

MOKI FORMATION, A MIOCENE RESERVOIR SEQUENCE, ITS FACIES' DISTRIBUTION AND SOURCE IN OFFSHORE SOUTHERN TARANAKI BASIN

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Abstract

A regressional phase associated with the influx of detrital sedimentation began in the early Miocene and continued into the middle Miocene. Submarine fans were deposited widely across the Taranaki Basin. To the south, the South Taranaki Graben received large quantities of sand as turbidites which formed a north-south trending submarine fan complex at bathyal depths. Stratigraphic relationships suggest the development of a basin floor fan at the foot of a continental slope near Tasman-1, North Tasman-1 and Maui-4 wells, followed and overlain by alternating stacked channel fill and levee/overbank deposits of a lowstand wedge-prograding fan complex.

Well correlations and provenance analysis of Moki Formation sands indicate that the Separation Point Massif to the south is likely the source for clastics in the South Taranaki Graben.

To date, only sub-commercial quantities of hydrocarbons have been found in the Moki Formation both in the onshore Kaimiro Field and offshore Maui Field and Moki-1 well.

Introduction

The Taranaki Basin, is to date, the only basin with proven commercial quantities of hydrocarbons in New Zealand. The basin is divided into three primary structural elements: the North and South Taranaki grabens and the Western Platform. The onshore McKee, Kaimiro, Ngatoro, Waihapa oil fields and the Kapuni and Tariki-Ahuroa gas condensate fields are all located within the South Taranaki Graben. Offshore, to the southwest of the Taranaki Peninsula is the giant Maui Gas Field, which has recently been proved to contain substantial oil reserves.

The South Taranaki Graben includes the Moki/Manaia area, which lies immediately south of the Maui Field and has strong structural and stratigraphic similarities with Maui. Despite intensive exploration efforts the Moki/Manaia area has failed to yield commercial hydrocarbon discoveries. Several phases of exploration in the area have resulted in a detailed knowledge of its structural and depositional history. One of the reservoir objectives is the middle Miocene Moki Formation, which tested 651 bopd at Moki-1 and contains subcommercial quantities of oil at the Maui Field.

This paper discusses the depositional facies, reservoir morphology, and provenance of the Moki Formation sandstones in the South Taranaki Graben.

Regional Geological History

The offshore portion of Taranaki Basin includes the Western Platform and part of the Taranaki Graben (figure 1). The area has been subjected to a series of marine transgressions and regressions, which have in places deposited thick

sequences of Cretaceous to Recent sedimentary rocks. The general lithostratigraphy of the area has been compiled from the available well data and is presented as figure 2.

The Taranaki Basin was initiated during the Cretaceous by a phase of extensional tectonics that created a basin and range topography consisting of down-faulted grabens with intervening basement horsts. The oldest known graben-fill consists of early to middle Cretaceous (Aptian) breccia and middle to late Cretaceous (Mata and Clarence Series) coal measures and conglomerates (figure 2). The sediments are known from only a few locations, but seismic data confirm that the Cretaceous succession is extensive within the Taranaki Graben (Thrasher, 1991).

Middle to late Cretaceous rocks of the Pakawau Group are known from wells drilled on the Western Platform and in the Taranaki Graben. Pakawau Group is a sequence of non-marine conglomerates, sandstones and coal measures that crop out in the northwest of the South Island.

Following a brief transgression, which is evident in wells on the Western Platform, the Pakawau Group was buried by the Kapuni Group, a Palaeocene to Lower Oligocene sequence of sandstones, mudstones and coals. Unlike the Pakawau Group, Kapuni Group sedimentation was not restricted to the Cretaceous grabens and the sediments are widely distributed across the Taranaki Basin.

Paleogeographic reconstructions indicate that the Palaeocene to Oligocene sea transgressed southeastward. Transgressive marine siltstones and shales drilled in offshore wells to the north and west are lateral age equivalents of the Kapuni Group. The top of the non-marine sequence becomes

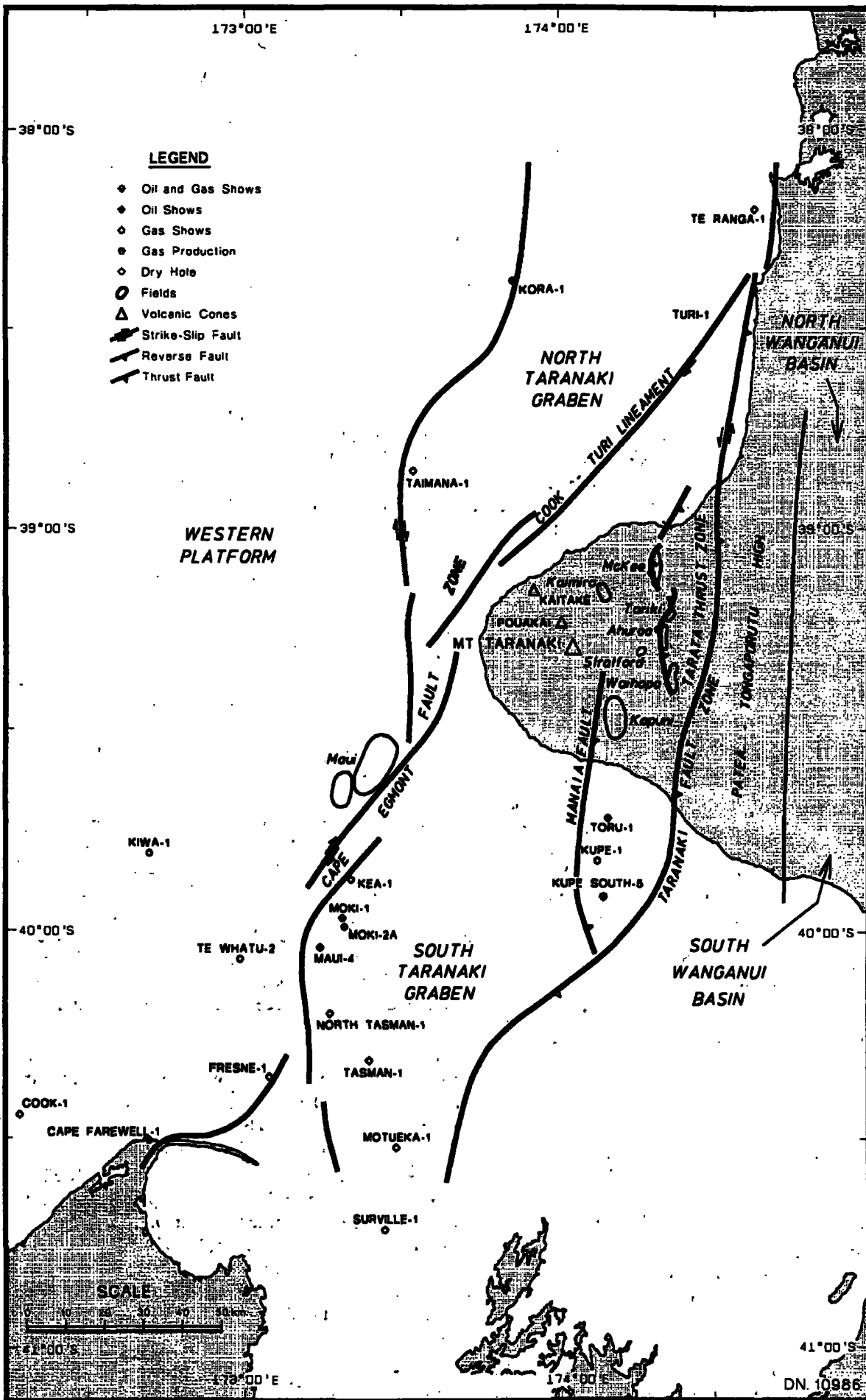


Fig. 1. Major Tertiary structural elements, Taranaki Basin.

progressively younger in a southeasterly direction (Palmer et al., 1993).

The Kapuni Group comprises five formations (Palmer et al., 1993). In ascending order they are the Kaimiro, Omata, Mangaehwa, McKee and Turi formations (figure 2). These stratigraphic units were defined on onshore wells and not all the formations extend or are recognised offshore.

The paralic and non-marine Kapuni Group is overlain by (and inter-fingers to the north and west with) the Eocene-Lower Oligocene Turi Formation, a sequence of marine siltstones and mudstones. The base of the Turi Formation becomes progressively older offshore, to the north and west.

In the Taranaki Graben the Turi Formation is unconformably overlain by a sequence of calcareous siltstones and sandstone, called the Otaraoa Formation in the onshore Taranaki area and the Abel Head Formation in the northwest of the South Island. Offshore, on the Western Platform, the Turi Formation is directly overlain by Tikorangi Formation limestones. The Tikorangi Formation is an Oligocene bioclastic limestone sequence that is widespread in the Taranaki Basin and is a regional seismic marker.

By early Miocene, the regional transgression had reached its maximum extent. Limestone deposition had slowed considerably and the argillaceous limestone and marls of the Taimana Formation were deposited.

The Miocene was an epoch of relative sea-level fluctuations and tectonism. The return to detrital sedimentation, which was predominantly tectonically controlled, commenced with deposition of deep water siltstones and mudstones of the Lower Manganui Formation. A major regression, commenced in the Early Miocene, and continued into the Middle Miocene; submarine fan sediments were deposited widely. These fans are of Altonian, Lillburnian to Clifdenian and Tongaporutuan age and are known respectively as, the Lower Manganui, Moki and Mt Messenger formation fans.

At the end of the Miocene, sea level dropped once again, a regional unconformity developed and another regression followed. A sequence of prograding strata was deposited, comprising the inner to middle shelf Matemateaonga Formation in the onshore Taranaki Basin and the outer shelf Giant Foresets Formation farther west and north. Marine deposition continued through the Pliocene to the present-day as the continental shelf built out to the northwest. Volcanism commenced during the Pleistocene in the central part of the Taranaki Graben and about that time the Taranaki Peninsula began to emerge.

Regional Tectonics

During the Late Cretaceous sedimentation commenced in a number of half grabens, which were generally oriented in a northeast-southwest direction. Faults bounding the half grabens continued to move, until the early middle Eocene.

At the beginning of the Miocene, sediments were deposited in the South Taranaki Graben, during a time of little tectonic activity except for syn-sedimentary faulting along the Cape Egmont Fault Zone. An influx of coarse clastics followed during the Middle Miocene. The major structural boundaries are still active at present.

During the late Miocene widespread reverse faulting commenced in the South Taranaki Graben as compressional tectonics intensified. Late Cretaceous-Palaeocene fault systems were reactivated as a series of low-angle reverse faults. At Maui-4 and Moki-1, seismic data indicate that inversion occurred no earlier than the Tongaporutuan, and was completed by the Opoitian (early Pliocene).

During the Plio-Pleistocene, normal faulting was initiated along the Cape Egmont Fault Zone. Thick Opoitian and younger sediments were deposited over the area, thickening on the downthrown western side of the fault.

The most prominent structures within the offshore South Taranaki Graben are the Maui, Fresne and Moki/Manaia inversion structures. The Kupe Field is located in the east of the South Taranaki Graben.

Exploration

Over the past two to three decades the South Taranaki Graben has been the site of sporadic exploration activity, with the major discoveries being the Maui and Kupe fields (table 1). The most recent seismic acquisition in the area is the 3D seismic survey over the Maui Field, which provided spectacular and impressive images of the channelised fan complex of the Moki Formation (Bussell, 1994).

The Moki/Manaia anticline is a similar structure to the Maui Field; subcommercial volumes of oil are present in the Kapuni Group and Moki Formation and the field is currently held under a Petroleum Exploration Permit (PEP 38413) by Cultus Petroleum NL.

The wells, other than Maui Field wells, that have contributed to the understanding of the depositional history and facies of the Moki Formation are listed in table 1.

Moki Formation

The first investigation of the Moki Formation was prompted by the presence of coal in the vicinity of Mokau River, onshore North Taranaki. Henderson and Ongley (1923) described the Miocene Mokau Formation and divided it into

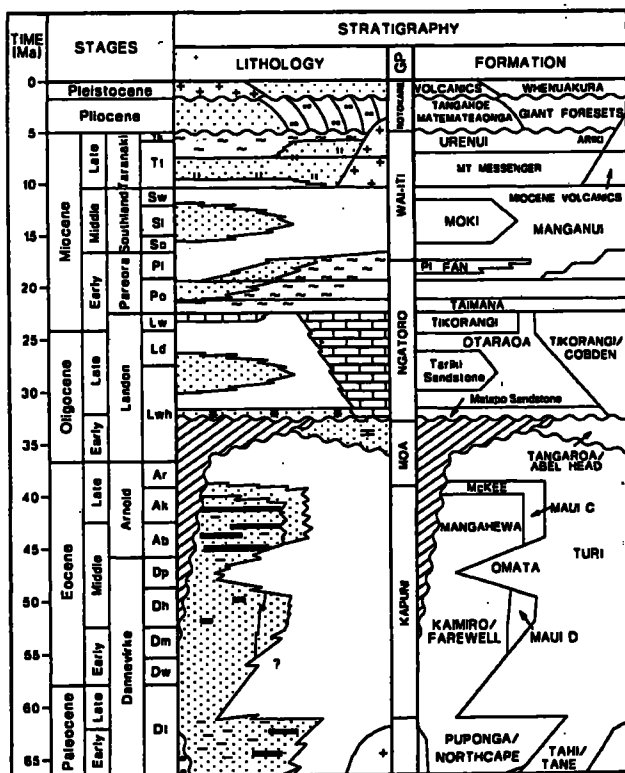


Fig. 2. Generalised stratigraphy of the Taranaki Basin.

Table 1. Exploration and appraisal wells drilled since 1970, South Taranaki Graben (excluding Maui wells).

WELLS	HYDROCARBONS	OPERATOR	YEAR
Tasman-1		NZ Aquitaine	1970
Maui-4	Oil discovery	Shell BP & Todd	1970
Fresne-1		NZ Aquitaine	1976
North Tasman-1		NZ Aquitaine	1978
Kiwa-1		Shell BP & Todd	1981
Moki-1	Oil discovery	Tricentrol	1983
Tahi-1		Petrocorp	1984
Kea-1		Tricentrol	1985
Moki-2A	Oil appraisal	Tricentrol	1985
Te Whatu-2		Petrocorp	1987
Toru-1		TCPL Resources Ltd	1990
KUPE FIELD:			
Kupe-1	Gas/oil discovery	Shell BP & Todd	1975
kupe south-2	Gas/oil/cond.appraisal	National Petroleum Ltd	1986
Kupe South-2	Gas/oil/cond.appraisal	TCPL Resources Ltd	1987
Kupe South-3B	Oil/gas appraisal	TCPL Resources Ltd	1988
Kupe South-4	Oil/gas appraisal	TCPL Resources Ltd	1989
Kupe South-5	Gas/oil appraisal	TCPL Resources Ltd	1990

three members. The stratigraphy has twice been revised and is now defined as the Mokau Group (Hay, 1976), consisting of three formations — the Upper Mokau Sandstone, the Maryville Coal Measures and the Lower Mokau Sandstone.

Onshore and offshore wells in Taranaki Basin penetrated an age-equivalent facies of the Mokau Formation and the term Mokau Formation Equivalent was adopted to differentiate the Taranaki Basin facies from the type Mokau Group. As the Mokau Formation equivalent extends over a very much larger area than the type Mokau Formation, Lock (1985) introduced the name Moki Formation to include all Taranaki Basin sediments called Mokau Formation Equivalent.

Bussell (this volume P240) in discussing the Moki Formation at the Maui Field, distinguishes between Moki-A and Moki-B intervals. The Moki-B sands correspond to the Moki Formation described in this paper.

Seismic and Electric Log Response

Seismic data, in offshore Taranaki, show a distinct reflection package recognised as the Moki Formation sand or silt dominated sequence. This interval lies between claystone-dominated units with little internal seismic character, which represent respectively the lower and upper Manganui Formation. Even in areas where wells have confirmed that the Moki Formation contains 10% or less total sandstone, the distinct seismic character enables regional correlation. The seismic character does not, however, allow the identification of individual fans or channels within the sequence.

Electric log response in wells reflects the seismic definition and shows a well-defined sandy interval, often with sharp top and base. This is clearly demonstrated in the well correlations (figures 3, 4 and 9). Occasionally, sandstones are present above and below the Moki Formation.

In wells with fewer sandstone beds, or with a lower proportion of sandstone in the total interval, top and bottom of the Moki

Formation is less distinct. Here biostratigraphy and/or well correlation, assists in distinguishing the Moki interval.

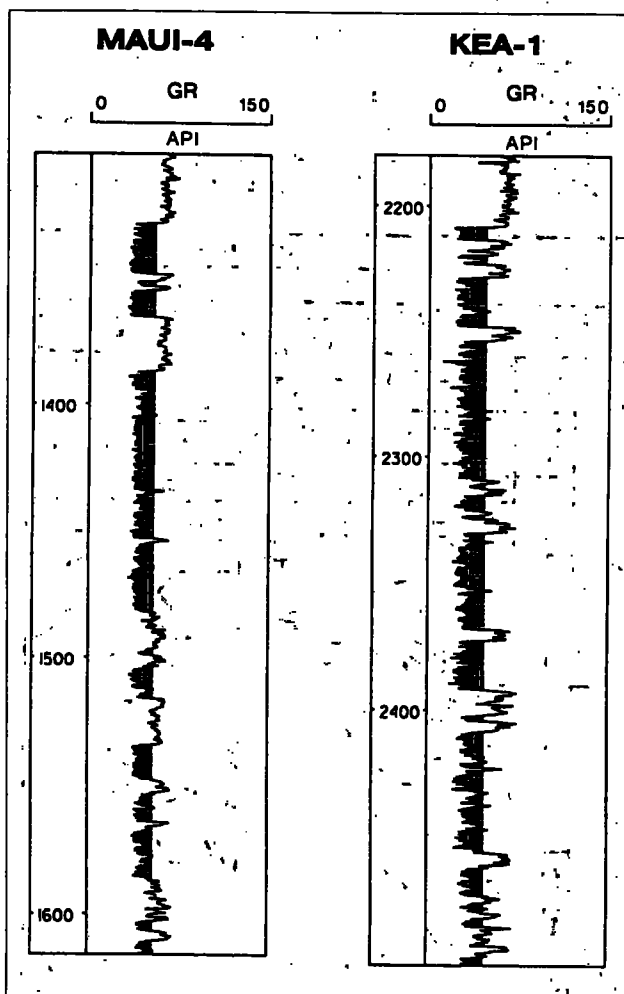


Fig. 3. Moki Formation log response, Maui-4 and Kea-1.

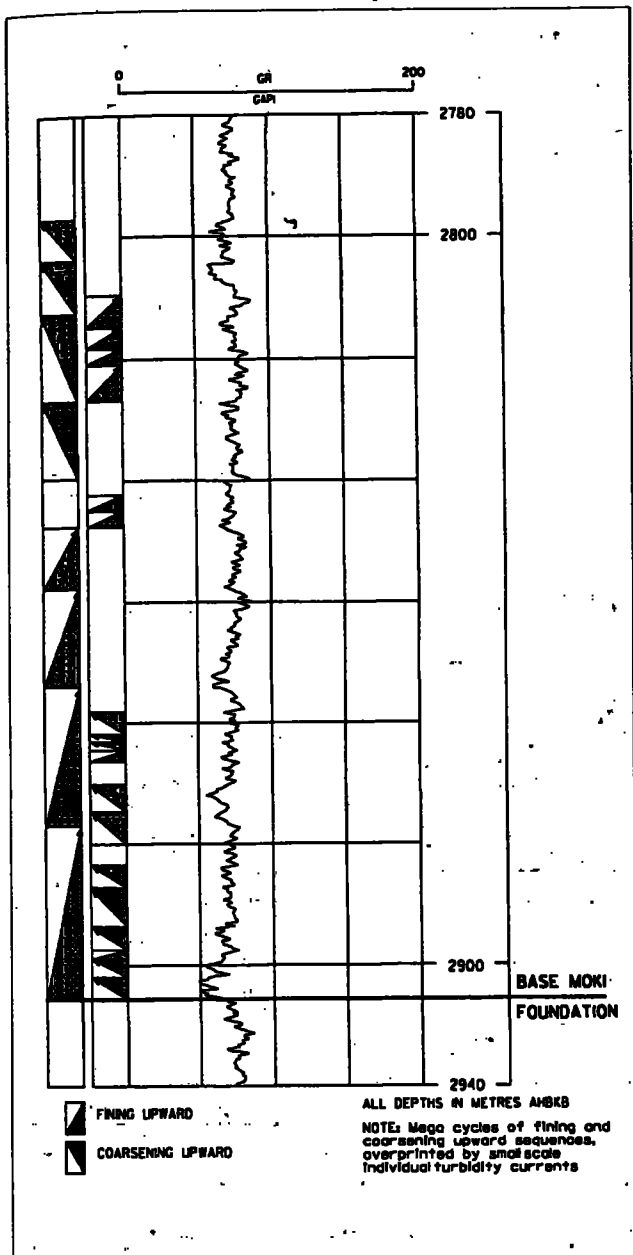


Fig. 4. Te Whatu-2 turbidite facies log response.

Moki Formation Facies

The Moki Formation sequence is interpreted to comprise a series of submarine fan systems built up by turbidite deposits. Dependent upon the relative position of wells in the fan system, log response reflects distal turbidite facies, strongly channelised fan deposits, or levee and overbank deposits.

Most wells are considered to have encountered a mid fan (supra fan) or channel-levee-overbank facies of an early highstand progradational fan system. Data from Te Whatu-2 suggests onlap of an overbank deposit in an off-fan position, with the main fan development to the east of the well. Kiwa-1 encountered no sands, and log character indicates only very minimal fan development. No wells in the study area penetrated a typical upper fan morphology.

The middle fan-channel deposits typically form fining- and thinning-upwards cycles. Fan studies show that a high degree of meandering develops in middle-fan settings, similar to river systems and suggest that in general only one active channel continues throughout the system. The degree of

sinuosity may be roughly proportional to the depositional gradient. The channel-levee morphology initially forms high flanks, which reverse after compaction, causing the next channel or fan lobe to be deposited over the levee. Meanders and crevasse-splays, in addition to providing new channel pathways, eventually result in the evolution of new fan valley systems that may systematically migrate during fan history.

Both composition and bedding are important factors in the response of well logs. The presence of interbedded shales increases the Gamma Ray response. The central channel facies are generally cleaner, with low API values, whereas the channel margin facies show an increase in GR response because of the greater number of interbedded shales. Resistivity is affected by shales and is generally lower in clean sands in, for example, central-channel facies than in the shale rich area at the channel margin. Well logs show a well defined concentration of thickest and coarsest beds of sandstone in the channel axis area, with thinner and finer beds along the channel margins and levee areas. The channels almost always form fining- and thinning-upward cycles. The characteristic bell-shaped curves on Gamma Ray allows the channels to be distinguished clearly on the electric logs. Progradation as the fan built up on the bathyal sea floor resulted in thickening- and coarsening-upward cycles near the top of the formation. This is the early highstand pro-gradational fan lobe build-up, or lowstand wedge-prograding fan complex (Vail, 1987). This is clearly visible especially in the Moki-1, 2A, Tasman-1, North Tasman-1, Kea and Maui-4 wells (figures 3 and 9). Fan progradation results in a coarsening-upward sequence very similar to that of a delta. Progradation of the lower fans onto the basin plain should result in a sequence of classic turbidites in which the sandstone beds become slightly coarser-grained and slightly thicker upsection.

Some channel flows exhibit sharp top and base contacts on the Gamma Ray and an erratic response of the dipmeter. These are mass flows of sand and can measure up to 60 to 90 m in thickness (Moki-1, 2A, Maui-4 and Kea-1). An indistinct basal Gamma Ray response may be due to:

- rip-up clasts of claystone embedded in the base of the channel flow obscuring the sharp contact
- a build up of fan sands preceding the channel cut

The reduced thickness of the Moki Formation at Tasman-1 suggests the well location may lie on or near the flank of the fan system or close to a bypass zone (figure 7). The Te Whatu area possibly underwent syndimentary structuring, resulting in a slight positive sea bottom relief. Therefore the Te Whatu location was a site of onlapping overbank deposits of the prograding fan, as reflected in the thin-bedded character of the Moki Formation interval (figure 4). The Moki Formation of Kiwa-1 does not seem to correlate with any of the other wells.

At Te Whatu the sediments were probably deposited by diluted, waning, turbidity currents that had deposited the bulk of their sand on the central axis of the fan lobes. The individual units are clearly vertically organised according to the Bouma sequence, consisting of (basal) fine to very fine sandstone, grading upwards to siltstone to mudstone near the top. Figure 4 shows the basal 125 m of the Moki Formation in Te Whatu-2. Large-scale and small-scale fining-upwards sequences are prominent, occasionally overprinted by smaller

individual turbidity gradings within these larger sequences. An overall coarsening, typical for the early highstand progradational fan, can be noted for the entire megasequence. An increased sandstone to shale ratio is also evident. In general, these deposits formed non-channelised depositional bodies.

The relative proximity of the fan sands to their source is clearly demonstrated in the sandstone percentage calculation for each individual well. Previous reports, interpreted high sand percentages for Kiwa-1, whereas in fact little to no sand was deposited. For this paper Vshale was calculated from the Gamma Ray for each well with the exception of Maui-4 where the spontaneous potential was used, which in many cases is a more precise measurement, provided that no KCl based mud was used. Using the Gamma Ray, which is a statistical tool, a silt response may in fact be interbeds of sand/shale beyond the resolution of the tool. However for the purpose of obtaining the relative position of a well in a fan system the measurement still reflects a distal or proximal position to the fan source. The method remains an approximation because fluid content and amount of hydrocarbons will still influence the Gamma Ray readings.

Vshale was calculated every 5 m and plotted as a histogram (figure 5). A Vshale less than 30% is considered to represent sand, Vshale 30–70% a siltstone, Vshale larger than 70% a shale.

The resulting histograms show that Kea-1, Moki-1, 2A, Maui-4, North Tasman-1 and Tasman-1 have similar sand-silt-shale ratios, with the possible exception of Moki-1 and 2A where a Vshale population between 20 and 30% is evident. North Tasman-1 and Tasman-1 seem to have relatively cleaner sands. The histograms for Te Whatu-2 and Kiwa-1 indicate a more distal or lateral position, with an increase in values of Vshale to over 70%. Using this method, either no sands were deposited in Kiwa-1 or the sands are beyond the resolution of the Gamma ray. Although this is a statistical way to demonstrate sand-silt-shale ratios within wells, differences in mineralogy from well to well could influence Vshale calculations. A high potassium- or glauconite-rich sand will result in a high Vshale measurement. Using these measurements of Vshale, a total sandstone percentage over the entire interval was calculated. Any unit with a Gamma Ray response that indicates Vshale less than 33% is considered sand. Total sand divided by total thickness of Moki Formation resulted in a measure of sand percentage (figure 6).

Correlation of Moki Formation

The criteria used to distinguish the Moki Formation within the well profiles are:

- seismic response
- sandstone dominated sequence, enclosed by clay-dominated sequences
- correlation of sands
- biostratigraphy

Although correlation of individual sands and shales between wells seems possible and permissible, serious consideration should be given to the validity of these correlations, especially with respect to the inferred continuity of the sands over the large distances between wells.

Correlation should honour the facies interpretation that the Moki Formation is a bathyal fan complex. Periodic cessation

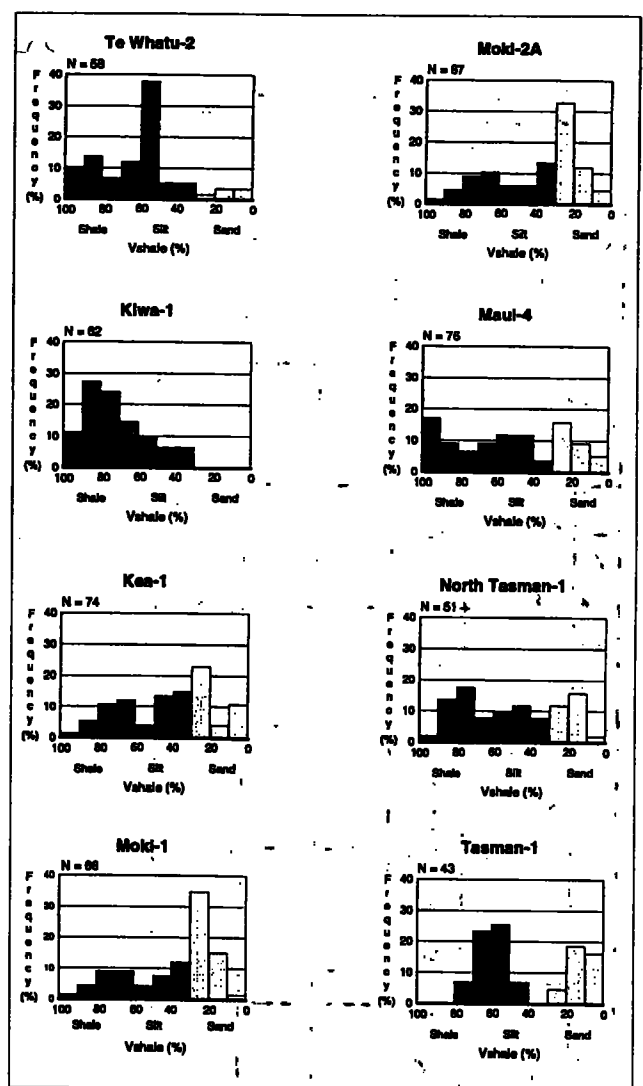


Fig. 5. Histograms of Vshale (%) showing sand-silt-shale proportions in Moki Formation (N = number of measurements).

of sand influx was punctuated by widespread mud deposition. Differential compaction of the mud and sand caused subsequent fan lobes to switch direction. Well-to-well and regional correlation of the mudstones allow the recognition of several fan turbidites with different depositional axes. Within a fan complex, sands on the lower (or distal) fan are usually more widespread and can be correlated with more confidence than sands in the supra and middle fan positions. Sands in the upper fan position, being feeder channels, are even more isolated.

As indicated at the beginning of this section, the Moki Formation depositional facies necessitates correlation of shales rather than sands. When this method is applied on a regional basis the correlation seems to illustrate major cyclicity of sand-dominated sequences. Six major cycles are distinguished, the last cycle being deposited on a bathyal plain of low relief and signalling the onset of mudstone/siltstone-dominated highstand system tract fan deposits. The first turbidity currents or fan lobes at the onset of Moki deposition will have filled relative lows in the bathyal plain relief. Therefore, the basal sand sequences (Cycle 1 on figure 7) in Tasman-1, North Tasman-1, Maui-4 and Te Whatu-2 are interpreted as an initial fill of a relative basin plain low. This cycle of sands is not present in more

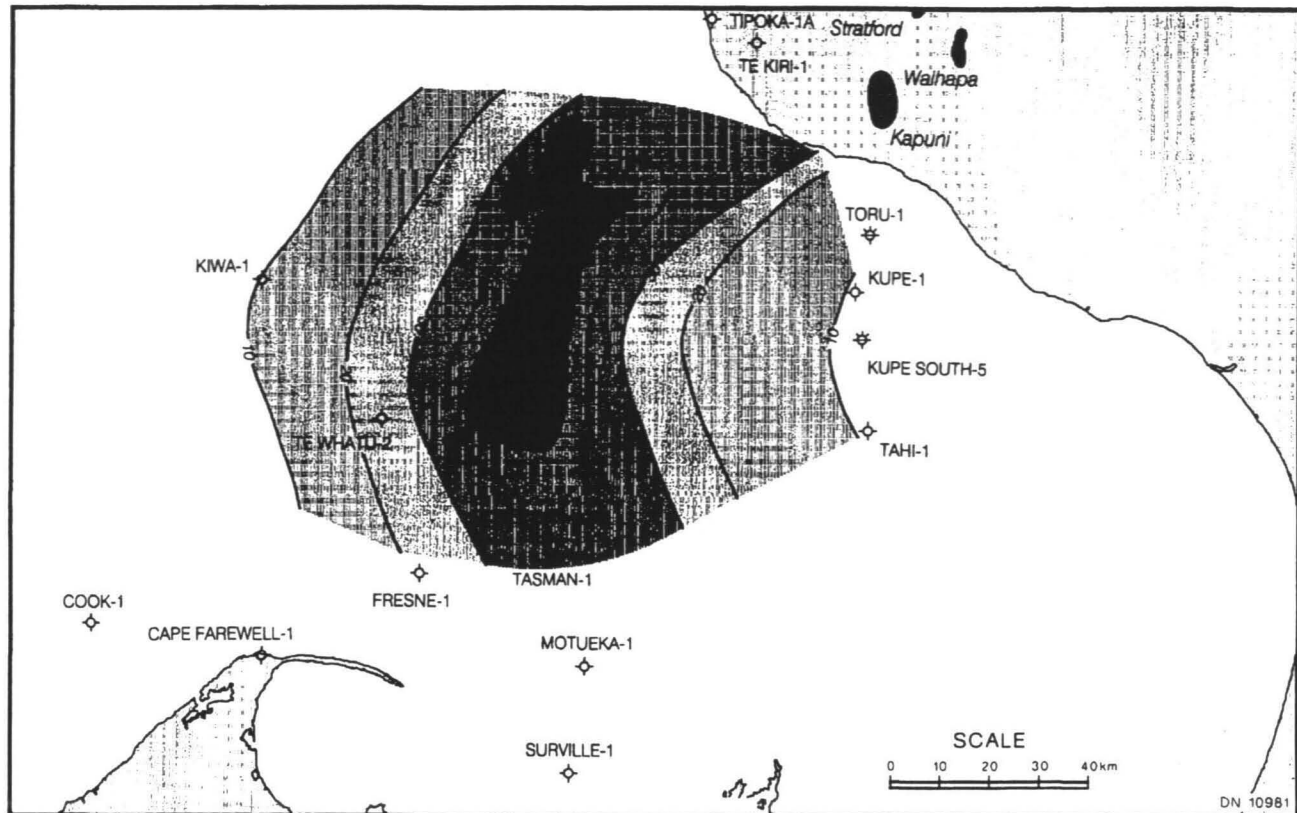


Fig. 6. Sandstone percentage of Moki Formation, offshore south Taranaki Graben.

northerly wells and is probably the low stand basin floor fan, marking the onset of fan build up.

The arrows in figures 7, 8 and 9 point to the direction where sands seem to thicken. Again, one should bear in mind the scale of the correlation and the distances between the wells. Continuity of the sands is dependant on the width of the middle to distal fan, which could possibly exceed several hundreds of kilometres in diameter. At the time of Moki deposition the depocentre for the South Taranaki Graben was elongated in a north-south direction. Therefore, dip and strike for the fan is respectively north-south and east-west. The direction of thickening of the cycles clearly suggests switching of the major fans. The correlation from Kea-1 to Tasman-1 is parallel to the axis of the fans (figure 7) and therefore less likely to demonstrate fan switching.

The regional isopach for the Moki Formation, the sand percentage map, and the regional correlations reveal a thinning and shaling out of the Moki Formation west and east of the Kea-1 to Tasman-1 north-south trend. Both the isopach maps and sand percentage map (figure 6) show a slightly curved northeast to southeast axis of the Moki depositional basin. Well control is limited to the west and northwest, therefore the contouring is open to some conjecture. The maps also suggest that during Moki time the Te Whatu structure was most likely a syn-sedimentary area of structuring. The lateral fringes of the overbank deposits onlap the proto-Te Whatu structure. The Te Whatu basin high may have formed a barrier, preventing most turbidity currents from reaching Kiwa-1. This fact is supported by both the lack of sands in Kiwa-1, and the poor correlation between silt-rich intervals at Kiwa-1 and the Moki Formation to the east.

Biostratigraphy

The available biostratigraphic data do not allow the definition of clear biozones to which the Moki Formation is restricted. Overall, paleo-dating shows the Moki Formation to be of Lillburnian to Clifdenian age (Middle Miocene). Assemblages are planktonic-dominated and represent a bathyal fauna of restricted oceanic access. Accepting the age restriction, the deltaic sands with true coal beds in Surville-1, described as Moki Sands (Lock, 1985), do not belong to the Moki Formation since they are of Altonian age. Here, shallowing near the end of the early Miocene and uplift of the Separation Point Massif resulted in deposition of fine and coarse sands in a deltaic to marginal marine environment.

In the east, the Kupe Field wells encountered little or no sand within the Moki Formation. Benthic foraminifera are more diverse and the proportion of planktonics is low (10 to 20%). The fauna is associated with molluscan chips, ostracodes and otoliths. The taxa indicate shelf deposition, perhaps outer shelf with some mid to inner shelf downshelf mixing. To the north, at Maui Field, the depositional setting of the Moki Formation was mid-bathyal to upper-bathyal.

Dipmeter Interpretation

Processed dipmeter data are available over the Moki Formation in Moki-1, Moki 2A, Maui-4, Kea-1 and Te Whatu-2. In all wells the structural dip does not exceed 5°. In Moki-1 and 2A blue and red dip patterns rarely exceed 20° dip magnitude. Maui-4 data show a highly scattered pattern of blue and red dips of up to 45°. In Kea-1 the blue and red patterns are mainly less than 8°.

Rose diagrams were plotted for blue patterns, which may represent paleo-current directions. The apparent current

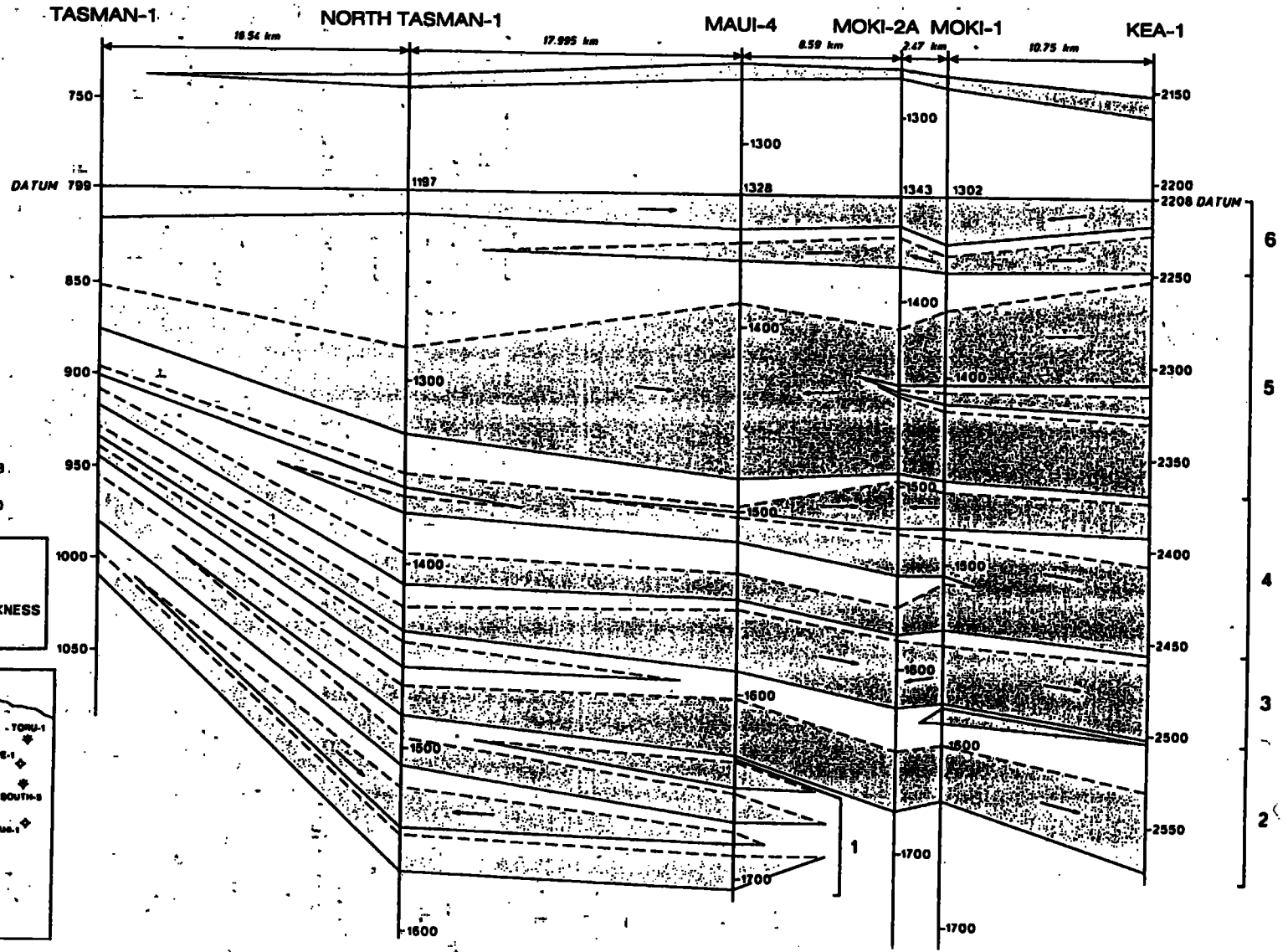


Fig. 7. Well correlation Moki Formation, Tasman-1, North Tasman-1, Maui-4, Moki-2A, Moki-1 and Kea-1.

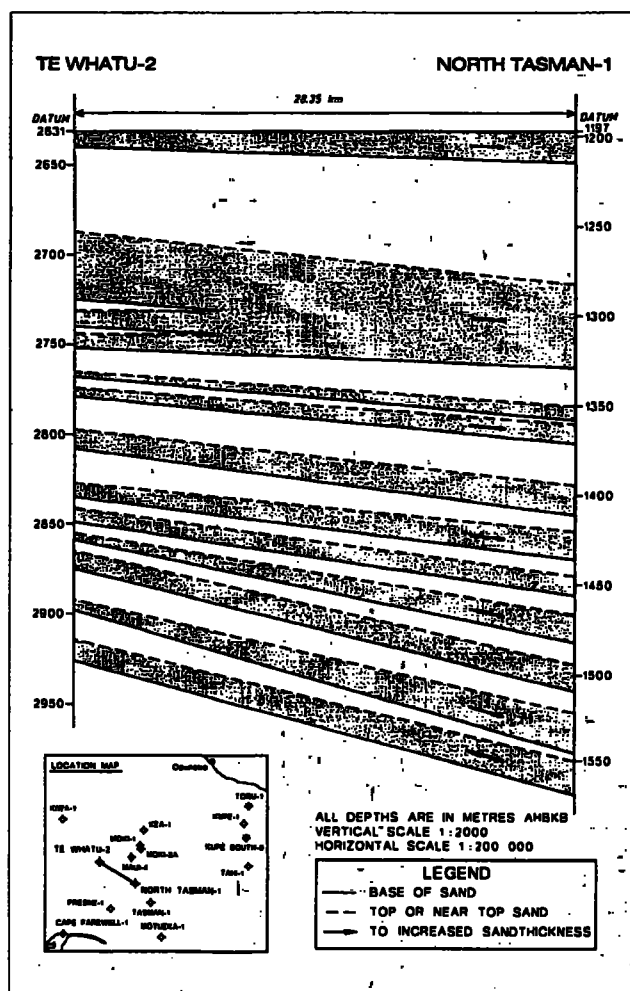


Fig. 8. Well correlation, Moki Formation Te Whatu-2 and North Tasman-1.

directions seemed to agree with the regional interpretation of sand source direction. However, the Moki-2A rose diagram showed a flow direction to the east, which is completely contradictory to the regional concept of source direction. The removal of structural dip did not alter the blue and red pattern azimuths to any significant degree. The structural depth map on Moki Formation and the position of the wells indicate that Moki-2A structural dip direction is indeed to the east.

These observations confirm that the structural position of the well and associated dip direction, overprints and influences the low-angle sedimentary dip of the current flow in the sands and shale interbeds. In addition, and possibly more significantly, the interpretation that sandstone dips represent transport direction, as in crossbedded fluvial sandstones, is not valid for turbidites (Berg 1979, Berg et al., 1990). The turbidites are mostly massive and lack well-defined stratification, and the recorded dips represent the attitudes of the thin shales between the sandstones. The shales drape over the sand flows to produce a predominantly convex shape. The dips therefore record the morphology of sand bodies; not current flow.

Mineralogy

The modal counts for core samples from Moki-1 and 2A show great variety between samples which plot on a QFR diagram as sub-feldsarenites, feldspathic litharenites and

litharenites. Samples contain coarse-grained plutonic or metamorphic rock fragments. Clay analysis shows that Fe-chlorite and muscovite/illite are the predominant species in all samples. Small amounts to traces of vermiculite and Na-smectite are present. Grain densities range from 2.55 to 2.66.

In general the sandstones in all wells, from Tasman-1, Tasman North-1, Maui-4, Moki-2A, Moki-1 to Kea-1, are very fine to fine with interbeds of siltstone and mudstone. At Tasman-1, which is the well closest to the projected source (see section 12), the basal sands are coarse and locally conglomeratic. Also they are slightly tuffaceous, with coaly streaks and some mica. At Tasman North-1 the basal sands are also coarse-grained and pebbly, with coaly streaks, slightly tuffaceous and calcareous. At Maui-4 the Moki Formation sandstone is generally very fine to fine grained with occasional pebble horizons (1646m AHBKB).

The Moki Formation at Te Whatu-2 consists of siltstone and mudstone with some sandstone. At Kiwa-1 the formation consists of mudstone-siltstone interbeds with a trace of sandstone.

Paleo-environment, Facies Distribution and Source

The Moki Formation sequence is interpreted to be a suite of turbidites, which reflect middle Miocene tectonism in the Taranaki Basin during the middle Miocene, and/or a sea level change, resulting in a regressive phase. A renewed influx of mainly fine clastic sediment was deposited near or on a shelf area.

Instability, due to rapid sediment building, earthquake shock, etc frequently caused the sands to flow down the continental slope into bathyal depths, as indicated by the foraminiferal assemblages in the sands.

Several models for the source and direction of flow of these sands have previously been proposed, but no study has resulted in a clear picture. Previous interpretations and deductions using sand distribution and thickness have been clouded by misinterpretation of the Kiwa-1 well logs. The well was recorded to have a thick sand-dominated middle and upper Miocene sequence, with individual sand bed thickness of up to 50 m. However, from an inspection of the mudlog, sidewall cores and wireline logs it appears that few sands were in fact encountered. Reinterpretation shows a maximum of 10% very fine sand in the Moki equivalent interval. Earlier reports used the dominance of sands in Kiwa as evidence of possible westerly or southerly source directions, with Kiwa-1 being close to the source. This report, however, demonstrates that all factors seem to indicate that Kiwa-1 lies in a distal position in the turbidite fan system.

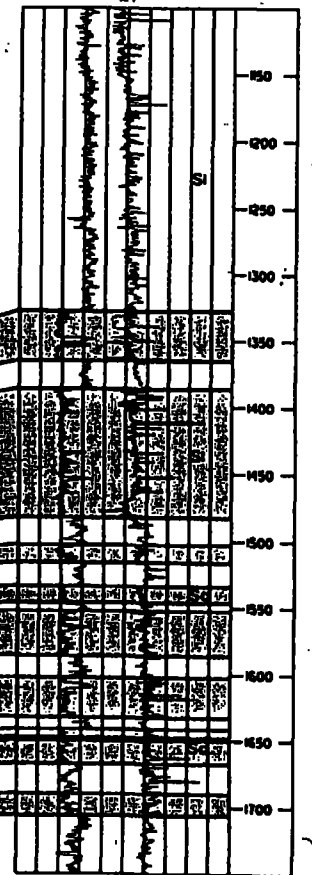
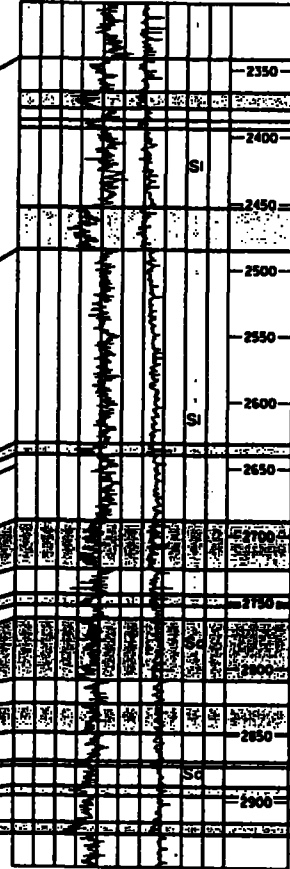
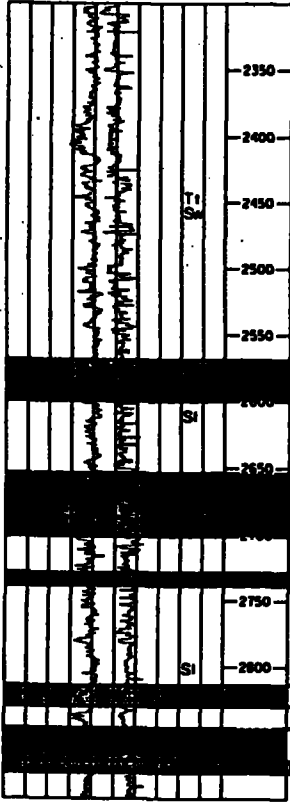
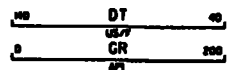
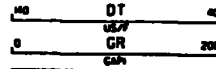
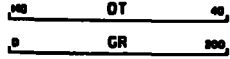
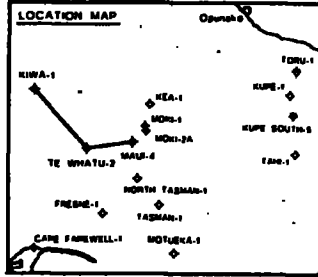
Using Vshale values to calculate sand-silt-shale ratios, a sandstone percentage map has been drawn (figure 6). The paucity of control points means that the contouring is open to some conjecture. For example, confidence in contouring to the south would be aided if Fresne-1 provided Moki Formation data. Unfortunately, the well probably spudded in the Moki Formation and logs do not permit any interpretation of sand occurrence and percentages.

Well correlations, sand distribution and biostratigraphy seem to exclude a northerly, westerly or easterly source for the Moki fans. The Western Platform remained submerged

KIWA-1

TE WHATU-2

MAUI-4



?

?

?

Fig. 9. Well correlation, Moki Formation Kiwa-1, Te Whatu-2 and Maui-4.

during the Miocene receiving very little clastic sediment. To the east the Kupe wells comprised middle Miocene mudstone, siltstone and marls with a shelfal fauna. To the north uplift along the Taranaki Fault and uplift of the Havelock Massif may have created the source for Moki sands seen in Kapuni, Kaimiro and most other northerly wells. Onshore wells to the north of Maui show very thinly interbedded fine grained sandstones of a distal character.

To the south, the tectonic history suggests an uplift phase of the Separation Point Massif during Altonian and Clifdenian times (King et al., 1987; King, 1990). The Separation Point Batholith is of Mesozoic age and comprises quartz diorite, leucogranodiorite, leucogranite, minor feldspar porphyry and pegmatites, and is an excellent candidate for sourcing Moki Formation fan sands. The mineralogical analysis on Moki-1 and 2A sands demonstrated that no fundamental difference exists between the samples as far as provenance is concerned. The study confirmed a southern source for the Moki fan sands, with the metamorphic rocks of the Nelson area, being the main candidate for the source (figure 10). The volcanic rock fragments detected in the sand samples, could have come from Miocene volcanoes which occur offshore the west coast of the North Island.

The 3D seismic at the Maui Field shows highly sinuous channels within the Moki Formation, with intricate tight, looping meanders along the entire length (Bussell, 1994). The southeast-northwest and south-north flow direction of the meanders supports the southerly source of the fan complex. The active channelling at Maui, despite being at a fairly distal position from the projected source in the south, could be the result of a sand conduit located immediately west of Maui — the Vity Canyon. This large present-day feature may well have existed at Moki Formation times enhancing the sand flow and forming the conduit from bathyal depths to abyssal depths. This explains why Tane-1, almost 100 km northwest from Maui, penetrated very thin sands correlatable to the Moki Formation.

Hydrocarbon Shows

At Maui-4 the Moki Formation contains some carbonaceous laminae and at 1478 m some lignite was encountered. Hydrocarbon shows vary over the entire interval without a clear relation to the lithology changes. At 1524 m an increase in shows seems to be associated with a decrease in compaction of the sandstone. The average porosity is 20%.

In Moki-1 the Moki Formation sandstone is generally fine- to very fine-grained, occasionally medium-grained, usually argillaceous and silty with white fluorescence over the entire interval. The interval 1306-1316 m AHBKB was drillstem tested and flowed a maximum rate of 660 bopd and 1.87MMSCF gas through a 24/64" choke. The average porosity is between 19% and 24%.

In Moki-2A the sandstones are fine- to coarse-grained, (but predominantly fine), with generally good visible porosity. Fluorescence is quite dispersed through the interval and varies from bright dull white to white gold, occasionally with a white residue ring. The average log derived porosity is 20%.

The sands at Kea-1 are very fine- to fine-, rarely medium-grained, slightly argillaceous with calcareous cement in part, trace coal and loose mica. The sands are water wet with a log derived porosity of 15 to 18%.

At North Tasman-1 no hydrocarbon shows were recorded within the Moki Formation sands. At Kiwa-1, Te Whatu-2 and at Tasman-1 there were no hydrocarbon shows in the Moki Formation.

Reservoir Morphology

Deep water sands formed by submarine fan systems form economically important hydrocarbon reservoirs in many parts of the world. Analysis of the depositional model of a fan may provide a layer model for calculation of reservoir volumetrics and possibly to identify flow units.

The size and shape of the reservoir in the Moki area was established by correlating well logs and defining and mapping the members which represent the major phases of turbidite deposition. These members are a complex of interbedded sandstones and shales that are bounded by major shale beds (figures 7, 8 and 9). In the Moki-Manaia area, from Tasman-1 in the south to Kea-1 in the north, a series of sandstone-shale cycles can be distinguished. Each cycle is defined by thick beds of sand separated by beds of shale between 10 and 40 m thick. The cyclicity is probably due to a complex interplay of eustatic sea level and tectonic changes; the eustatic sea level changes being the more dominant factor. The shales are persistent between wells and are recognised by a high Gamma-Ray response. Each cycle is built up of a number of complete and incomplete Bouma sequences. Each bed within a cycle possibly represents a single depositional event and, where the separating shales are continuous, each bed also represents a "flow unit" that is homogeneous and can transmit fluid laterally through the extent of the bed. These beds are probably lenses that have restricted lateral extent and allow fluid communication through small areas only. In other words, while correlation of sands and shales between wells seems possible and acceptable, it does not necessarily imply that sands are laterally continuous and interconnected. A correlatable horizon may merely reflect an event which triggered widespread turbidity activity over the bathyal plain. Switching of sand lobes due to differential compaction of intermediate clay deposits will result in separate depositional lobes.

Sediment transport within the fan axis was accomplished primarily by distributary channels similar in morphology to those found on lobate deltas. In all probability, each fan gradually built up from the ocean floor by the oscillatory swinging of a major feeder channel emanating from a submarine canyon. In this manner, sediment layers were gradually built up until all bathymetric irregularities were smoothed out to form a low relief bathyal plain with a slightly convex upper surface.

Conclusions

The Moki Formation in the South Taranaki Graben is an excellent example of a restricted, elongated, submarine fan complex deposited at bathyal depths.

The fan facies is interpreted as a lowstand buildup comprising basin floor fan, overlain by lowstand wedge-prograding sequences of turbidites in channel, levee, and overbank sequences.

The facies model for the Moki Formation in this region is complemented by spectacular 3D seismic amplitude imaging over the Maui Field, displaying highly sinusoid meandering submarine channels in the Moki sequences.

Mineralogic provenance analysis, palinspastic reconstruction, well correlation and sand distribution support a southern source for the Moki Formation clastics, the most likely source being the Separation Point Batholith, near Nelson.

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