

A PETROLEUM GEOLOGY ANALYSIS OF THE CANTERBURY BASIN, NEW ZEALAND

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The Canterbury Basin developed over an active low relief Cretaceous erosion surface. Tectonic activity began in the Albian when a series of failed rift grabens developed. These were infilled by fluvial and coastal paralic coal measures, and conglomeratic sandstone and breccias. Thermal subsidence and related transgression in the late Cretaceous resulted in widespread deposition of coal measures in the western part of the basin. Slow progressive marine transgression continued, culminating in deposition of Oligocene limestones. A change to a compressional regime during the Miocene caused partial eversion of the basin, generating its present configuration with a regional southeast dip. The Miocene to Recent sequence represents a regressive cycle with deposition of mainly calcareous siltstones, sandstones and minor bioclastic limestones.

Canterbury basin is a "median" basin with normal to high geothermal gradients, and trap styles comprising broad and gentle basement block uplifts over which structural-stratigraphic culminations and pinch outs are developed.

Cretaceous to early Paleocene coal measures and carbonaceous shales constitute the most obvious potential source rocks. These are restricted to the southeast of the region.

Isotherms deepen in the southeast due to extensive Miocene and Pliocene foreset bedding related to slope and shelf progradation. The onset of oil generation occurs in the 2500-3600+ m range, limiting maturation of the coal measures to the offshore eastern part of the area, although half-grabens locally carry the sequence deeper.

Sandstones of the transgressive system are the principal potential reservoirs. A widespread sandstone unit is also associated with the Oligocene depositional system and provides an additional reservoir model.

TECTONIC HISTORY

The Canterbury Basin system (Fig. 1) was initiated in the Aptian, with the development of localised grabens and half grabens associated with major rifting of Gondwana to the distant east. This rifting in the Bounty Trough Fracture system coincided with the initiation of a period of quiescence along the convergent margin between the Gondwana and Pacific plates. This margin lay along the northern margin of the paleo-Chatham Rise, which was also the northern margin of the Canterbury Basin. The fracture system developed into the Bounty Trough, and remained active to the early Cenomanian. This major crustal break, coupled with a virtual cessation of activity on Gondwana's convergent margin, began the isolation of the New Zealand continent and its tectonic and sedimentary systems. Complete isolation was established in the Campanian, when the New Zealand continent split from the then combined Australian and Antarctic plates, with development of the Proto-Tasman Sea by generation of new oceanic crust. As a consequence of this activity, continental cooling began in the Campanian, and resulted in regional thermal depression.

Subsequently, the New Zealand continent drifted away from the Australian and Antarctic plate. As it moved beyond the

site of up-welling and heating of the lithosphere, it cooled further, accelerating thermal contraction, and causing regional subsidence within the continent. In the Canterbury area, this effect reached its zenith in the Maastrichtian. The effect slowed through the basal Tertiary and was complete in the Oligocene, when the basin, along with much of the New Zealand continent, was submerged.

From the Aptian to the early Eocene, much of the Chatham Rise, then the continental margin, was above sea level. As part of the development of the Marlborough-East Coast Basin, the north face of the rise was progressively depressed, essentially submerging the feature from the north. The Upper Cretaceous and early Paleogene sequences of the Canterbury Basin thin northwards onto the rise, and the Oligocene rocks cover it (Fig. 2, 3 and 4).

Australia and Antarctica began to break apart in the late Eocene, and although the structural effect on New Zealand was negligible, it led to a change in the movement of ocean currents. The circum-Antarctica current developed in the Oligocene as part of this change. The current entered the Canterbury Basin area in the Oligocene, causing a period of sub-marine erosion.

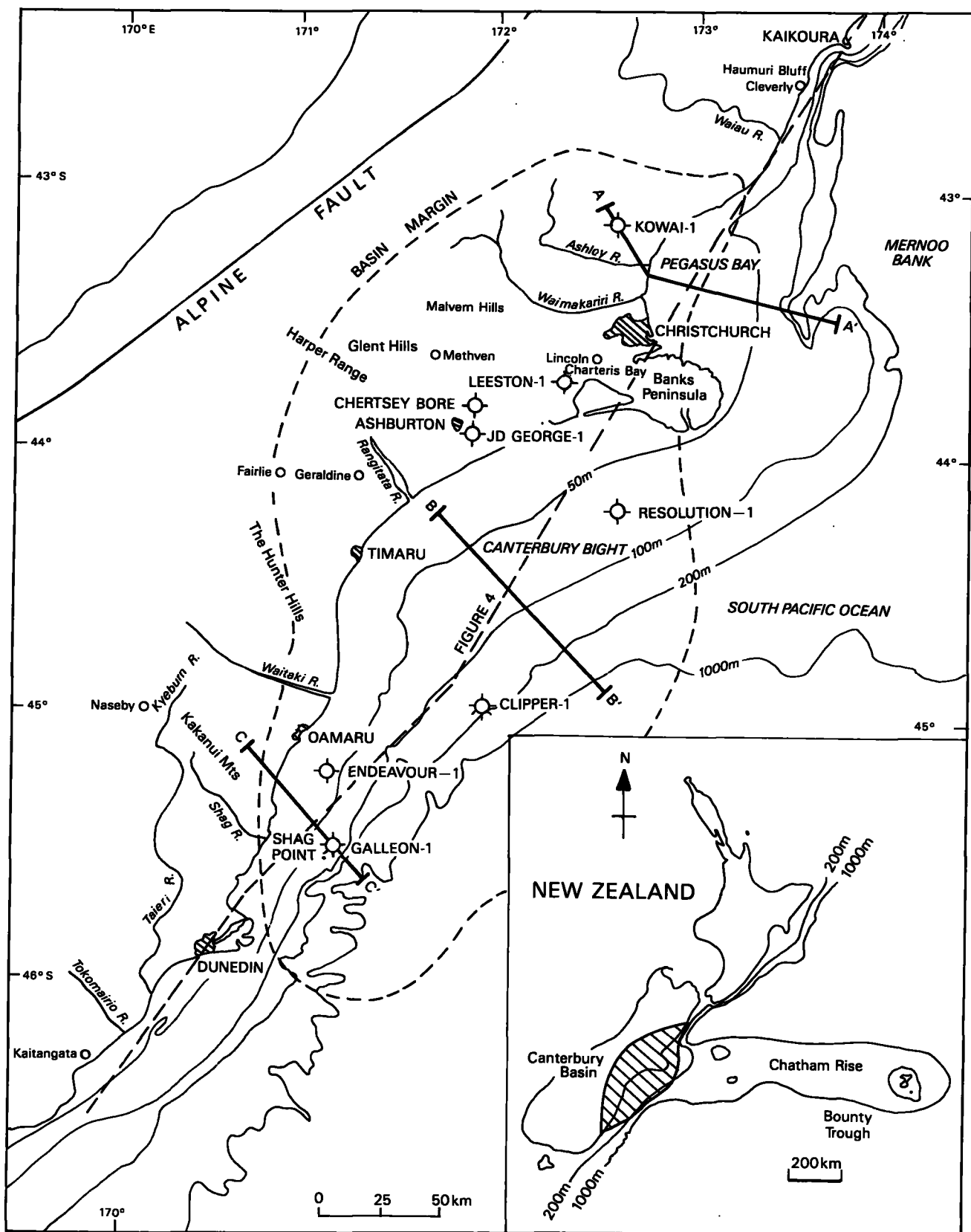


Fig. 1: Location map.

In the early Oligocene the Indo-Australian plate collided with Asia, stopping its northward drift. Almost immediately after, as part of the same activity, the Pacific plate began to bear against the Indo-Australian. This resulted in the development of a new subduction zone along the line of the earlier

Permian Neocomian Gondwana system, and in the rotation of the New Zealand continental plate west of the Chatham Rise to its present position. The resulting realignment of stresses caused the mid-Miocene development of the transform fault system, which became the Alpine Fault. Activity

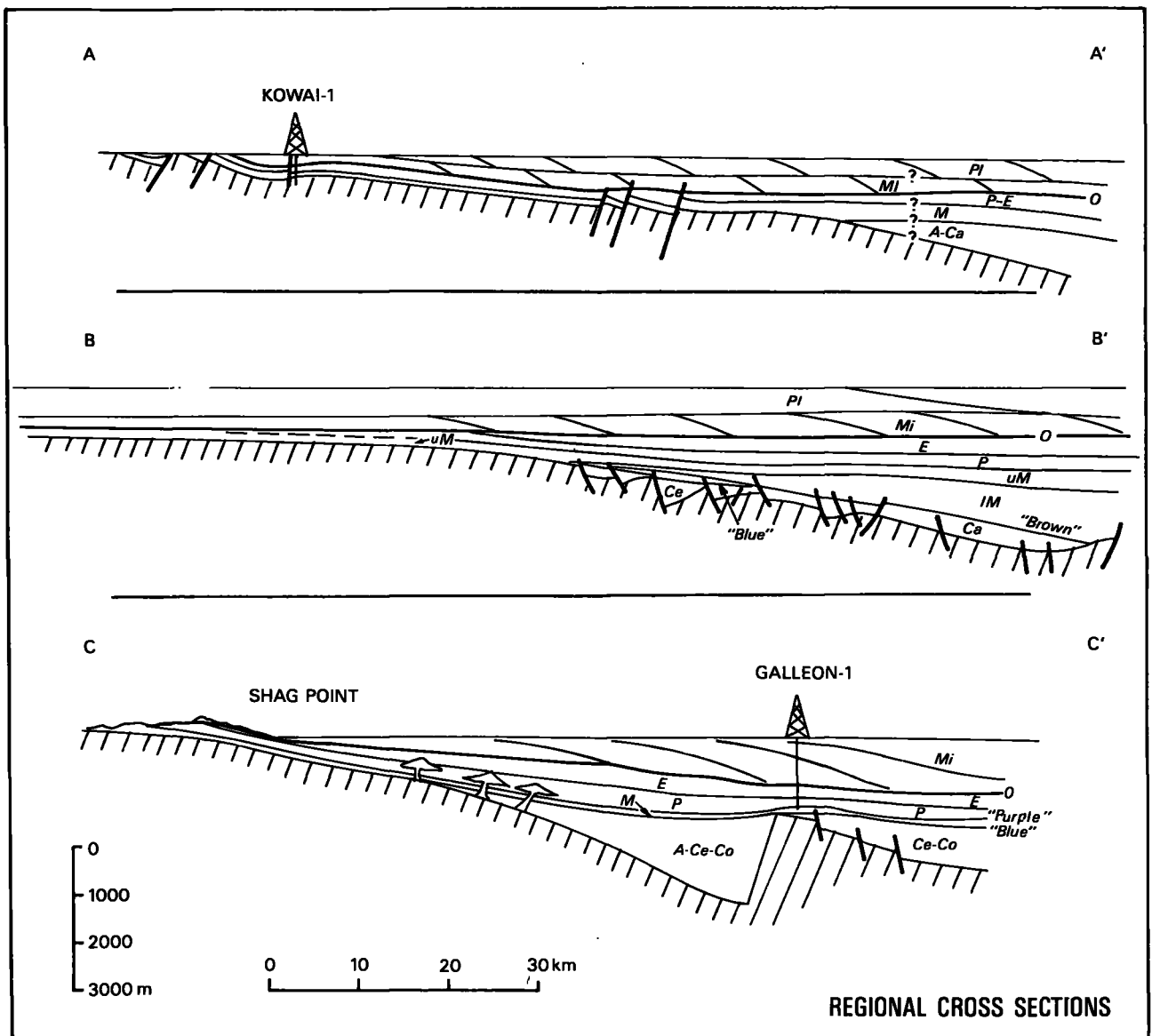


Fig. 2: Regional cross-sections, Canterbury Basin (annotations see Fig. 3).

on the fault initiated Miocene uplift of the Southern Alps, renewed sedimentation into the Canterbury Basin, and regional regression to the present situation.

The following discussion is based on outcrop data, largely from the basin margin, five onshore wells, four offshore wells and some 5000 km of offshore seismic. It is essentially a summary of the commercial volume (Harmsen, Haskell and Perry, 1989).

STRATIGRAPHY

Basement

Basement to the basin comprises variably metamorphosed Permian to Cretaceous volcanics and fore-arc, slope and trench sedimentary rocks of New Zealand's Eastern Province. Two rock systems of this province affect the basin, both as undermass and sediment source. These are the Torlesse Terrane, and the Haast Schist, respectively the Permian to Neocomian slope and basin floor sequences of Gondwana, and their regionally metamorphosed equivalents. The metamorphism of these slope and basin floor rocks is the result of the progressively increasing depth of burial of the sediments

within the convergent Gondwana margin system. The age of the metamorphism ranges from Cretaceous at the top of the eastern low-grade, Chlorite-1, margin of the schist system, to Pliocene (H. W. Wellman, pers. com.) in the high grade garnet schist areas adjacent to the uplift along the Alpine Fault.

Aptian and Albian sequences

The initial sedimentation in the Canterbury Basin system was in syn-rift faulted depressions developed in basement at the time of Bounty Trough rifting (Figs. 2, 4). The Kyeburn Formation, dated as Aptian-Albian by palynomorphs (Haskell, 1964) is one example of this type of sequence.

The mid-Cretaceous Kyeburn Formation is preserved over a sixty square kilometre area near Naseby in the upper reaches of the Kyeburn River, a tributary of the Taieri River in North Otago (Fig. 1). It comprises up to 3300 m of schist and greywacke cobble and pebble breccia and conglomerate, interbedded with carbonaceous siltstone and sandstone. The formation was deposited in a *fault-angle depression* (Harrington, 1955) and the lithologies in the conglomerate represent adjacent basement. The distribution of lithofacies,

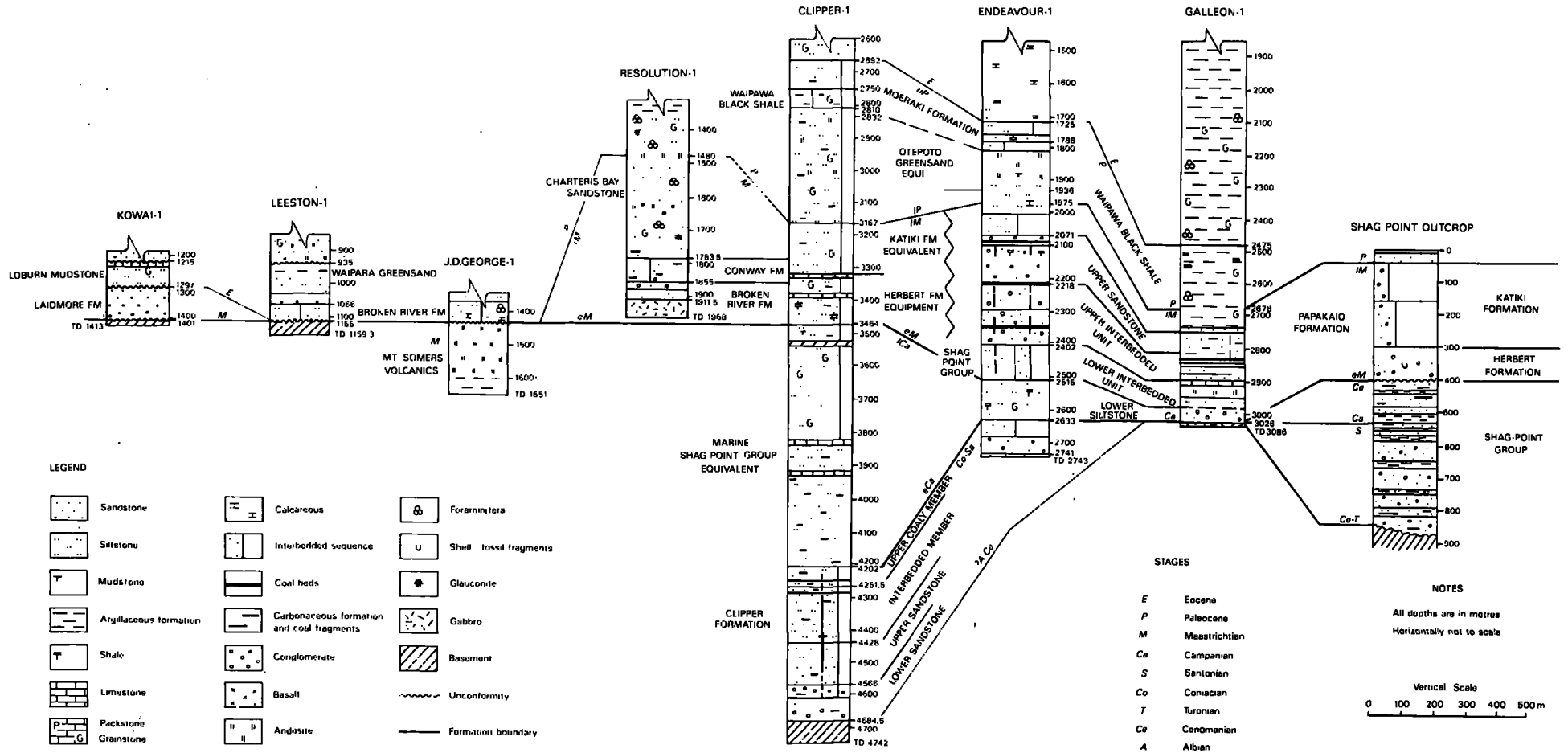


Fig. 3: Correlation of Cretaceous and Paleogene sequences in the principal wells and southern outcrop, Canterbury Basin.

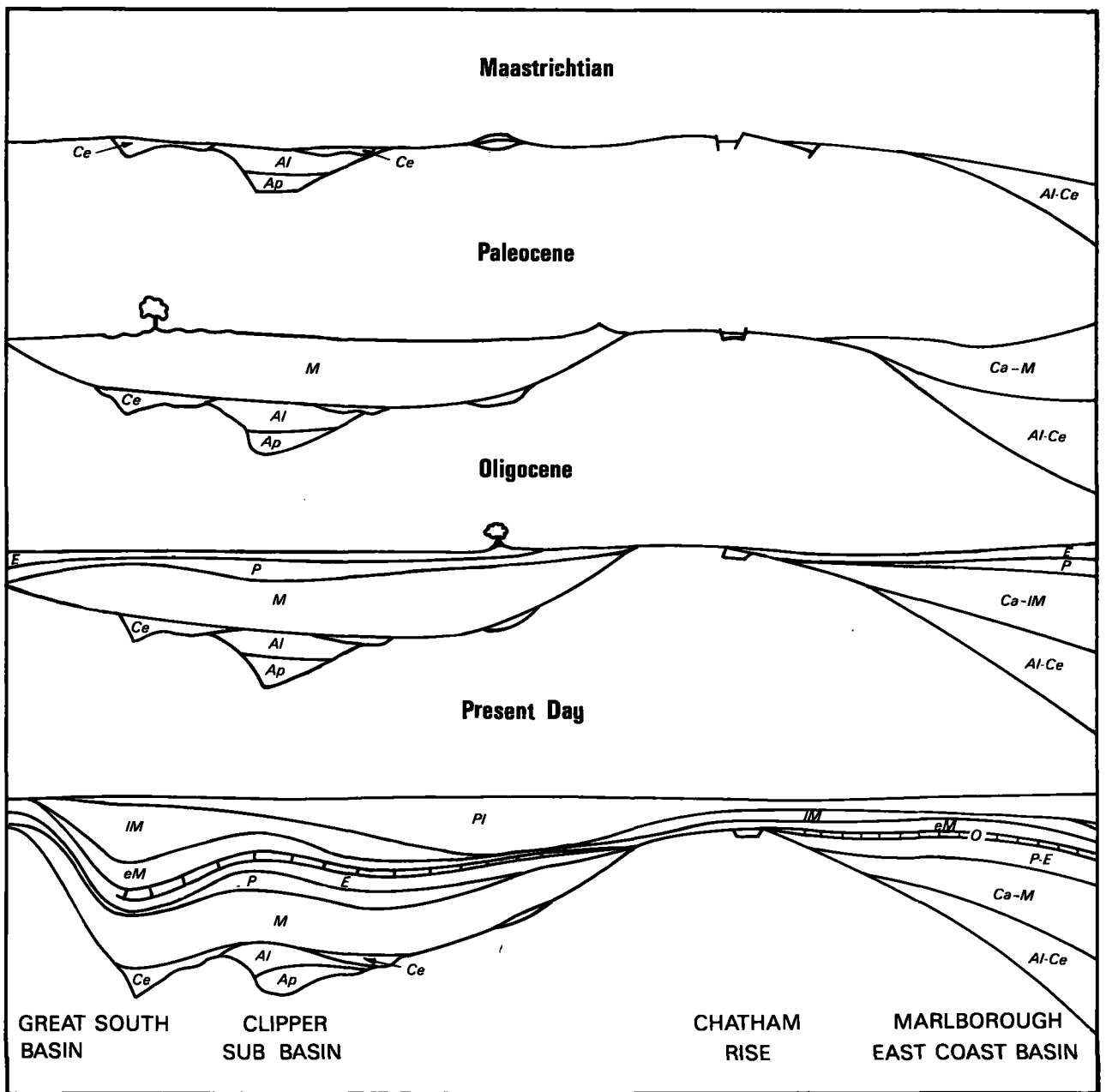


Fig. 4: Palinspastic diagrams showing development of Canterbury Basin.

direction of fining and increasing pebble roundness, nature of clasts, imbrication, and orientation of channels indicate derivation of the sediment from a northwesterly fault scarp system (Bishop and Laird, 1976). Breccias close to the boundary faults represent talus deposits. Alluvial fan, flood plain and lacustrine deposits occur, representing successively more distal parts of the half-graben.

Similar rock systems include the Henley Breccia, developed in a half-graben in south Otago near the mouth of the Taieri River; the Hewson Formation of Harper Range, South Canterbury; the Monroe Conglomerate in the Malvern Hills, Central Canterbury; and the Stanton Conglomerate of Haumuri Bluff, North Canterbury (Fig. 1). Aptian marine fossils have been identified in the Hewson Conglomerate (Stephens and Speden in Suggate, Stevens and Te Punga, 1978). These mid-Cretaceous ages of the Kyeburn and Hewson Formations confirm the time of opening of the

Bounty Trough. This rifting phase continued to the Turonian, as shown by the age of the latest beds in the Henley Breccia.

A similar sequence crops out in the Horse Range and Horse River area inland from Shag Point, north of Dunedin (Figs. 1, 3). It was deposited in a Cenomanian-Turonian half-graben, and consists of 10-70 m thick alternations of conglomerate and sandstone, with coal stringers, and coal, sandstone, siltstone and mudstone cycles 15-20 m thick (Fig. 3). In the upper, probably Turonian, part of this sequence, the coaly beds become prominent, indicating a decrease in depositional energy as the graben filled. The sequence continues into the basal Maastrichtian, where coaly beds are less common. The whole sequence is known as the Shag Point Group. The Turonian portion is here considered to be the Clipper Formation, by correlation with a like sequence in BP Shell Todd Clipper-1 (discussed below). This younger Horse Range system is notably more texturally mature than the

Aptian-Albian sequences as typified by the Kyeburn Formation. The clasts are rounder, and sandstone and coal layers are more common. This is interpreted as reflecting a more widespread channel-dominated fluvial system, rather than the restricted alluvial fan deposition characterising earlier sequences. A similar half-graben feature is evident on seismic shot west of the Galleon-1 well, and is probably Aptian to Campanian in age. In addition, a complex of smaller grabens and half-grabens is present in the central offshore area (Fig. 2).

These graben and half-graben sedimentary systems are not confined to the Canterbury Basin. The Hawkes Crag Breccia of Westland and Night Caps Coal Measures of Southland are of a similar age and lithology. However, it is notable that most examples are in the Canterbury Basin area.

Rocks of this latter age and type of sequence are represented in the Clipper-1 and Endeavour-1 wells (Fig. 3). In the latter, the penetrated interval is thin, developed from T.D., 2743 m, to 2633 m, but probably extends to seismic basement at around 3000 m. It comprises a gradation from a conglomeratic sandstone, to micaceous and carbonaceous well-sorted, fine to very fine sandstone with siltstone interbeds. Cenomanian-Turonian marine fossils are reported in this interval (Wilding and Sweetman, 1971).

In Clipper-1, the equivalent interval is from basement, 4684.5 to 4251.5 m (Fig. 3). It is divided into four intervals by Hawkes *et al.* (1985) the oldest of which, 4684-4566 m is massive 5-20 m coarse to very coarse and conglomeratic sandstones, with minor mudstones and coal. Though finer, the sequence is consistent with the sedimentary models from middle and latter parts of the onshore half-graben sequences of the Kyeburn Formation types and to much of the Horse Range sequence. The subsequent sequence from 4566-4428 m is fine to coarse quartzose and carbonaceous sandstone and mudstone. The interval, 4428-4251.5 m, is finer again, comprising variably carbonaceous siltstone and claystone interbeds with some one to five metre thick fine sandstone beds. The uppermost Campanian sequence, 4251.5-4202 m, comprises carbonaceous siltstone and mudstone with thin coal interbeds.

The succession represents a further in-filling model, varying from basal outer alluvial fan deposition with flow directions perpendicular to the basin, through an equivalent, but lower energy regime in the second interval, to crevasse-splay sediments of a meandering river system in the third, with lower coastal plain, and probably tidal channel and mudflat systems, in the fourth. It is notable that the sequences of the later Cenomanian and Turonian portions of the exposed half-grabens are alluvial fan to braided stream deposits. The base of the equivalent in Endeavour-1 is similar, but becomes braided stream to crevasse-splay within the interval, then coastal plain. This contrast reflects the more distal location of the Clipper area in the Cenomanian sedimentary system.

Seismostratigraphic analysis initially undertaken by BP (Hawkes *et al.*, 1985) and continued in this study confirm the subdivisions noted above are regional. A seismic marker termed the Brown Horizon intersects the well at a depth corresponding to the top of the lower interval at 4566 m. The seismic interval from basement to the Brown Horizon is characterised by discontinuous and variably contrasting and dipping reflectors relating to graben infill. Based on the well

sequence model, the Brown Horizon separates underlying alluvial fan half-graben sequences developed extensively along the central southeastern and southwestern parts of the offshore basin (Fig. 2) from overlying fluvial systems.

A second major seismic reflector, the Blue Horizon, corresponds to the top of the non-marine sequence at 4202 m in Clipper-1 (Fig. 3). The Late Cenomanian-Santonian rocks overlying the Brown Horizon and extending up to the Blue Horizon are seismostratigraphically distinctive, reflecting the changes in sedimentary type evident in the wells (Fig. 2). This interval fills a broad basement depression developing in the central area basin (Figs. 2, 4). There is considerable variation in the seismic character of the interval. To the west, where the interval thins and internal seismic elements onlap basement, it is generally areflective. This portion of the interval has been interpreted as sand dominated upper-lower coastal plain deposits with sediments being derived from northwestern greywacke or schist basement. To the east, particularly in the area of the present shelf edge, the seismic character changes to a strong series of sub-parallel reflectors and discrete high amplitude events. These are interpreted as coal measures of the Upper Cretaceous similar to the earlier units of Clipper-1 and to the Maastrichtian sequence in the Endeavour-1 well. They are thought to have been deposited in a paralic limnic environment and comprise coal layers interbedded with sandstones and possibly conglomerates. The unit eventually thins southeast onto an offshore basement ridge which limits the early Upper Cretaceous sedimentary basin to the southeast (Fig. 5a), but laps more continuously to the northwest onto basement. This sequence is part of the Clipper Basin, a sub-basin in the Canterbury Basin.

From seismic mapping, the subsidence leading to the Clipper Basin is partially fault controlled, and partially regional down warp. As such it appears to represent the transition from rift to thermal subsidence.

Maastrichtian sequences

Thermal subsidence, begun in the mid Cretaceous, proceeded in earnest in the Maastrichtian. As noted above, the zone of crustal attenuation lay to the east in the Bounty Trough Rift. The resulting depression formed the Bounty Trough and spread north and northwestwards to the Canterbury area, continuing activity in the Canterbury Basin. To the north of the Chatham Rise, progressively southwards subsidence associated with continuing development of the Marlborough-East Coast Basin continued (Figs. 4, 5) entering the Marlborough area and combining with the southeastern subsidence in Northern Canterbury. The rise to the southeast of the Clipper Basin locked with the sub-basin and both were covered by later Campanian sequence as thermal depression continued.

The southeastern offshore well sequences are the thickest and most continuous, reflecting their position closest to the rapidly subsiding Bounty Trough. This is particularly evident in the Campanian and Maastrichtian sequence in Clipper-1. In Clipper-1, both Campanian and Maastrichtian are marine mudstone and siltstone, with minor limestone, reflecting its distal position on the late Cretaceous Basin system (Fig. 5). This sequence is atypical of other wells and exposures, where the equivalent interval is largely sandstone and coal measures.

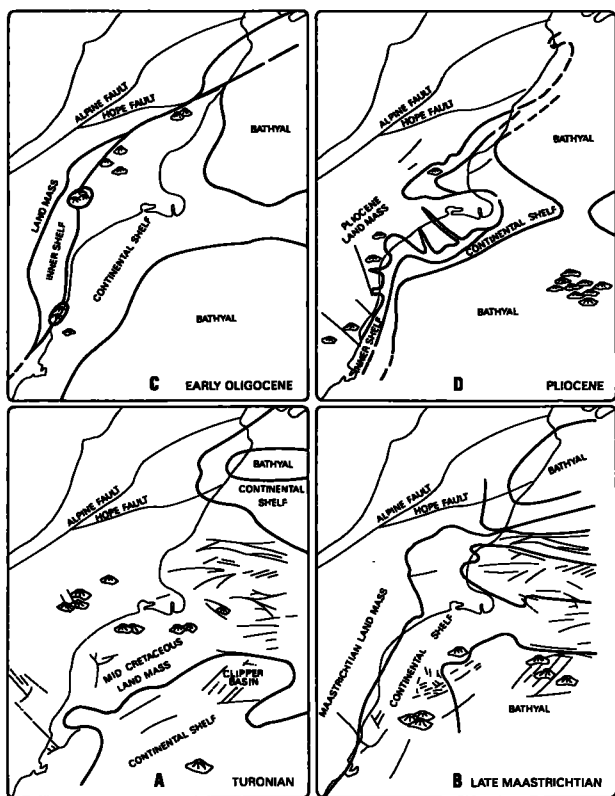


Fig. 5: Paleogeographic diagramming of the Turonian, Late Maastrichtian, Early Oligocene, and Pliocene, Canterbury Basin.

In Endeavour-1, the Maastrichtian sequence is in four parts (Fig. 3). The basal interval, 2633-2515 m, is grey, hard, and slightly carbonaceous siltstone. It is overlain, 2515-2402 m, by three 20-25 m thick, grey, fine to very fine sandstone beds, which grade to mudstone beds up to 10 m thick. The third interval, 2402-2218 m, comprises irregular interbeds of fine conglomeratic sandstone, carbonaceous mudstone and hard, black, coal. From 2218-2071 m are thinner, 2-12 m interbeds of similar lithologies.

In Galleon-1, to the south-southeast (Figs. 1, 3), the Maastrichtian interval, 3026-2678 m, again comprises four units (Fig. 3). The lower part of the first interval, up to 2896 m, is mostly dark brown marine mudstone with metre bedded fine to medium sandstone. It is overlain by tuff to 2921 m, then a 22 m interval of dolomitic limestone before. The second interval from 2943-2814 m comprises irregular fine, pebbly sandstone and coal interbeds. The third upper interval, 2814-2748 m, is a moderately mature, very fine to fine, uncemented sandstone with minor mudstone stringers, before reverting to mudstone and good porosity. The uppermost Maastrichtian, 2748-2687 m, is medium to dark grey mudstone.

The Upper Cretaceous part of the sequence onshore in the Horse Range area relates to the Endeavour-1 and Galleon-1 wells. The basal 100-150 m of this sequence is a Campanian breccia, grading upwards to fine conglomerate and sandstone with carbonaceous stringers, then to coal and claystone. The late Campanian-early Maastrichtian is shallow marine pebbly and shelly mudstone. The whole sequence transgresses north and northwestwards overlapping basement and becomes progressively later Maastrichtian. Massive six

metre thick sandstone beds are developed at the top of the conglomerate cycles in the Waitaki River area.

The Maastrichtian interval of Endeavour-1 and Galleon-1 is correlated with the Papakaio Formation, comprising the coarser elements of the upper Shag Point outcrop (Fig. 3). The interval grades to finer grained Herbert and Katiki Formations southeastwards. In the northern part of the offshore basin, the Maastrichtian sequence of Resolution-1, 1911.5-1480.5 m, at the base of the well is some 100 m above seismic basement (Figs. 1, 3). The basal interval of the well, up to 1885 m, is conglomerate in a sandy matrix with lignitic coal lenses and stringers of the Broken River Formation. From 1885-1783.5 m the rocks are silty sandstone and very fine sandstone with thin peat layers correlated with the Conway Formation. From 1783.5-1480.5 m is fine to coarse porous sandstone with minor glauconite. This sequence ranges up into the Paleocene. This well lacks the upper conglomerates and coals of the southern wells and outcrop discussed above, but is more typical of the onshore Maastrichtian of the central, northern, and northwestern basin.

In Kowai-1 (Figs. 1, 3), the Maastrichtian Laidmore Formation sequence comprises 9 m of sandy, glauconitic conglomerate, then 37 m of very fine to fine glauconitic sandstone and glauconitic siltstone, overlain by siltstone and mudstone extending to 1297.5 m. The latter interval includes a 8.5 m very fine, silty glauconitic sandstone at the top of the interval.

A similar system of lithologies is recognised in exposures northeast of Kowai-1, relating to the transition from the Canterbury Basin to the Marlborough-East Coast Basin, but more influenced by the latter. Typical of this northern system is the sequence in the Haumuri Bluff area (Fig. 1). Here, the continuation of the Stanton Conglomerate extends into the basal Maastrichtian. It is overlain by Okarahia Sandstone, comprising basal, hard, calcareous sandy conglomerate, grading to carbonaceous sandstone and sandy siltstone, then to coarse cross-bedded medium to coarse sandy siltstone. Equivalent beds further south, towards the axis of the Chatham Rise, are non-marine. The Okarahia Sandstone is overlain by the Tarapuhi Grit, comprising about 240 m of sandy granule conglomerate. It is overlain by 240 m of sandy Conway Siltstone, then 45 m of fine glauconitic and calcareous sandstone called the Claverly Sandstone.

The Upper Maastrichtian in Resolution-1 comprises massive sandstones, with localised glauconitic beds. This interval is similar to the Paleocene sequence exposed on Banks Peninsula, east of Christchurch, known as the Charteris Bay Sandstone. The Maastrichtian sequence in Resolution-1 is correlated with the Charteris Bay Sandstone.

The Maastrichtian exposed along the extensive northwestern outcrop of the basin, southwest of Kowai-1, was deposited late in the stage, and the rock sequences extend into the Paleocene. Light grey to green, soft, fine to very fine carbonaceous and glauconitic quartzose sandstone, carbonaceous mudstone, and common coal predominate in the Broken River Formation. Sequences here are relatively thin, usually 50-200 m in thickness. The outcrop is discontinuous, eventually merging with the Papakaio Formation outcrop in the Horse Range.

The top of the Maastrichtian coal measure sequence in the Endeavour-1 and Galleon-1 wells equates to a characteristic seismic horizon, the Purple Horizon. The coal measure sequence from the Blue to Purple interval extends to the south west of the basin, including the Endeavour-1 and Galleon-1 areas, and rises westwards in an orientation which would intersect the top of the Papakaio Formation onshore.

Offshore and north from Oamaru both the coal measures and Purple Horizon onlap basement. The Purple/basement intersection, marking the northwestern edge of Papakaio Formation deposition, is developed in a westwardly convex arc which passes southeast of Resolution-1. Southeastwards, the coal measure signature in the Blue-Purple interval dies out on a northeast-southwest trend beyond Clipper-1.

Paleocene sequences

The thermal subsidence characterising the Maastrichtian, continued into the Paleocene. The rate slowed, and deposition was largely marine in the axial basin areas. The Paleocene in Clipper-1, 3167-2692 m, is marine mudstones with some basal tuffaceous beds. A thin sequence, 2800-2750 m, is dark grey or black carbonaceous shale. In Galleon-1, the Paleocene interval, 2678-2475 m, is medium to dark grey dolomitic and calcareous silty mudstone. Again, a highly carbonaceous bed is present over a restricted interval, 2517-2506 m. The Paleocene in Endeavour-1, 1975-1725 m, is dominantly dark mudstone, with a basalt intrusion from 1906-1829 m. Here, chocolate brown carbonaceous mudstones occur between 1765 and 1725.7 m. This characteristic interval is correlated with the Waipawa Black Shale of the Marlborough-East Coast Basin. A combined Paleocene and Eocene interval is present from 1480-1415 m as tuffaceous and pyritic mudstone in Resolution-1.

Onshore in North Canterbury, the Claverly Sandstone, Loburn Mudstone and Conway Siltstone extend up into the Paleocene. The first is restricted to Northern Canterbury. Glauconitic sandstone, the Waipara Greensand crops out extensively in the northern and central basin, and is present from 1066.8-935 m in Leeston-1 (Fig. 1). The Conway Siltstone extends into Resolution-1, and along with the Waipara Greensand, crops out in central Canterbury. The Loburn Mudstone also extends into central Canterbury. The Charteris Bay Sandstone is Paleocene at its type locality. In South Canterbury, the Broken River Formation also extends into the Paleocene. At Shag Point, and in the Horse Range, the Paleocene is marine mudstone.

Eocene sequences

The Eocene saw a continuation of the same pattern of deposition. Fine-grained marine beds continue in Clipper-1, 2692-2410 m, and in the Lower and early Upper Eocene of Galleon-1, 2475-1887 m, though the Upper Eocene here is limestone. The interval in Endeavour-1, 1725-1260 m is again mudstone, topped by a thin limy bed (Fig. 3).

The Eocene in Resolution-1 is pyritic and glauconitic mudstone, 1480-1328 m, with a grainstone limestone, 1328-1306 m. In Kowai-1 it is mudstone, 1297-1236 m (Fig. 2).

Eocene outcrops include the top of the Claverly Sandstone in northern Canterbury, the upper Loburn Mudstone in northern and central Canterbury, the 30 m thick Otepoti Greensand in central and southern Canterbury, and the apparently highly transgressive Broken River Formation

coal measures in southern Canterbury. The latter is overlain by Kauru Formation shell beds, Waihao Greensand, and Otepoti Greensand. In North Otago the sequence is largely mudstone, however one interesting variation is the presence of the Totara Limestone in eastern North Otago, immediately north of Shag Point. It is a pure, massive, bryozoan coquina grainstone 50 m thick developed on a paleo-high formed by Waiareka Volcanics. The limestone has excellent reservoir characteristics, with porosities of 30%.

The petroleum geology of the basin, in terms of the reservoir, source and sealing rocks was largely established by the Eocene.

Oligocene sequences

The regionally thin Oligocene rock sequences reflect a tectonic quiescence, the submerging of the continent, and the effect on the area of the circum-Antarctica current. The two principal features of the Oligocene are the deposit of the Amuri Limestone and a major regional unconformity. The latter relates to both the lack of available terrigenous material, and to the eroding effect of the circum-Antarctic current.

The limestones of the Clipper-1 sequence, 2350-2200 m probably provide the most complete Oligocene section in the basin, though there is a possible hiatus around 2230 m, where a thin mudstone is developed. There is little textural change evident, and limestone beds above and below the mudstone are hard, white wackestones of the Amuri Limestone. In Galleon-1 the Oligocene sequence, 1871-1815 m, covers the Amuri Limestone sequence and the base of the overlying marine siltstone (Fig. 2.). Here the limestone is white to light grey, argillaceous, and cryptocrystalline to micritic. There is no Oligocene sequence in Endeavour-1, the equivalent interval being represented by an unconformity at 1260 m. In Resolution-1, the Oligocene, 1340-1306 m, includes mudstone to 1328 m and extends up to an unconformity. The basal limestone is tuffaceous, but the remainder is a porous white grainstone of shell fragments and Foraminifera. The Oligocene in Kowai-1 is restricted to the interval 1236-1215 m, and is cream to white wackestone (Fig. 3). Oamaru-2 (Fig. 1) encountered tuffaceous Oligocene sandstones between 323 and 89 m.

Miocene sequences

In the early Miocene a transpressional tectonic regime developed, and the western side of the basin began to rise, initiating the sedimentary regime which eventually resulted in the present-day geography.

The early Miocene is thickest in the Endeavour-1 and Galleon-1 wells. Hard, tight, Amuri Limestone extends to the basal Miocene of the former well, 1260-1241 m. It is overlain by a fine, variably calcareous sandstone, correlated with the Caversham Sandstone of North Otago, from 1241-1223.7 m. The early Miocene in Galleon-1 is developed between 1815 and 1646 m, and is mudstone with minor siltstone and calcareous beds.

The interval in Clipper-1 is fine, porous, non-calcareous, Caversham Sandstone, 2201-2139.5 m, overlain by siltstone up to 2100 m. The interval in Resolution-1, 1302-1287 m, is within the Amuri Limestone. It is glauconitic calcareous siltstone in J.D. George-1, 1431-1306 m, and basal interbedded mudstone with overlying limestone in the interval 1215-

965 m in Kowai-1. This limestone, 1087-965 m, is a pack- and wackestone (Fig. 3).

The mid-Miocene is thickest in the central offshore in Clipper-1, 2110-1650 m, and Endeavour-1, 938-430 m. These intervals are mudstones, siltstones and sandstones, representing shelf and slope out-building.

The out-building process continued in the late Miocene, with the thickest sections developed in Clipper-1, 1650-1200 m, and Resolution-1, 1160-680 m. Again, the rocks are interbedded sandstones, siltstones, and mudstones.

It is notable that the Miocene depocentre shifts northwards during deposition in the basin (Fig. 4).

PALEOGEOGRAPHIC ANALYSIS

The early Aptian to Cenomanian half-graben sequences comprise the piedmont deposition systems on the Gondwana Supercontinent, which are present on- and offshore (Fig. 4). The onshore sequences typically comprise talus and alluvial fan deposits, and the seismic signature of equivalent sequences in offshore depressions indicates similar rocks there. These sequences locally reflect, as the model would require, lower energies of deposition in the later and more distal parts of the half-grabens, particularly on the higher parts of the half-graben floor. This results in more sandy and carbonaceous rocks in these parts of the sequences.

The Cenomanian to Campanian sequences include the latter parts of the half-graben systems and the developing system in the Clipper Basin (Figs. 3, 4). The presence of a marine influence in the earliest parts of the Endeavour-1 well sequence, and a like occurrence on the Chatham Islands reflects an early marine incursion at the time of the opening of the Bounty Trough. The Turonian paleogeography shown in Fig. 5a is typical of the middle part of this period.

The Horse Range sequence, and rocks of the lower interval of Clipper-1 (Fig. 3), represent prograding alluvial fans, though given the rounded nature of conglomeratic elements, this was deposited on the upper and distal edges of the systems. Onshore deposition systems remained in this sedimentary format. Offshore, as indicated by Clipper-1 the succession passed through progressively lower energy regimes, reflecting successively alluvial fans, with flows perpendicular to the basin, grading through to braided river flows in the succeeding second interval (Fig. 3), but from a northwest to northeast sector, in the direction of the basin axis (Fig. 5a).

Cross bedding and fining upwards sequences in the third unit of Clipper-1 indicate point-bar deposition in a crevasse-splay system associated with a meandering stream in the Clipper Basin, with final deposition in a lower coastal plain fluvio-deltaic to paralic system, with a marine influence. Seismo-stratigraphic analysis shows that this type of deposition, with minor variation, is common to much of the sub-basin.

The Campanian to Maastrichtian Shag Point Group sequences in the southern Horse Range, Endeavour-1 and Galleon-1 locations are related. The first-named remained firmly in a distal alluvial fan situation (Fig. 5). The marine carbonaceous siltstone of the lower interval of Endeavour-1 equates to the basal, pebbly marine, sandstone and siltstone

of Galleon-1. The marine nature of the latter reflects its more distal position relative to the basin margin. The partially marine lower interbedded unit of Endeavour-1 is here correlated with the succeeding marine siltstone and limestone unit of Galleon-1 (Fig. 3). The former is lower coastal plain to inner neritic in origin, the latter is neritic to inner neritic, again reflecting the more distal position of Galleon-1 with respect to the outcrop and adjacent well.

The upper interbedded interval of Endeavour-1 (Fig. 3) was deposited in a lower coastal plain situation, and comprises very irregular coarse to fine then coaly cycles. The coarse beds represent meandering stream deposits, the finer intermediate beds sand- silt- and mud-flat deposits, and the coals originated as peat in swamps. The equivalent interval in Galleon-1 is similar, but more finely bedded, probably relating to a locally more stable tectonic situation near the south of the basin. The upper sandstone unit in this sequence in both wells is relatively massive, locally conglomeratic in Endeavour-1, and silty and carbonaceous in Galleon-1. The latter is an estuarine to inner neritic deposit. The former is probably the same, but from a more proximal position, adjacent to the pebbly beaches. A thin coal sequence and pebble band tops the more inshore Endeavour sequence, probably representing back-swamp and storm beach beds as the front of the marine transgression passed the location. The Upper Maastrichtian in both wells is neritic to inner slope siltstone and mudstone. As noted above, the Maastrichtian Papakaio Formation is confined to the southeastern basin, lapping out against basement to the northwest and passing laterally to marine beds to the southeast.

Transgression continued northwestwards across the basin in the late Maastrichtian onto the Canterbury area, and simultaneously southwest into central and north Canterbury, from the Marlborough-East Coast Basin. Work by Forder (1976) and Dean and Hill (1976), indicates that the Maastrichtian sequence in Resolution-1 was deposited initially in a beach/dune situation, and then in inner and mid-shelf situation associated with migratory offshore bars as the sea locally deepened. The other Maastrichtian sequences in Canterbury and Otago, deposited by the continuing transgression, follow this pattern. The maximum extent of the later Maastrichtian depositional systems are shown in Fig. 5b.

The Paleocene and early Eocene saw a continuation of the same processes as the transgression continued, albeit at a progressively lower rate. Local basal coals, and coaly or carbonaceous beds are characteristic, overlain by more continuous sandstones, reflecting the change from lower-most coastal plain to mid-shelf depths in the regional deposition patterns associated with the transgression. There is little evidence of extensive coastal plain development. The continuation of this system ensured that sandstones were widespread across the basin. The deeper marine sequences followed, depositing fine-grained sediments above the sandstone beds.

Siltstone and equivalent silty sandstone, was deposited in the northern and central basin in what was probably a brief halt in the thermal depression. The fine-grained marine beds are thickest in the southern wells, probably related to an advance into this area of the Great South Basin system. The extent of deposition and the regional variations in the marine sedimentation patterns are shown in Fig. 5c.

The Oligocene saw the regional submergence of much of the area, and the final stages of development of a virtually peneplained hinterland. The peneplanation was followed by the sea spreading over virtually the whole area, although thin Oligocene coal measure sequences occur in local depressions to the west of the basin margin.

The Miocene saw a reversal of the previous process, and a progressive out-building of the continental shelves to their present position (Fig. 5d). The Caversham Sandstone, noted above, is associated with the characteristically widespread limestone deposition, and represents deposition on the outer shelf and upper slope.

PETROLEUM GEOLOGY

Source rocks

Modern source rock models are available from BP's work. This principally comprises Pyrolysis data, expressing theoretical oil (P_1), and theoretical oil and natural gas available for expulsion in the rocks (P_2), as kilograms per tonne. Some total organic carbon (T.O.C.) readings are also presented. The source potential of the sequences relates to the coals and associated carbonaceous parts of the sequences. The lower interval of Galleon-1 (Fig. 3) has a low T.O.C. and the overlying coal sequence, 2898-2814 m, has P_1 and P_2 values of 3.5-38 kg/tonne and 17.8-232 kg/tonne respectively. In the final sandy unit (Fig. 2) these values are again low, with maximum P_1 and P_2 respectively 4.4-12.4 kg/tonne. The succeeding marine rocks have values of less than half these. The Waipawa Black Shale equivalent has excellent source rock potential, with P_2 of up to 27.7 kg/tonne, but is not mature, as discussed below. The Endeavour-1 sequence reflects similar values. The basal Cenomanian-Turonian interval has P_1 and P_2 values in the range 0.1-0.8 and 0.5-3.6 kg/tonne. The succeeding two mudstone intervals are a poor source, with values similar to the lowest from the basal interval. The coals and carbonaceous mudstones in the remaining succession include typical P_1 and P_2 values of 5.8 and 199.1 kg/tonne at 2279.9 m in coal, and 0.6 and 27.5 kg/tonne in younger carbonaceous mudstones such as at 2112.3 m.

The Clipper-1 mid-Cretaceous Clipper Formation has good source potential. The coals of the upper coaly member have P_1 and P_2 values of 2.6-6.1 kg/tonne and 45.8-80 kg/tonne respectively while mudstones range from 0.0-3.5 kg/tonne and P_2 0.0-19.5 kg/tonne. The coals are a net 22 m of the 34.5 m upper coaly member mudstone. Again the dark shales of the Moeraki Formation here have source potential, with P_1 and P_2 ranging from 0.5-3.1, and 3.5-28 kg/tonne. Samples from a composite section from Shag Point exposures indicate that the coals of the Santonian section have P_1 and P_2 values of up to 0.5 and 42.4 kg/tonne, with shale values up to 2.4 and 93.7 kg/tonne. Equivalent values in Maastrichtian carbonaceous shales range up to 41 and 22 kg/tonne.

Maturation data

Existing geothermal gradients have been detailed in Clipper-1 by BP. The well has a net gradient of 3.6°/100 m. Atypically for the basin these comprise four *legs*, 2.8° C/100m from sea-bed to 1900 m, 3.7° C/100 m from there to 3500 m, 4.49° C/100 m from 3500-4300 m and 1.6° C to T.D.

Maturation follows depth of burial in a more regular manner. Again, BP undertook detailed work on the maturation levels, principally using vitrinite reflectance. These are summarised in Fig. 6. The Clipper-1 profile shows the poorly understood inflections evident in the geothermal gradient arrangements.

The top of the oil generation and expulsion window, using a threshold value of $R_o=0.8\%$, in Clipper-1 is at 3800 m. The window extends to 4200 m using $R_o=1.2\%$. The gas-condensate window is 4200-4500 m and the base of the gas window is at 4980 m. The top of the gas-condensate window at 4200 m corresponds exactly to the top of the Clipper Formation source rocks in the well, so the theoretical yield of oil from Clipper-1 has been realised. A plot of R_o versus depth for the four offshore wells shows that only Clipper-1 drilled mature rocks (Fig. 6).

Reservoir potential

Production in Galleon-1 was from 2752-2789.9 m, the upper 21 m of the thick, estuarine to inner neritic interval. This interval comprises a lower coarse to granular litharenitic sandstone sequence, grading up to fine-grained, well-sorted sandstones. Net on gross within the interval is 100%. Porosities from core and log data average 17%. Porosity of sandstones in the upper interbedded member averages 12%, and in the lower member, 13.4%. Permeabilities range up to 600 mD, but are usually 400 mD or less. Core porosity in cyclic sandstones from 4265-4273 m range from 5-16% and permeabilities from 1 mD at 10%, to 10 mD. The Maastrichtian shallow marine Charteris Bay Formation in Resolution-1 is described as having *good visual porosity*, and those in the

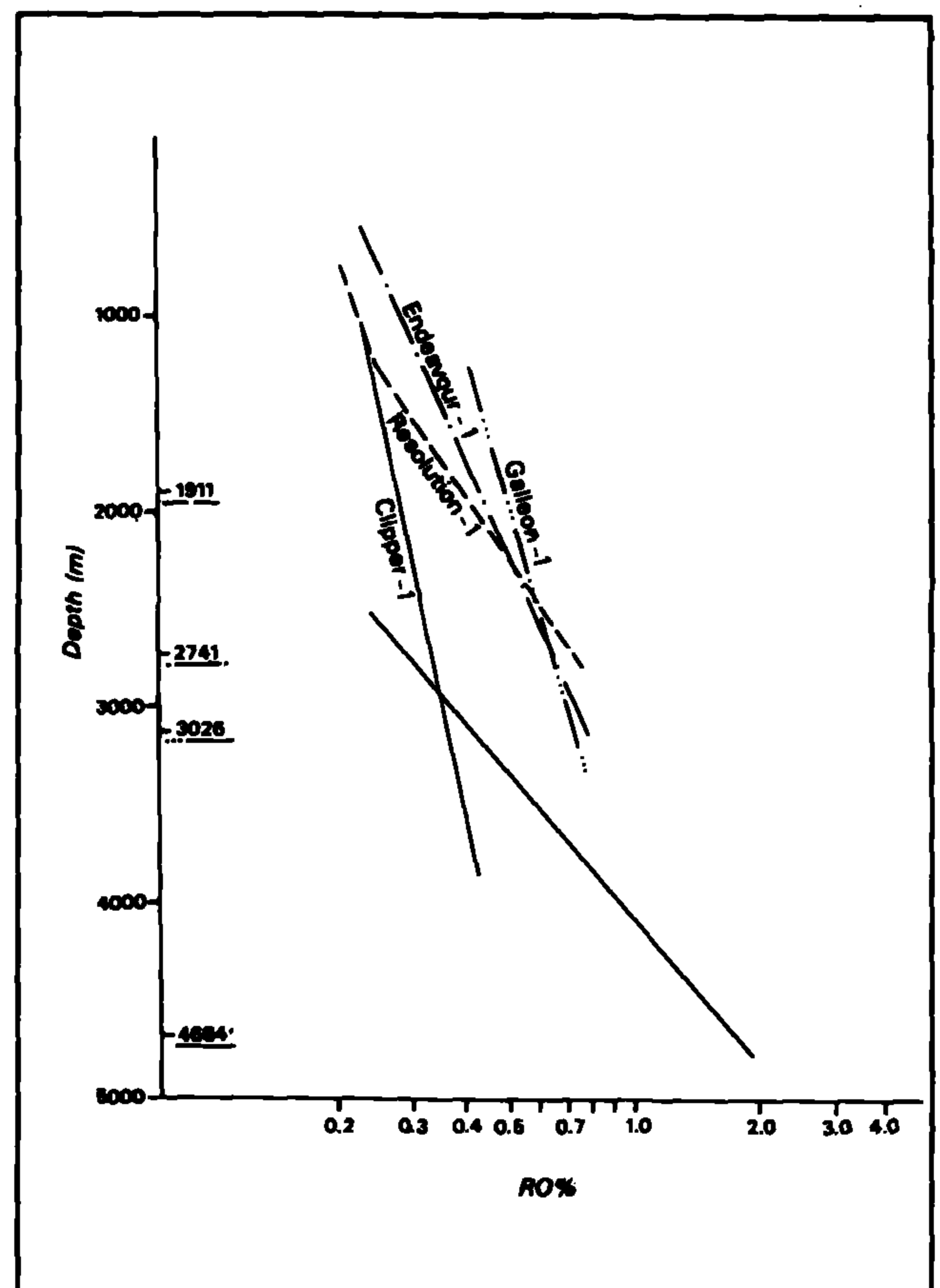


Fig. 6: Degree of maturation versus depth in Clipper-1, Endeavour-1, Galleon-1 and Resolution-1, Canterbury Basin.

Laidmore Formation in Kowai-1 are around 24-26% (Fig. 2).

The earlier Clipper Formation sequence shows porosity ranges of 1-12% in elements of the lower sandstone member, 1-14% in the upper sandstone member and 5-16% in the interbedded member.

These data sets indicate that the various environments of deposition characterising the Upper Cretaceous and Paleogene of the Canterbury Basin are all capable of depositing sandstones with good porosity and permeability potential. This is supported by Taranaki Basin models. The upper, neritic, sandstone interval of 2218-2017 m in Endeavour-1 and 2814-2748 m in Galleon-1 has its equivalent in the McKee Formation, which is the primary reservoir in the Maui, McKee, Kaimiro, and Stratford Fields, and is a secondary reservoir in Kapuni Field. The primary reservoir in the Kapuni Field is a sequence of tidal channel sandstones in irregular coaly cycles similar to those of the coal measures encountered in Endeavour-1 and Galleon-1.

Structure

Closed structures are a relative rarity in the basin, principally because the major tectonic episodes, the initial Aptian Maastrichtian half-graben formation, the Campanian to Oligocene thermal depression, the Oligocene-basal Miocene still stand and the subsequent continued up to the west and down to the southeast rotation, resulted in successive subsidence. However, a number of features with four-way dip closure have been mapped and provide models for similar structures elsewhere. In the Clipper and Galleon structures the southeastern dip is regional, and northwestern dip relates to differential compaction towards adjacent half-grabens (Fig. 2).

The Resolution structure is one of several with localised uplift on a southeasterly throwing fault. Onshore in central and northern Canterbury are a number of closed structures of a similar type, including the Cass anticline drilled off-structure by Kowai-1. These relate to structural developments in the northeastern Marlborough and East Coast Basin. Reconnaissance seismic offshore North Canterbury shows like leads. Other closure is developed stratigraphically, relating to elements of the Cretaceous onlap.

In summary, the geology of the basin is such that coaly source rocks are widely initially developed in mid and late Cretaceous half-grabens, but are most common in the regional Campanian to Paleogene transgressional system. The reservoir sequences are sandstones and are related to specific elements of the retreating coastal plain and advancing neritic systems of the late Cretaceous and Paleogene. Both dip-closed structure and stratigraphic closure are known and widespread, though of relative low amplitude, in the basin. Maturation can be demonstrated in the southeastern basin,

with the top of the oil window at about 3800 m. Possible maturation is demonstrable in basement onshore in the north, and northeastern offshore, and shows occurred in two of the seven modern wells drilled.

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