyeroo 1 (average 1.17 m/my) in the central Nappamerri Trough is also related to slow uplift from the east.

During the Early Pliocene (~5.3 Ma), an epeirogeny caused the study area to be a site of erosion and non-deposition. Based on a restored isopach map, it is calculated that the amount of section lost ranges between 15 m (in Toolachee 36) and 54 m (in Bulyeroo 1; Table 9.2). The amount of section lost may have been more, but the paucity of data does not allow confirmation of this much erosion. It is also interpreted that the maximum estimated thickness of sediment eroded during this period was >100 m on the western flank of the Innamincka Dome (Fig. 9.12), related to gradual uplift of the dome. The amount of uplift and erosion was probably more severe in the western Eromanga Basin where up to 500 m of sediment were eroded on the crest of the Dalhousie–McDills Ridge (Alexander and Jensen-Schmidt, 1995). On the southern margin of the basin 350 m of uplift and erosion of the northern Flinders Ranges occurred during Miocene time (Foster *et al.*, 1994).

In the Late Pliocene – Quaternary, the basin subsided and sedimentation resumed as fine to coarse-grained siliciclastics were deposited in fluvial and aeolian environments. The rate of subsidence was relatively higher in the Nappamerri Trough and Patchawarra Trough (average 16 m/my) than the Merrimelia and Murteree–Nappacoongee Ridges (average 12.42 and 5.45 m/my in Merrimelia 30 and Jena 1 respectively; Figs 9.14, 9.16). An isopach map of the surface to top Namba Formation (sequence T_3–Q; Fig. 9.13) indicates that the thickness of this sequence is <10 m over the Murteree–Nappacoongee Ridge and the Strzelecki and Toolachee Fields. Thinning over ridges and highs is related to late Tertiary and Quaternary structural activity and basement movement along pre-existing structural trends, which are still active today.

IMPLICATIONS FOR PETROLEUM EXPLORATION

Important implications derived from this burial history analysis include an understanding of timing of hydrocarbon source maturity and of the effects of burial history on petroleum reservoir properties. In addition subsidence and sedimentation rates for all 14 modelled drillholes enabled adjustments to age interpretations based on limited palynological data for the Late Jurassic Birkhead Formation, Adori Sandstone, Westbourne Formation and Namur Sandstone.

HYDROCARBON SOURCE MATURITY

During Early Jurassic – Early Cretaceous deposition of the lower non-marine sequence set, sediments subsided at a higher rate in the Patchawarra Trough than other parts of the basin.

Some Late Jurassic and Early Cretaceous source rocks reached maturity during the Late Cretaceous, when thick siliciclastic sediments of the Winton Formation were deposited. This is also supported by evidence of high to very high subsidence and sedimentation rates during this period. However, oil generation commenced according to the depth of burial and the local palaeogeothermal gradient. Moore and Pitt (1984) stated that in the Nappamerri Trough, where palaeotemperature was high, the Late Jurassic source rocks reached the initial stage of maturation in the early Late Cretaceous (~ 90–100 Ma), while in other parts of the basin these rocks reached maturity in Late Cretaceous – early Tertiary. Kantsler *et al.* (1986) also believed that the lower and Middle Jurassic source rocks reached maturity after deposition of Winton Formation, in the Late Cretaceous – Tertiary. Based on data from oil and source maturity, Tupper and Burckhardt (1990) concluded that generation of hydrocarbon in the Eromanga Basin commenced prior to maximum burial depth and that peak expulsion of oil occurred during the Late Cretaceous. Consequently, structures that formed before the early Tertiary uplift are the best exploration targets. Based on the above discussion, generation and migration of petroleum in the Eromanga Basin may be continuing at the present time.

RESERVOIR QUALITY

Porosity in the Eromanga Basin reservoir rocks, such as Hutton and Namur Sandstones, is mainly intergranular primary (E. Alexander, MESA, pers. comm., 1996). Minor secondary porosity is also present in the Hutton Sandstone in southwestern Queensland and formed from dissolution of feldspar and lithic fragments (Green, Eadington *et al.* 1989). These porosities may have been generated at maximum depth of burial sometime during the Early–Late Cretaceous.

LATE JURASSIC CHRONOSTRATIGRAPHY

Using the palynological framework of Price *et al.* (1985), >200–250 m of fine to coarse-grained siliciclastic sediments of the Adori Sandstone, Westbourne Formation and Namur Sandstone were deposited in a very short period of time (~5 Ma) in the Late Jurassic (Tithonian). However, the subsidence and sedimentation rates, using standard chronostratigraphy, were anomalously high during this period and considering that the central part of the Australian continent was not tectonically active during the Early–Middle Jurassic (Veevers, 1984; Veevers and Li, 1991; Veevers *et al.*, 1991), this high sedimentation and subsidence rate is unlikely. The spore–pollen biozonation of the Eromanga succession is of low resolution and is difficult to correlate with other regions where radiometric age control is provided. Thus, a revision of the absolute age date was necessary to produce a more realistic and consistent lower rate of subsidence and sedimentation. This revision (Table 9.3), used for reconstruction of the burial history and sedimentation-rate charts, illustrates clearly that prior to very rapid deposition in marine environments and high subsidence in the Early–Late Cretaceous, this region was subsiding at a very slow to moderate rate.

CONCLUSIONS

Burial history analysis of the Eromanga Basin in northeast South Australia, using data from 14 key drillholes in principal structural elements of the basin, leads to the following conclusions:

- During the Early Jurassic to the beginning of the Early Cretaceous, the subsidence rate in the north (Patchawarra Trough) was higher than other parts of the Cooper region.
- The subsidence rate during the Early–Late Cretaceous was high due to rapid deposition of fine-grained siliciclastic sediments of the marine and upper non-marine successions of the Eromanga sequence set.
- The Jurassic source rocks of the Eromanga Basin are likely to have reached initial stages of hydrocarbon

generation in the late Early to Late Cretaceous, when the subsidence rate was relatively high, and became fully mature in the Late Cretaceous – early Tertiary.

- Based on reconstruction of the restored isopach maps, the amount of section lost at the Late Cretaceous unconformity ranges from 150 to 440 m in the Cooper region.
- The combination of burial history curves and sedimentation-rate diagrams can be used to improve the absolute stratigraphic age and correlation in thick, non-marine siliciclastic sequences where biostratigraphic resolution is low.

Table 9.1 *Simplified glossary of subsidence rate descriptors used in this study.*

Descriptor	**Total subsidence rate** (m/my)	**Example**
Low	<5	Intracratonic basins (e.g. Cooper, Eromanga, Lake Eyre Basins)
Moderate	5–25	Intracratonic basins
Rapid	26–200	Foreland basins (e.g. Officer Basin; Moussavi-Harami and Gravestock, 1995)
Very rapid	201–500	Rift basins (e.g. Otway Basin; Hill, 1995)
Pulsed rapid*	>500	Rift basins (e.g. Otway Basin; Hill, 1995)

*Transient, short-lived movements.

Table 9.2 *Interpretive amount of section lost by erosion at each unconformity.*

Drillhole	**Top Winton Fm (Eromanga) unconformity** (m)	**Top Eyre Formation unconformity** (m)	**Top Namba Formation unconformity** (m)
Bulyeroo 1	230	28	54
Cuttapirrie 1	440	19	54
Jena 1	150	25	22
Kirralee 1	310	16	18
Kobari 1	240	36	32
Kuenpinnie 1	250	12	15
Lycium 1	320	20	17
Merrimelia 30	200	20	35
Moomba 57	200	32	25
Mulga 2	270	13	30
Pinna 1	225	18	37
Strzelecki 5	250	24	40
Tinga Tingana 1	320	29	26
Toolachee 1	260	25	15

Table 9.3 *Former and revised absolute ages of the lower boundaries of some Late Jurassic formations. The revised ages were used for construction of burial history diagrams.*

Formation	**Age** (Ma)	**Revised age** (Ma)
Murta Formation	145	135.5–145
Namur Sandstone	147	145–151
Westbourne Formation	148	151–159
Adori Sandstone	150	159–165
Birkhead Formation	167	165–175