SEQUENCE STRATIGRAPHIC ANALYSIS OF THE TANGAROA SANDSTONE, NORTHERN TARANAKI BASIN, NEW ZEALAND

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Abstract

A study of the Tangaroa Sandstone, consisting of seismic sequence and biostratigraphic analysis, well log interpretation, and core descriptions, confirms the Tangaroa Sandstone as a Late Eocene-Early Oligocene, sand-rich, submarine fan complex within the northern Taranaki Basin of northwest New Zealand. The Tangaroa Sandstone typically consists of two, 25 to 150 metre-thick, vertically-stacked sandstones, separated by a thin (8 m) limestone. Conventional core data suggest that the Sandstone comprises fine- to coarse-grained clastics that were deposited by debris flows, liquified flows, and turbidites. Paleobathymetric data, based on micropaleontology, confirm a shelf-to-deep-water genesis of the Tangaroa. The Tangaroa is underlain by deep-water shales (Eocene Kaiata Shale) and overlain by a thick deep-water limestone (Oligocene Te Kuiti Limestone).

The external geometry of the Tangaroa interval, defined by seismic stratigraphic interpretation, is a fan-shaped lobe of sediments with internal character composed of erosional channels and progradational wedges. The erosional channels, 1 to 5 km wide and approximately 70 to 150 m thick, are interpreted as upper bathyal submarine fan channels. Thin progradational wedges are located basinward of the channels.

The Tangaroa Sandstone is subdivided into two sequences: the Lower Tangaroa sequence and the Upper Tangaroa sequence. Each sequence formed during two distinct relative lowstands in sea level, possibly the eustatic falls at 40 and 36 Ma defined by Haq *et al.* (1987). The intervening thin limestone and the overlying Te Kuiti Limestone apparently were deposited during periods of relative highstands in sea level. The proposed location of the Eocene-Oligocene boundary is within the thin limestone of the Lower Tangaroa sequence.

Introduction

This report is a compilation and integration of a series of independent and jointly-undertaken projects by ARCO's Research and Technical Services and Geoscience Operations staff for ARCO Petroleum New Zealand Inc. This report condenses, integrates, and places the results within a sequence stratigraphic framework for the possibility of future exploration for Tangaroa Sandstone or time-equivalent depositional facies.

The Tangaroa Sandstone Member of the Kaiata Formation was first penetrated in 1981 with the drilling of the Shell BP Todd Tangaroa-1 well (Figure 1). It was the first pre-Miocene deep-sea fan penetrated in the Taranaki Basin. The thickness (155 m), high porosity and permeability, and hydrocarbon shows within the Tangaroa in this well made it an attractive potential reservoir. Three subsequent wells, Ariki-1, Kora-1, and Kora-4, have penetrated the Tangaroa without commercial success (Figure 1).

The Tangaroa-1 well was located on a basement structure over which the Tangaroa sandstones were draped. Approximately 155 m of clean, fine to medium grained sandstones were encountered in this well (Figure 2). Interpretation of conventional cores suggest the Tangaroa contains characteristics of turbidite and debris flow deposits.

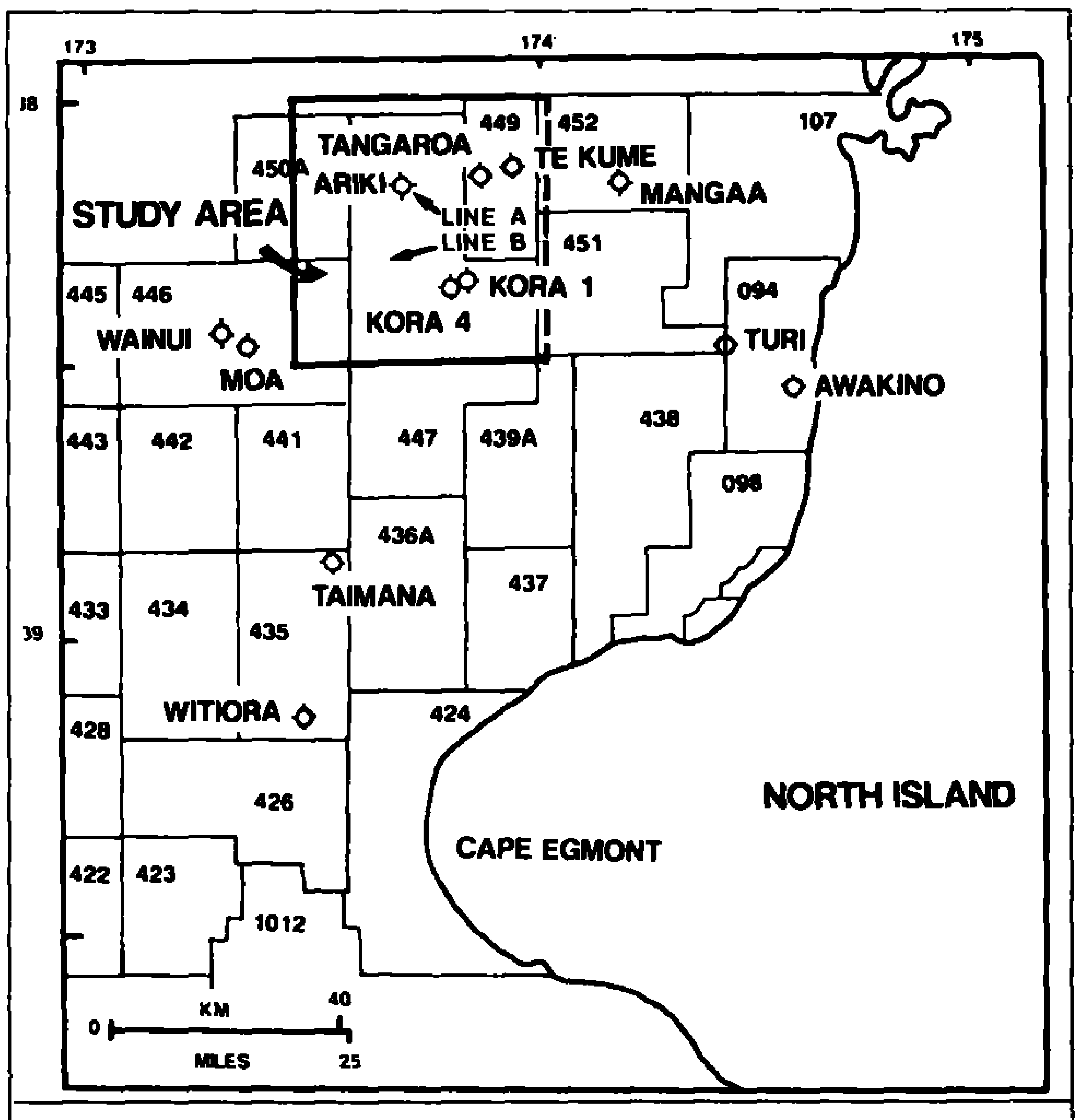


Figure 1: The study area. Offshore Taranaki Basin, west coast of North Island, New Zealand. Wells are identified by name and conventional map symbols.

Of the four Tangaroa tests drilled, all encountered good, thick reservoir sections. However, one sub-volcanic test, Kora-1, encountered poor reservoir quality Tangaroa Sandstones due to localized chemical and thermal alterations associated with close proximity to a Miocene volcanic plug (Bergman *et al.*, 1991; Nedland, 1991). Wells located further away from post-depositional volcanic activity, Kora-4 and Ariki-1, demonstrate the good quality of the sandstones.

Geologic History

The Taranaki basin has undergone a complex tectonic evolution from the mid Cretaceous to the present (King, 1990). The tectonic history evolved from a rift basin in the Cretaceous to passive margin setting in the early Tertiary, a possible foreland basin in the Miocene, to a passive margin setting that remains today.

In the nomenclature of King (1990), the Tangaroa sandstones were deposited on the Western Platform of the Taranaki Basin. Time equivalent facies may be located within the deeper portions of the basin, such as the North Taranaki Graben, but no wells have been drilled deep enough to penetrate a time-equivalent section.

The area of Tangaroa deposition had been tectonically stable from the Late Mesozoic to the latest Eocene-earliest Oligocene (Shell BP Todd, 1981). The basin-wide transgression that was initiated in the Danian (lower Paleocene) reached a maximum in the early Oligocene. During this time the Kaiata Shale was deposited, representing a coarsening-upward or shallowing-upward sequence capped by the Tangaroa Sandstones and the Te Kuiti Limestones.

Stratigraphy

The Tangaroa sandstones were first described by Shell BP Todd (1981) subsequent to the drilling of the Tangaroa-1 well. The proposed target of the Tangaroa-1 were sandstones beneath the Te Kuiti Limestones, assumed to be facies equivalent of the non-marine to marginal marine Kapuni Formation encountered toward the east. Sandstones were encountered below the Tikorangi Limestone, however, interpretation of core data suggest a turbidite genesis for the sandstone. Biostratigraphic data (Shell BP Todd, 1981) place the sands as uppermost Eocene in age, making them part of the underlying Kaiata Formation (Figure 2).

Based on the results of the Tangaroa-1 well, the Kaiata Formation was informally subdivided into two major units: the lower unit is composed of the Kaiata Shale, the upper unit, the Tangaroa Sandstone (Shell BP Todd, 1981) (Figure 2). Overlying the Kaiata Formation are the carbonates of the Oligocene Te Kuiti Formation. The lower contact of the Tangaroa Sandstone is defined where the massive sandstones overlie the Kaiata Shale and this contact is either sharp or gradational. The massive sands grade upward to interbedded sands and shales and finally the pure limestones of the Te Kuiti Formation.

Sedimentary Facies

Shell BP Todd (1981) describe the Tangaroa Sandstone as being comprised of buff to grey-buff, arkosic and quartzitic arenites, locally tending toward arkosic arenites. The sandstones are quartz-rich with up to 15 % feldspar and lithic components of predominantly dark grey mudstone clasts, rare glauconite and up to 20 % matrix, which may be partially calcareous. The average total thickness of the Tangaroa Sandstone is 150 m, with the thickest section found at the Tangaroa-1 well (155 m) and thinnest section at the Ariki-1 well (110 m).

A total of 23 m of the Tangaroa within the Kora-1 (8.8 m) and Kora-4 (14.2 m) were described and interpreted for this

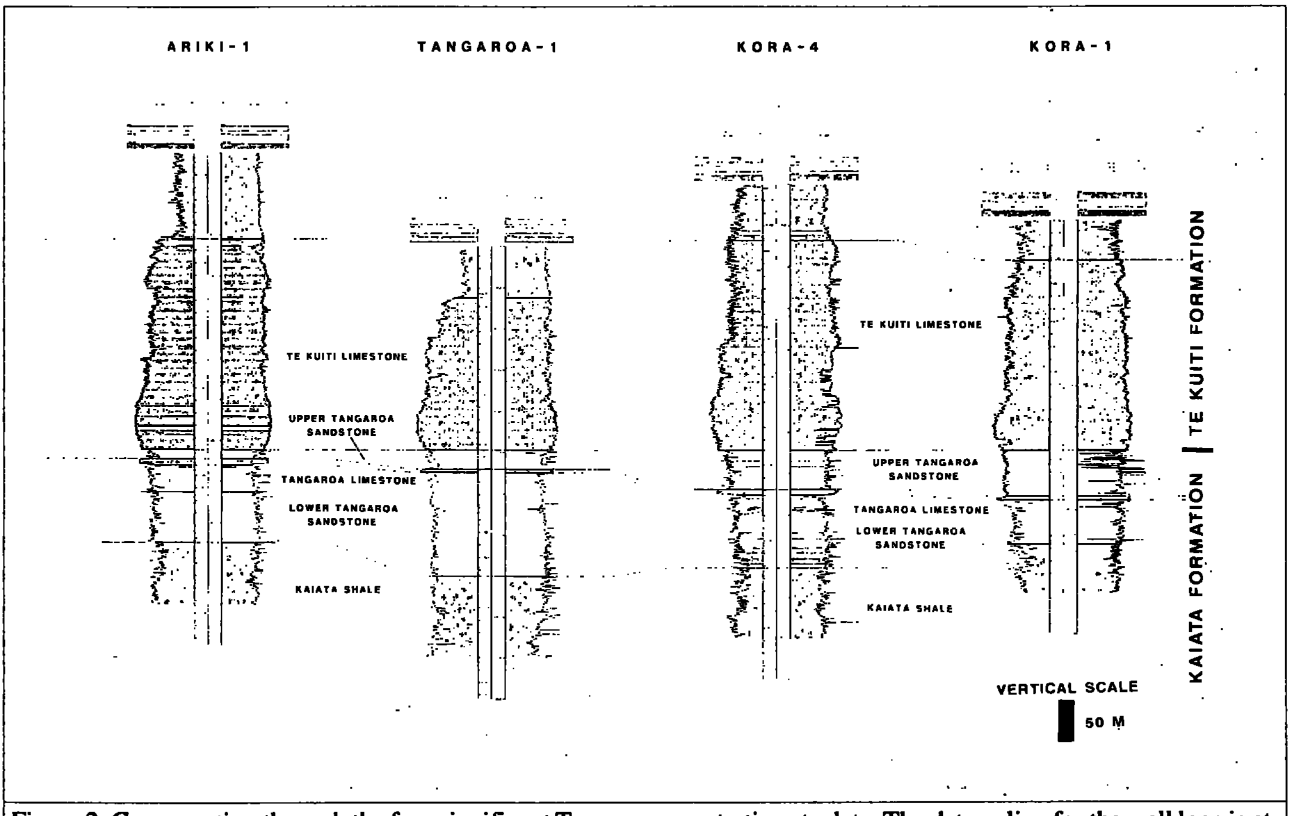


Figure 2: Cross-section through the four significant Tangaroa penetrations to date. The datum-line for the well logs is at the base of the Te Kuiti Limestone. Horizontal scale varies. Basinward is toward the left of the diagram.

study. Interpretation of the cores is consistent with the original interpretation of Shell BP Todd (1981) from cores from the Tangaroa-1 well. All cores recovered in the three wells were from the interval called the Upper Tangaroa Sandstone.

In general, the cored intervals exhibit a poor to moderate sorting, contain fine- to coarse-grained sandstones, claystones, and conglomeratic siltstones, and are locally calcareous cemented.

Description of Cored Intervals

The cored interval in the Kora-4 well is from 3134.9-3149.0 m (14.1 m). Porosities range from 4.6-23.3 % (average 17.7 %). Permeability values range from 0.01-339 (average 106 millidarcies). Core depth is 0.5 m deeper than log depth (Figure 3).

The cored interval in the Kora-4 well (Figure 4) is characterized, by two large-scale sequences (approximately 7-8 m thick) of sandstones, siltstones, and thin claystones capped by a 0.5-0.7 cm thick burrowed marlstone. Each large-scale sequence, in general, contains the following units, from bottom to top:

(1) a series of stacked, small-scale sequences composed of fine to medium-grained sandstone locally interbedded with conglomeratic silty sandstone and silty claystone;

(2) medium- to coarse-grained sandstone having dish structures and soft sediment deformation,

(3) massive beds with faint subhorizontal laminations, local dish structures, and sandstone on sandstone contacts; and

(4) thin interbedded marlstones and burrowed glauconitic marlstone containing *Planolites*, *Zoophycos*, *Thalassinoides*, and *Chondrites* trace fossils.

Small-scale sequences in Unit 1 consist of a 1-10 cm-thick, moderate to well-sorted, fine- to medium-grained, massive to flat-laminated sandstone with a basal poorly-sorted, silty sandstone or sandy siltstone locally containing sandstone, siltstone, coal and claystone clasts, overlain by thin graded beds (1 cm thick) with local claystone and siltstone clasts, capped by a 1-3 cm-thick claystone bed (Figure 5). Subvertical (escape?) to horizontal, sandstone-filled burrows containing retrusive spreite locally occur within conglomeratic siltstones. Very fine, disseminated coaly and clayey debris are found within this bed. Claystone beds are massive to very thinly laminated (with siltstone). Claystone clasts are angular to rounded, elongate and lenticular, and locally extend across the core surface as thin bands (Figure 6A). Clasts range in size from 0.1-6.0 cm (claystone clasts are larger than other clasts within the same interval). Many clasts appear to have been locally derived from the interbedded sandstone, siltstone, and claystone beds which range in thickness from several millimeters to several tens of centimeters.

Only the uppermost part of the sandstone interval immediately below the claystone bed is normally graded. Locally, the 'clean', massive sandstone is absent, and the conglomeratic sandstone overlies the claystone bed. Thin silty and clast-rich sandstones have between 13-20.1 % porosity and 0.42-3.6 md permeability.

Unit 1 is overlain sharply by Unit 2. Unit 2 consists of medium- to coarse-grained sandstones having dewatering or 'dish' structures and internal, sandstone-on-sandstone contacts. Thin silty laminations and soft-sediment deformation locally occur. Scattered small claystone clasts occur directly below the silty laminations (Figure 6B). Coal and claystone clasts are present at the top of some beds and this zone is overlain by a thin graded bed and a 4 cm-thick claystone bed.

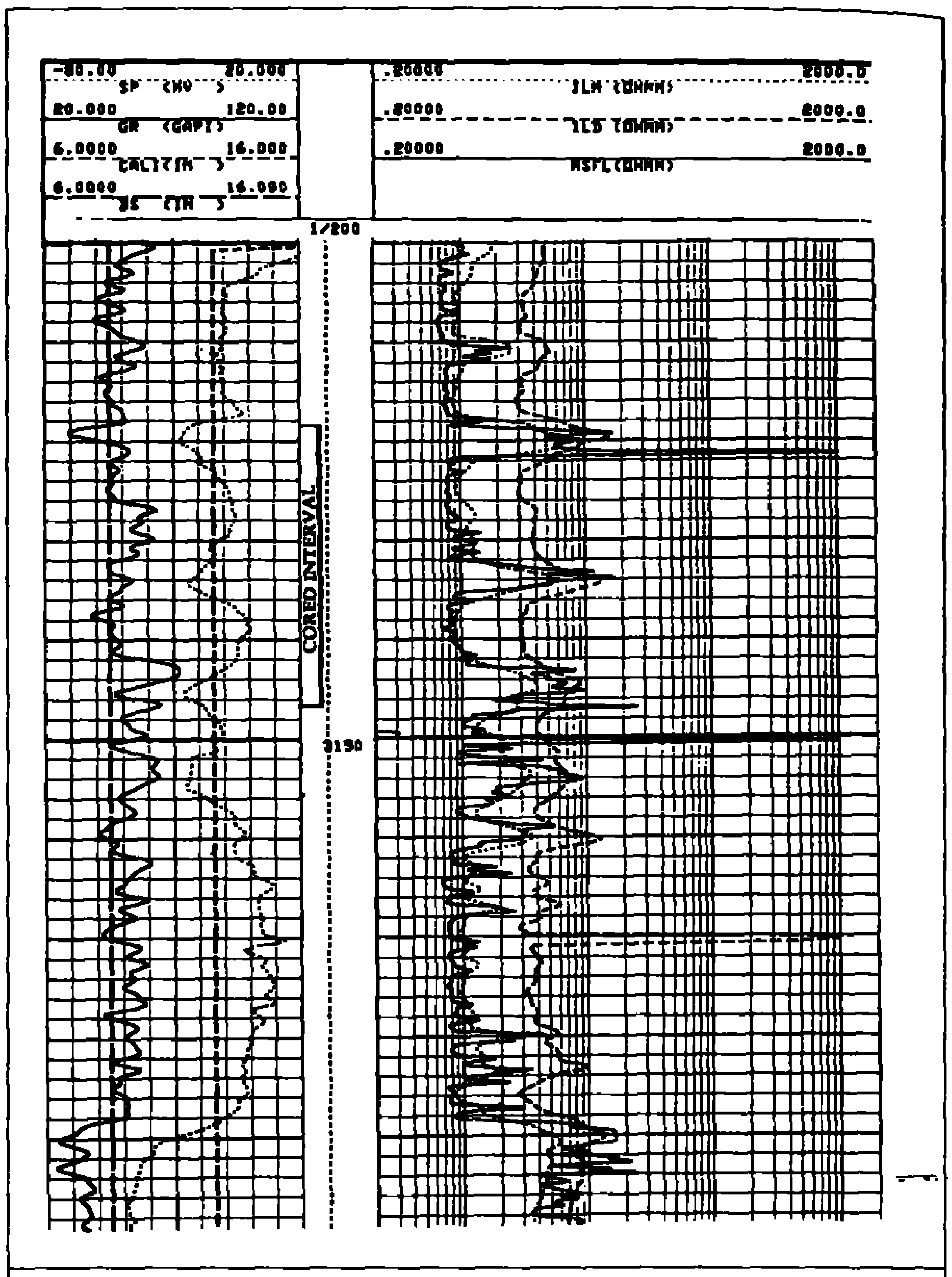


Figure 3: Down-hole log and cored interval in the Kora-4 well. Vertical grid is calibrated in metres. The core depth is 0.5 m greater than the log depth. High resistivity streaks (i.e. at 3142 m log depth) represent thin burrowed marlstones that suggest a period of decreased clastic sedimentation.

Unit 3 consists of massive to slightly graded, amalgamated sandstone with local claystone interbeds (Figure 6C). Unit 3 contains the best reservoir-quality sandstones observed in the two sequences. The unit contains moderately-sorted sandstones throughout with locally present, small claystone and siltstone clasts. Porosities range from 8.5 % (poorly-sorted sandstone) to 21.7 % (massive-appearing, 'clean' sandstone), and permeabilities range from 0.37-339 md, respectively. Dish structures are locally present (Figure 6D). Claystone beds are locally overlain by coarse-grained, massive-appearing sandstones up to 2 m thick.

A very thin (1.04 cm thick), burrowed, glauconitic marlstone interbedded and overlain by a dark gray claystone comprises Unit 4 (Figure 7). Burrows are horizontal and vertical and occur in the greenish-gray marlstone. The upper part of this thin unit is scoured into by the overlying unit. Burrow types include *Thalassinoides*, *Teichichnus*, and *Chondrites*, as well as some unidentifiable vertical, claystone-filled burrows. The uppermost claystone is scoured into by the base of the overlying unit.

Depositional Processes and Model

The larger-scale sequences are interpreted to represent deposition as submarine sheet sands or fan lobes within a

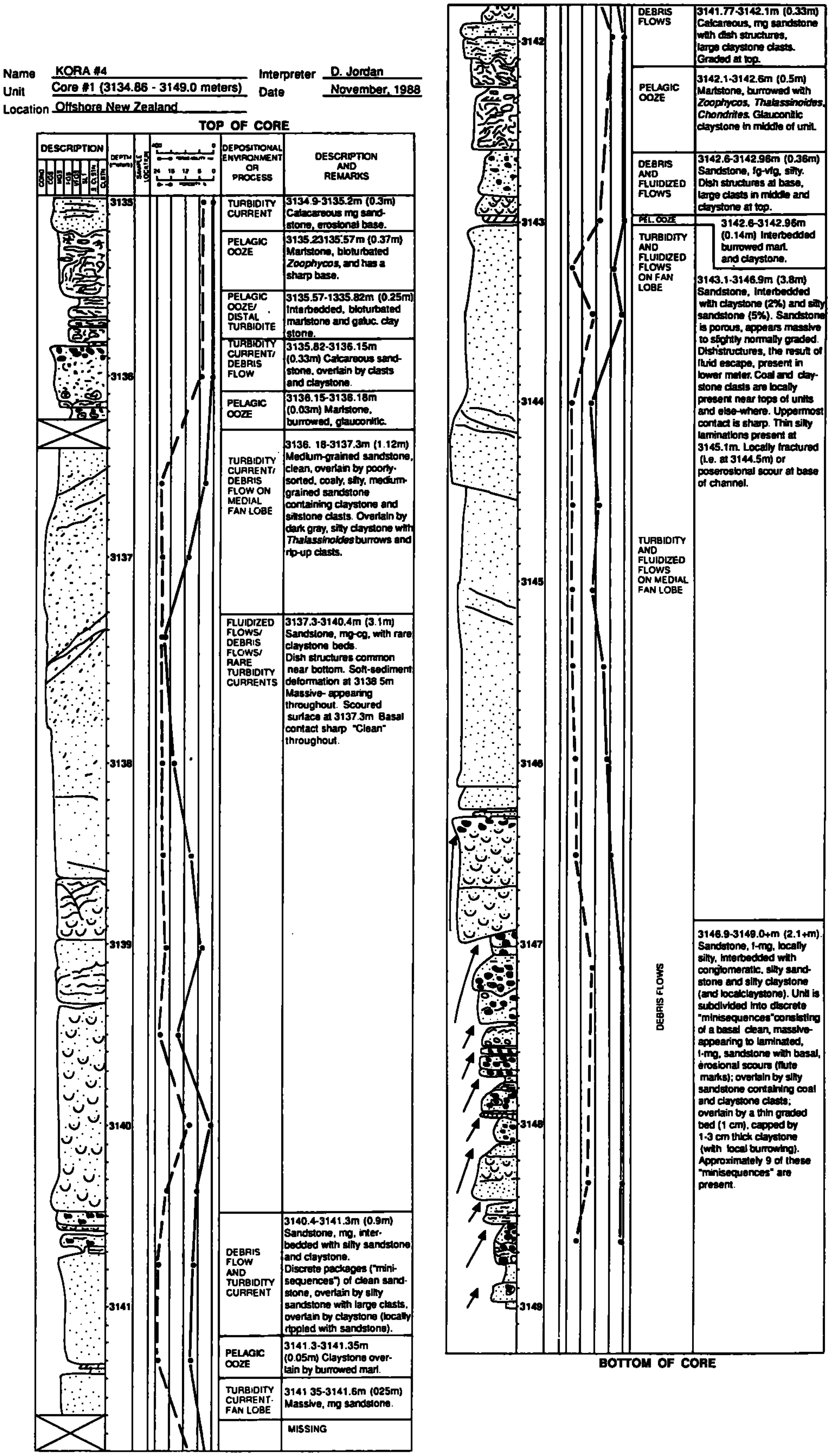


Figure 4: Core description from the Kora-4 well. Two major sequences (3142.1-3149+ m and 3135.2+-3142.1 m), in general, contain debris flow deposits in the lower part, liquified or fluidized flow deposits in the middle part, turbidity current deposits in the upper part, and are capped by marlstones. These sequences represent stacked retrogressive flow deposits within a submarine canyon.

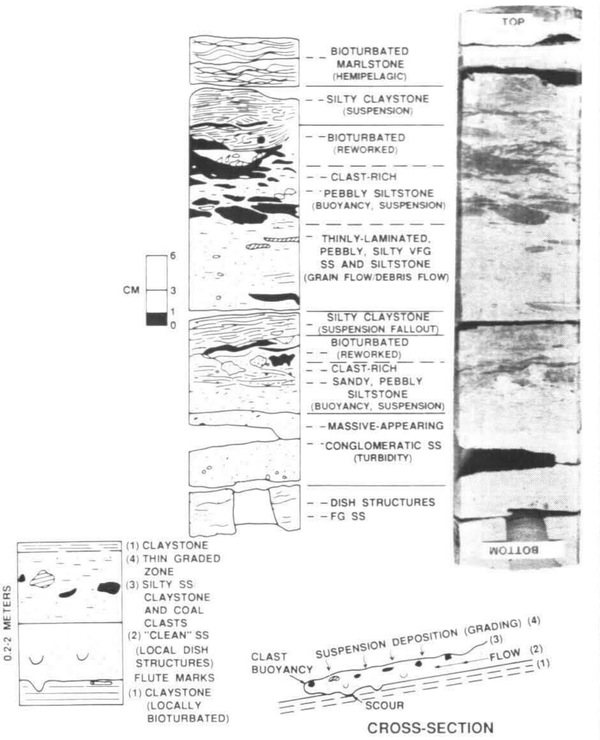


Figure 5: Small-scale sedimentation units present in Unit 1 debris flow deposits.

larger feeder channel or canyon (Figure 8). Slumps, generated by failure of the nearby shelf edge, incorporated seawater and sediment and were transformed from proximal to distal locations into debris flows, fluidized or liquified flows, and turbidity-current deposits. Debris flow deposits (pebbly siltstones and claystones) derived from shelf edge, slope, or channel wall failures in the lower part of the sequence are overlain by fluidized and/or liquified deposits (i.e. sandstones containing dish structures) and turbidity-current deposits (massive sandstones similar to that described by Ingersoll, 1978). The sequence is capped by hemipelagic marlstones representing quiet energy conditions and decreased clastic sediment influx.

Debris and/or mud flows are sediment gravity flows that have matrix-supported clasts supported above the base of the bed by the cohesion strength of the mud matrix or by clast buoyancy (Lowe, 1982). Upward dispersive or fluid turbulent forces act to keep clasts buoyant. Derivation of many of the clasts appear to be local (claystone and siltstone clasts) and from nearshore paralic sequences (coal clasts). Pertaining to the origin of the coal clasts, perhaps the erosion of the shelf edge/slope enabled downcutting into earlier-deposited paralic deposits. A different scenario could be that the coals were ripped up from nearshore coeval strata and transported to the basin as debris flows.

The presence of upward-coarsening, massive-appearing beds (high-density turbidity current deposits), dewatering or 'dish' structures, parallel laminations, soft-sediment deformation, erosional bases, amalgamated beds, and local ripped-up and redeposited claystone clasts in the cored intervals from the Eocene Tangaroa suggest processes of sediment transport similar to Facies "B" described by Mutti and Ricci Lucchi (1972, 1978).

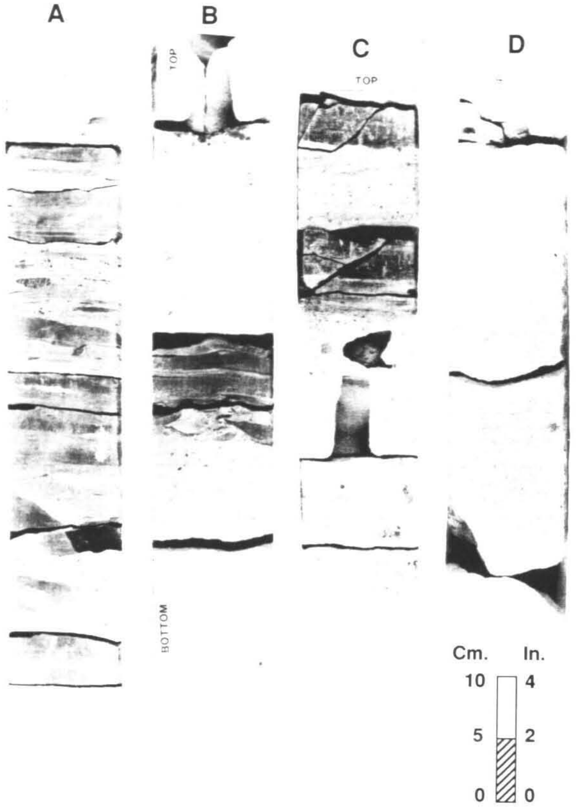


Figure 6: Sedimentologic features of the cored interval in the Kora-4 well. (A) Unit 1. Dark grey, laminated to rippled silty claystone and claystone (L), interbedded with pebbly claystone (C), siltstone, and sandstone (S). Note sharp basal and upper contacts. Clasts are composed of claystone, coal (arrow), and siltstone fragments. Unit 1 represents abrupt, episodic deposition by debris and/or slurried flows, with intervening periods of hemipelagic deposition or suspension fallout. (B) Unit 2. Interbedded massive, fine- to medium-grained sandstone and flat-laminated to graded and rippled silty claystone and claystone. Note subangular, flattened(?) clasts at top of sandstone, representing clast buoyancy due to high-density turbidity flow. (C) Unit 3. Interbedded medium-grained sandstone and flat- to wavy-laminated siltstone and silty claystone. Lower sandstone grades abruptly into siltstone and silty claystone. This sequence may represent rapid suspension fallout as the turbid flow ceased. The upper thin sandstone may represent an incomplete "Bouma sequence" (massive sandstone changing to laminated to rippled or contorted sandstone, to laminated siltstone and claystone), indicative of waning turbid flow. (D) Medium-grained sandstone containing crescent-shaped, fluid-escape ("dish") structures, locally present in Unit 3.

The introduction of oxygen to basinal waters by density and gravity-driven currents is probably responsible for the presence of the various trace fossils. The presence of locally non-burrowed, laminated claystones in the Kora-4 core suggests periods of low energy, anoxic conditions. The presence of *Chondrites*, a common burrow type in deep-water sediments (Ekdale, 1985) commonly occurs in zones adjacent to non-burrowed, laminated mud and suggests

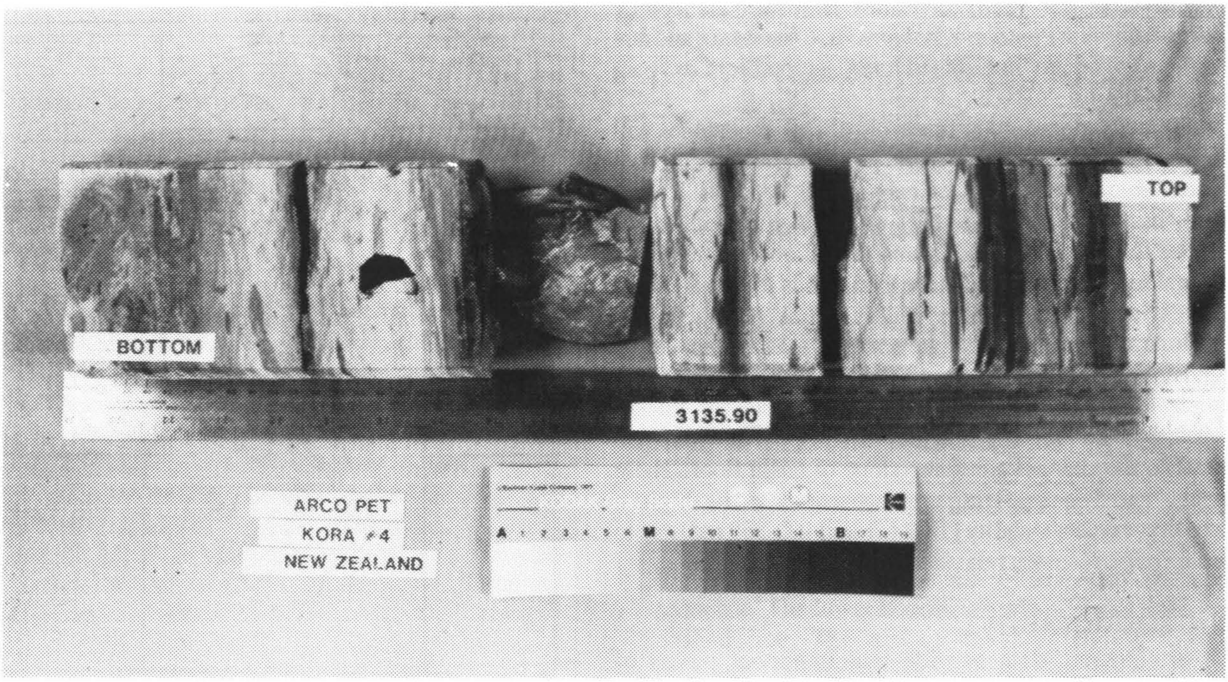


Figure 7: Interbedded burrowed, glauconitic marlstone and dark gray claystone comprising Unit 4 at 3135.4-3135.9 m. Burrows are primarily horizontal and occur in the greenish-gray marlstone. Burrow types in Unit 4 include *Zoophycos* (arrow), *Thalassinoides*, *Teichichnus*, and *Chondrites*.

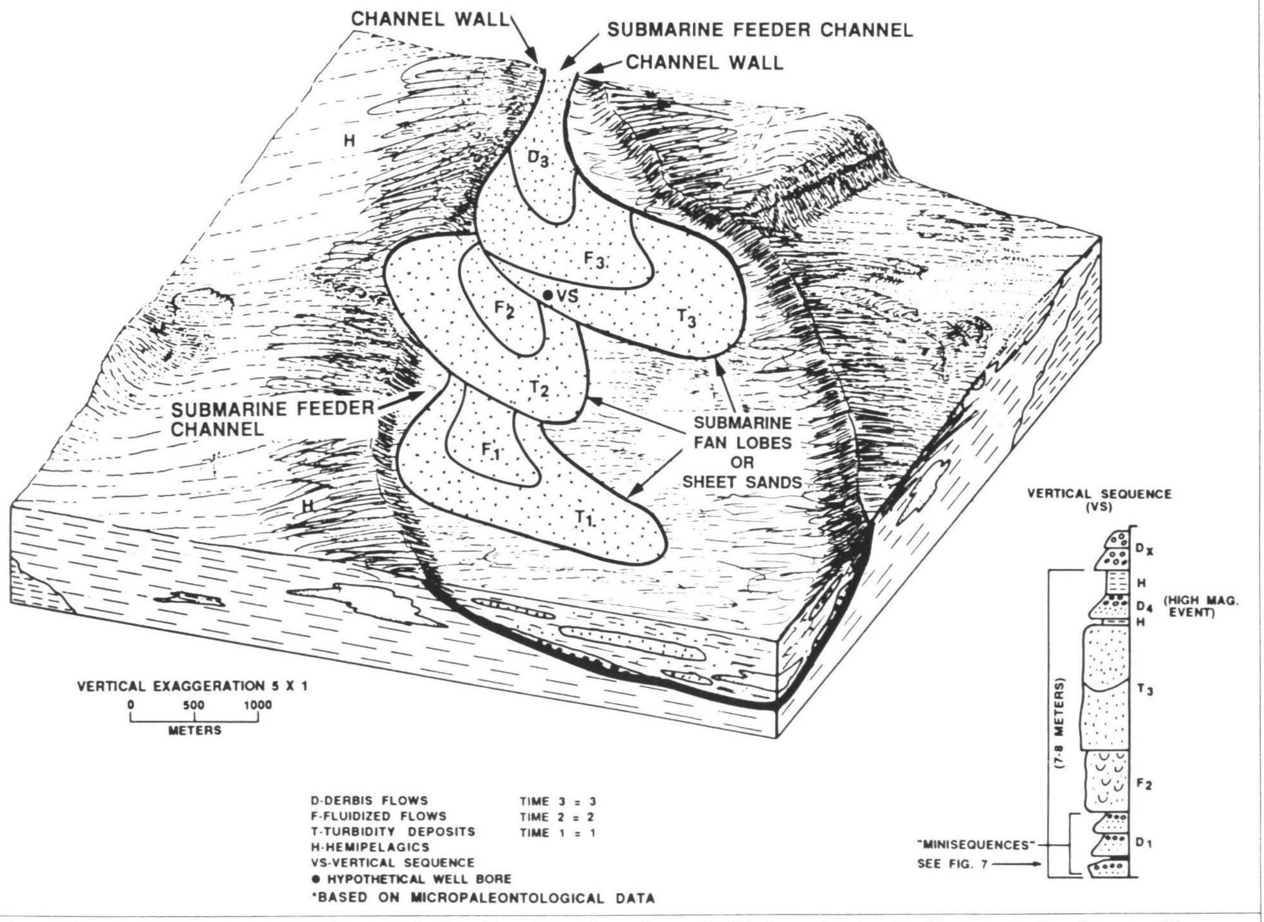


Figure 8: Depositional model of upper bathyal* submarine channel-fill deposits in the Tangaroa Sandstone. Slumps, generated by failure of the nearby shelf edge, incorporated seawater and sediment and were transformed from proximal to distal locations into debris flows, fluidized or liquified flows, and turbidity-current deposits. The vertical sequence displayed in the cored interval shows portions of these retrogressive flows and suggests at least two major episodes of retrogressive failure.

dysaerobic (low oxygen) conditions. Burrowed glauconitic marlstones (with *Planolites*, *Zoophycos*, *Chondrites*, and rare *Thalassinoides*) to bioturbated intervals represent oxygen-rich conditions.

Future exploration for reservoir-quality sandstones will concentrate on predicting the location and distribution of these submarine channel or canyon fill deposits. Recent work has suggested that sheet to channel-shaped bodies similar to those described in this report are centimetres to several tens of metres thick, and hundreds to thousands of metres long, with variable widths (Cook *et. al.*, 1982). Exploration should concentrate on clean, massive-appearing sandstones of a turbidity current origin that occur within the larger feeder channel, or perhaps exploring for thicker submarine fan lobe deposits that should exist downdip and distal to the channel along the slope or basin floor. These clean, massive-appearing sandstones have the highest porosity and permeability (18-24 % and 100-339 md) due to the sorting processes related to deposition.

Biostratigraphy

Biostratigraphic data provide two important pieces of evidence for the depositional history of the Tangaroa Sandstone: paleoenvironment and age control. Analysis by Shell BP Todd (1981) and the New Zealand Geological Survey (Hayward, 1985) of these faunal assemblages within the Tangaroa Sandstone and adjacent units suggest these sediments were deposited in upper bathyal to abyssal depths, the deepest deposits recorded within this stratigraphic interval. These interpretations support the core interpretation of deep-sea fan deposition.

Due to the sandy nature of the Tangaroa, biostratigraphic data is typically sparse within the massive sandstone. However, intervening limestones and marlstone typically contain abundant fauna. Based on the occurrence of foraminifera, biostratigraphic age assignments for the Tangaroa range from Late Eocene (Runangan Stage) to Early Oligocene (Whaingaroan Stage). Interpreted paleoenvironments also vary, from upper bathyal (Shell BP Todd, 1981) to lower bathyal-abyssal (Hayward, 1985). Both interpretations support a deep-water genesis for the Tangaroa deposits. Reinterpretation by ARCO (P. Thompson, 1989; written communication) supports that the Tangaroa Sandstone ranges in age from Late Eocene to Early Oligocene and that the Eocene/Oligocene boundary is present within the thin limestone separating the two massive sandstone units of the Tangaroa.

Seismic Stratigraphic Interpretation

An isochron map of the entire Tangaroa interval (Upper and Lower Tangaroa Sandstone and Tangaroa Limestone) is shown in Figure 9. The Tangaroa interval is a fan-shaped feature covering an area of approximately 400 km^2, has a maximum thickness of 250 m, and depositionally thins to the north, west and south. The progradation vector of the clinoforms as well as the lobate shape suggests the fan complex prograded from east to west with a slight southerly component.

Based on interpretation of seismic reflection data, the Tangaroa Member is subdivided into two sequences. The lower Tangaroa sequence contains the Lower Tangaroa Sandstone and the Tangaroa Limestone. The younger upper Tangaroa sequence contains the Upper Tangaroa Sandstone and the overlying Te Kuiti Formation (Figure 2).

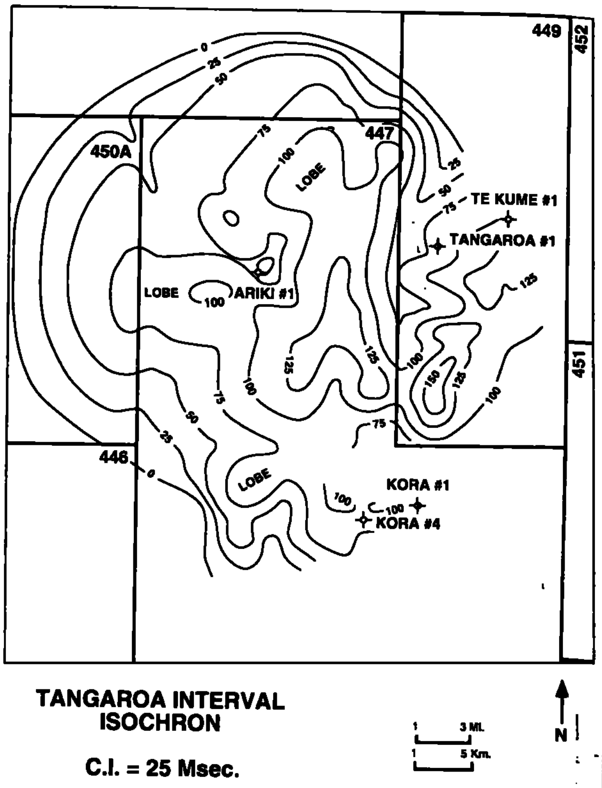


Figure 9: Isochron thickness map of the entire Tangaroa interval. Top of the interval is defined as the base of the Te Kuiti Limestone. Base of the interval defined as the contact between Lower Tangaroa Sandstone and underlying Kaiata Shale.

The basal surface of the lower Tangaroa sequence lies at the contact of the Lower Tangaroa Sandstone and the underlying Kaiata Shale (Figure 2). The surface is characterized on seismic data by erosional channels and offlapping reflections. The Lower Tangaroa Sandstone is an arkosic to quartzose sandstone, with an average thickness of 120 m. Because of erosion at the top of this sequence, internal reflection character within the sequence is difficult to recognize.

Above the Lower Tangaroa Sandstone is a thin (8 m average), light grey, argillaceous Tangaroa Limestone (Figure 2). This limestone is found at the top of the lower sequence and is interpreted to represent a period of reduced clastic deposition (Shell BP Todd, 1981). The contact between the limestone and the overlying Upper Tangaroa Sandstone is the base of the upper sequence.

The base of the upper Tangaroa sequence is defined by numerous erosional channels and offlapping reflections. This surface ties (using synthetic seismograms) into the study wells at the top of the Tangaroa Limestone (Figure 2). Like the Lower Tangaroa Sandstone, the Upper Tangaroa Sandstone is an arkosic to quartzose sandstone, though thinner with an average thickness of 24 m. The Upper Tangaroa Sandstone grades upward from a massive sandstone through interbedded sands and shales, to calcareous mudstone, and finally to the pure limestone of the overlying Te Kuiti Formation (Figure 2).

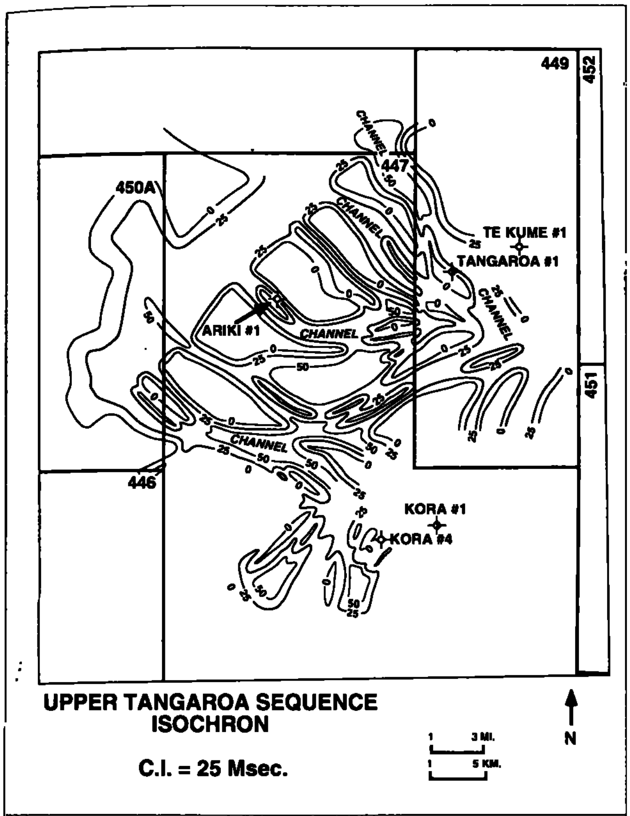


Figure 10: Isochron thickness map of the upper Tangaroa sequence. Linear thicks define infilled erosional channels. Zero-thickness defines interchannel areas. Progradation direction was to the northwest.

An isochron thickness map of the upper Tangaroa sequence is shown in Figure 10. Channel fills are expressed as linear isochron thicks; depositional lobes appear as lobate thicks. Interchannel areas are defined as isochron thins. All the wells in the North Taranaki Basin that penetrate the Tangaroa are located in interchannel areas of the upper sequence (Figure 10).

An example of erosional channels observed on seismic data are shown in Figure 11. The erosional channels are defined by seismic onlap and erosional truncation and average 1 to 5 km in width and 70 to 150 m in thickness. The channels have erosional bases that are incised into the relatively horizontal, underlying strata. On seismic data, the channels contain onlapping internal reflections (Figure 11). On isochron thickness maps (Figures 9 and 10), channel-fills are expressed as linear isochron thicks and are interpreted to have the highest potential for reservoir quality sands. Interchannel areas are expressed as isochron thins and have the lowest reservoir potential.

Stratigraphically above the Upper Tangaroa Sandstone and still within the upper Tangaroa sequence is the Te Kuiti Formation (Figure 2). The Te Kuiti Formation is a thick (200-250 m), light grey limestone with fauna that suggest its deposition in bathyal depths (Shell BP Todd, 1981).

The upper contact of the Te Kuiti Formation with the overlying Mahoenui Formation (mudstones with interbedded sands) defines the upper bounding surface of the upper Tangaroa sequence. This contact is difficult to pick on logs and in core, and is arbitrarily defined at the depth where carbonate content exceeds 30 % of the lithology. On the scale of the seismic data, however, the contact is expressed by seismic onlap.

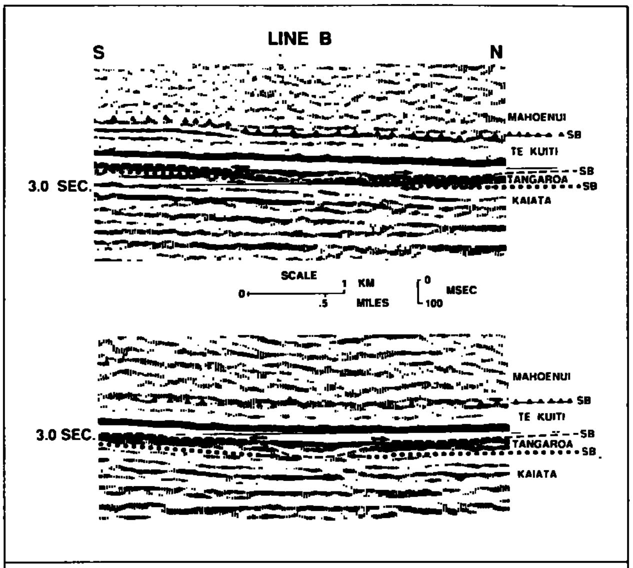


Figure 11: Erosional channels of the upper Tangaroa sequence. The lower bounding surface is marked by the dashed line. The arrows show onlapping internal reflections. Seismically defined sequence boundaries are indicated by individually characterized/coded lines.

Regional Sequence Stratigraphic Model

To aid in correlation of large-scale stratal geometries from seismic data, Vail (1987) developed a sequence stratigraphic systems tract model (Figure 12). This proposed sub-division of the rock record into systems tracts enables one to place sedimentary strata into a sequence stratigraphic model by identifying significant stratigraphic surfaces and stratal geometries.

Work by ARCO (P. Thompson, 1991, written communication) has improved the traditional model of Vail (1987) by including a series of hypothetical wells showing potential biostratigraphic information within the systems tracts (Figure 12). Paleobathymetric interpretations, hypothetical fossil ranges and their relationships to significant sequence stratigraphic surfaces, such as sequence boundaries (SB), transgressive surfaces (TS), and maximum flooding surfaces (mfs) are shown. This additional information aids in regional correlations in areas, such as onshore to offshore transition zones, areas with structural complexities, or areas without regional seismic coverage.

Due to its basin-restricted nature, deep-water genesis, and seismic characteristics, the Tangaroa Sandstone is interpreted to consist of lowstand slope fans (sf) within the lowstand systems tract (LST) of Vail (1987) (Figure 12). The overlying Tangaroa and Te Kuiti Limestones represent times of depositional quiescence within the overlying transgressive systems tract (TST) and highstand systems tracts (HST).

Attempts were made to develop regional correlations for the northern Taranaki Basin to determine the genetic relationships of shelf, slope, and basin depositional sequences in order to gain an understanding of the distribution, thickness, and depositional history of potential reservoir, seal and source facies for the Tangaroa Sandstone. Correlation of the

Tangaroa Sandstone onto the Western Platform and western margin of the Taranaki Graben to wells located to the east is problematic due to intense faulting and poor resolution of seismic data.

An integrated regional model, similar to the Vail (1987) sequence model, but specific for the Eocene/Oligocene interval of the northern Taranaki Basin, was developed for this study (Figure 13). Biostratigraphy from well reports was refined by statistical treatment to derive a high-resolution biostratigraphic zonation. These results were placed in a sequence stratigraphic framework, and integrated with lithostratigraphic data. Using this data, it was then possible to infer genetic relationships of slope and shelf units contemporaneous with the Tangaroa deep-sea fans.

During the Eocene and Oligocene, shelfal deposition was restricted predominantly to times of relative highstand of sea level (Figure 13). During these times, thick accumulations of sediments, such as the Kapuni Formation (HST), Matapo Sandstone (TST), Otarao Formation (HST) and Tikorangi Limestones (HST) were deposited on the shelf. Slope areas, such as the Turi-1 location, were sites of either nondeposition during highstands of sea level or sediment bypass during lowstands. Deep-water turbidites were deposited in the basin during relative lowstands in sea level. These sandstones, the Upper and Lower Tangaroa, were deposited during two distinct sea level falls separated by a rise in sea level during which the Tangaroa Limestone was deposited (Figure 13).

Eustatic Correlation

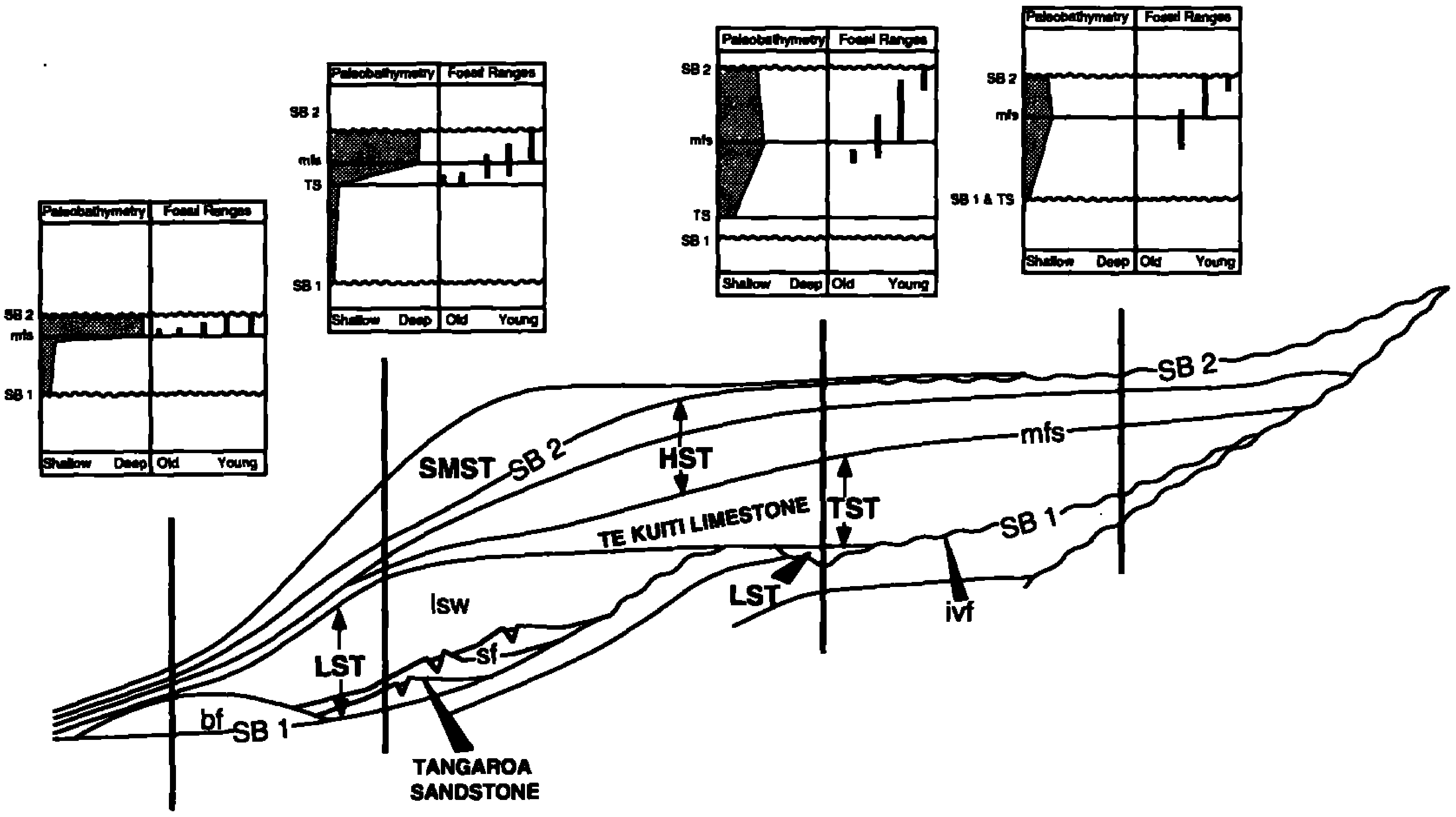
Using the chronostratigraphic framework developed in this study, the changes in sea level that controlled the deposition of the Tangaroa Sandstones can be correlated to global sea-level changes reported in Haq *et al.* (1987). The base of the lower Tangaroa sequence is a sequence boundary representing a lowering of sea level which occurred near the base of the Kaiatan Stage. This correlates with the 40 Ma global sequence boundary from Haq *et al.*, (1987).

The base of the upper sequence relates to a drop in sea level occurring in the Runangan Stage. This correlates to the 36 Ma sequence boundary of Haq *et al.*, (1987). Within this sequence, the condensed section occurs at the Eocene-Oligocene boundary and is represented on the seismic data by the downlap surface. The top of the upper sequence occurs within the Waitakian Stage, near, but not at the boundary with the Otaian Stage. This correlates with the 24 Ma sequence boundary, and marks the lithologic contact between the Mahoenui Formation and the Te Kuiti Formation.

It is likely that similar deep-sea fans, both time-equivalent and older were probably deposited within the Taranaki Basin. Drilling within the deeper portions of the basin, such as the Taranaki Graben to the east of the study area should encounter additional deep-sea fan deposits.

Summary

The Tangaroa Member is a deep-sea fan complex composed of upper bathyal submarine fan channels and thin



SURFACES

(SB) Sequence Boundaries
(SB 1)-Type 1
(SB 2)-Type 2
(TS) Transgressive Surface
(First Flooding Surface Above Maximum Progradation)
(mfs) Maximum Flooding Surface

SYSTEMS TRACTS

HST Highstand Systems Tract
TST Transgressive Systems Tract
ivf-Incised Valley Fill
LST Lowstand Systems Tract
ivf-Incised Valley Fill
lsw-Lowstand Wedge-Prograding Complex
sf-Lowstand Slope Fan
bf-Lowstand Basin Floor Fan
SMST Shelf Margin Systems Tract

Figure 12: Sequence stratigraphic systems tract model of Vail (1987). Included are paleobathymetric and fossil ranges at hypothetical wells. Also shown are possible system tract interpretation for the Tangaroa Sandstone and Te Kuiti Limestone.

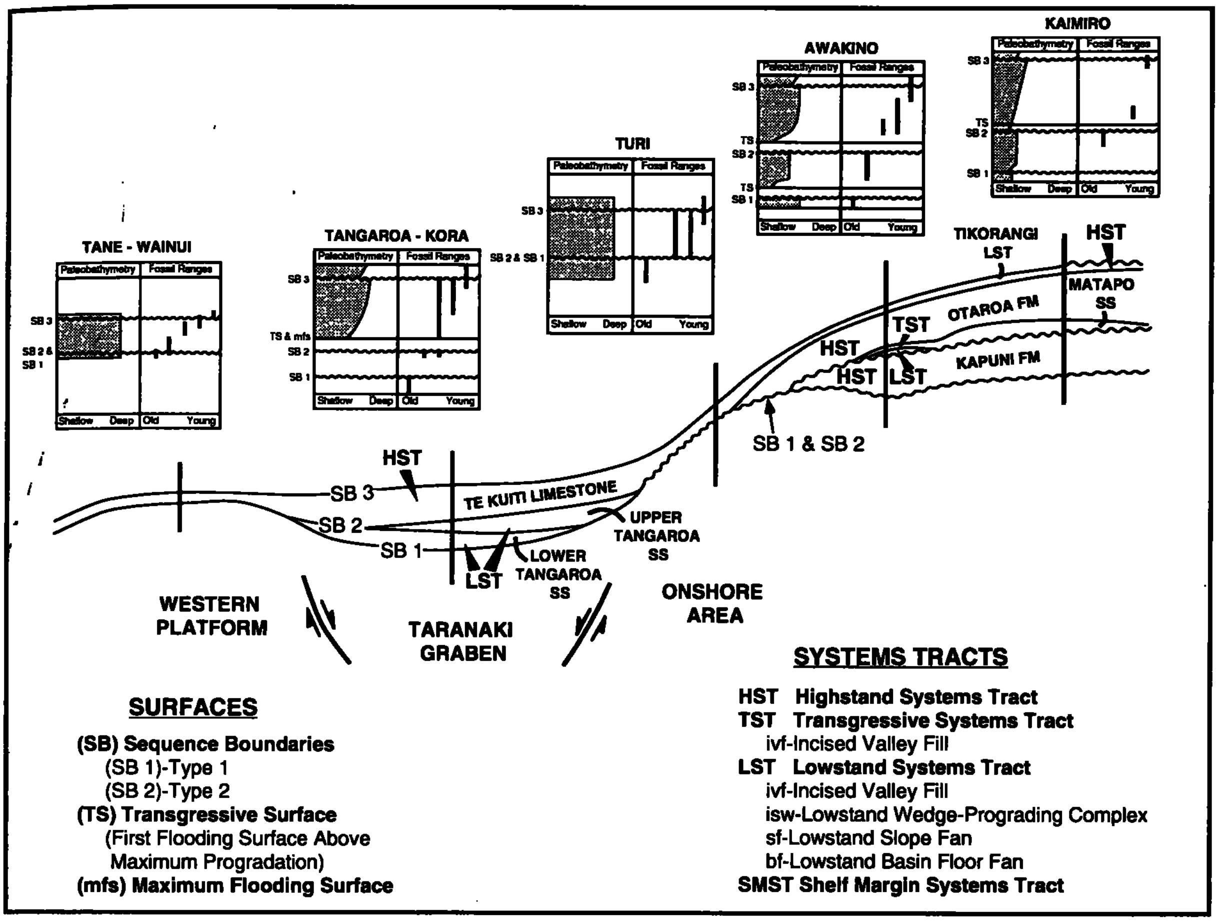


Figure 13: Sequence stratigraphic systems tract model, modified from Vail (1987) developed specifically by this study for the northern Taranaki Basin during the Eocene and Oligocene. Shown are the systems tract interpretations for the Tangaroa Sandstones as well as other significant depositional facies.

progradational wedges. The erosional channels are defined by seismic onlap and average 1 to 5 km in width and 70 to 150 m in thickness. Thin progradational wedges onlap the front of the channelized portion of the fan and are thinner than the erosional channels, averaging 50 to 100 m thick.

The Tangaroa deep-sea fan complex is comprised of two sequences. Both sequences are composed of channelized and progradational deep-sea fan systems; each was deposited during a lowering of sea level and are overlain by carbonates deposited during a rise in sea level. The lower Tangaroa sequence (40 ma. sequence boundary, Thompson *et al.*, 1988), as penetrated in the Tangaroa well, contained over 120 m of well-sorted, massive, channelized sandstone (Lower Tangaroa Sandstone) with a thin (8 m) limestone (Tangaroa Limestone) at its top. The upper Tangaroa sequence (37.3 ma. sequence boundary, Thompson *et al.*, 1988) includes the Upper Tangaroa Sandstone (24 m average thickness) and the thick (200 m) Te Kuiti Limestone.

The wells in the North Taranaki Basin have penetrated channelized and progradational facies of the lower Tangaroa sequence as follows; Tangaroa-1 and Kora-4, the proximal-fan (channels) facies; Ariki-1, the distal-fan (progradational) facies; Kora-1, the interchannel facies. To date, the upper Tangaroa sequence has been penetrated in interchannel areas only.

It is probable that fan complexes similar to the Tangaroa exist undiscovered in other parts of the Taranaki Basin. Identification of genetically related fan complexes can be aided by using seismic sequence analysis and the depositional model for the Tangaroa presented in this study. Likely locations for such fans are to the south, southwest, and west of the study area.

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