SEISMIC INTERPRETATION OF THE MOKI FORMATION ON THE MAUI 3D SURVEY, TARANAKI BASIN

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Abstract

The Moki Formation in the Maui PML comprises a Middle Miocene sequence of turbidite sandstones interbedded with bathyal claystones which are cut by numerous submarine channel complexes. Oil and gas shows have been observed in Moki sands in some Maui Field appraisal and development wells, however, no commercial hydrocarbon accumulations have been discovered anywhere offshore in the Moki Formation in Taranaki.

The Moki sequence has been previously subdivided into the Moki A Sands, B Shale, and B Sands over the Maui area. The Moki B Sands were deposited as mid-bathyal submarine fans distal from the slope break. The slope advanced progressively towards the Maui area from the southeast during the Lillburnian (Middle Miocene). The Moki A Sands were deposited near the base of the slope during the Lillburnian to Waiauan (Middle Miocene) and are associated with several major submarine channel complexes. The slope prograded across the Maui PML in a northwesterly direction during the Tongaporutuan to Kapitean (Late Miocene), depositing the Giant Foresets.

Seismic mapping of the entire Moki sequence on the Maui 3D survey has revealed more clearly the stratigraphic relationships between sands penetrated by the wells. Most sands are not considered to be laterally extensive over the Maui PML, however, one strongly developed seismic softkick in the Moki B sequence is readily mappable across the entire survey area (west of the Cape Egmont Fault Zone) and corresponds with a regionally developed c. 20 m thick sand unit.

Seismic attribute displays have been used to image paleogeography and faults for different levels in the Moki sequence. Moki submarine channel complexes are clearly imaged for the first time in Taranaki, showing spectacular meandering patterns within linear zones of channel development, oriented northwest–southeast across the Maui area. In some cases sandprone submarine fans are also imaged.

Fault mapping at Moki level reveals a series of SSW–NNE oriented normal faults over the eastern half of the Maui PML, whereas the western area is dominated by the presence of the deep-seated Whitiki reverse fault that only partly offsets some Moki B horizons but causes the Moki sequence to be tightly folded with steep westerly dips. There is no observable offset of channels that are oriented perpendicular to the main faults, therefore the amount of lateral offset is probably minor west of the Cape Egmont Fault Zone.

Analysis and modelling of seismic amplitude variations shows that increase in amplitude for a single softkick event is caused by an increase in either sand thickness or sand to shale nett to gross ratio when hydrocarbon saturation is constant. Thus, seismic amplitude displays can provide a means to identify areas of better sand development and recognition of sand body geometrics.

Introduction

Taranaki Basin (figure 1) is New Zealand's only commercially producing hydrocarbon province, with average 1992 production rates of 5994m^3 oil and condensate per day and 12.7 x 10^6 m^3 gas per day (Ministry of Commerce, 1992). Most production is from pre-Neogene formations, with the largest reserves by far being contained in the Maui Field.

Moki Sandstone play

Although Miocene sandstones were the primary oil exploration targets of operators in Taranaki Basin prior to 1960, with the discovery of commercial quantities of gas-condensate within the deeper Eocene Kapuni Group in 1959 at the onshore Kapuni Field, the Miocene objectives were largely ignored until the late 1980s. In 1983/84 the offshore Moki-1 well discovered oil in Middle Miocene turbidite sands and production tested at a constrained rate of 105m^3/d 32° API waxy crude, from sands with average porosity of 21% and permeabilities up to 588 mD (Tricentrol, 1984a). Appraisal drilling (Tricentrol, 1984b) deemed the find sub-commercial but it focused attention on Miocene sands as a potential shallow primary exploration play in Taranaki.

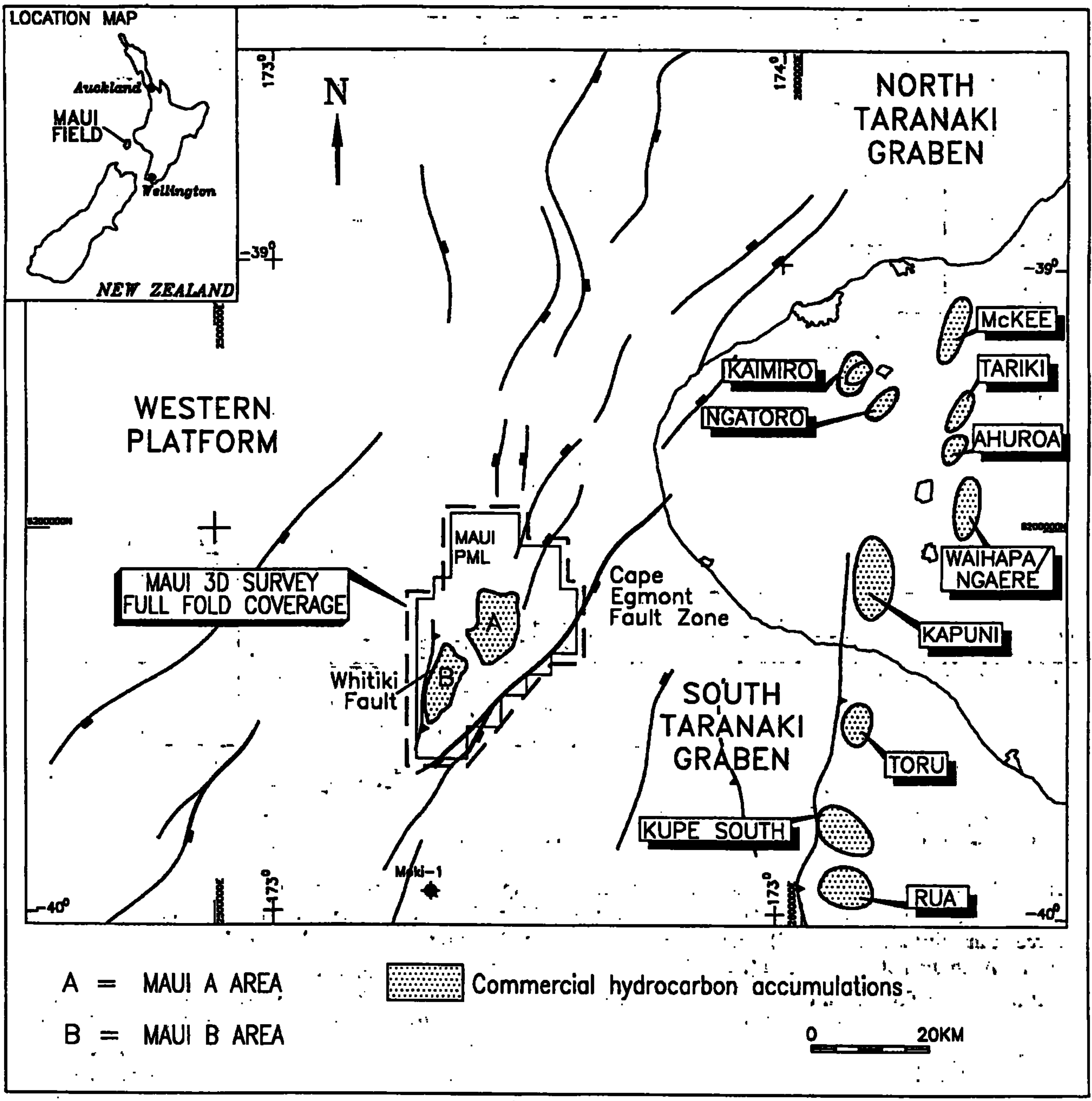

Fig. 1. Location of the Maui Field, main structural elements and hydrocarbon accumulations.

Recent reappraisal of this discovery by Petrocorp also deemed it uncommercial (Petrocorp, 1991).

The principal Miocene reservoir sands recognised in Taranaki Basin are within the Moki Formation (Lock, 1985) and the Mt Messenger Formation (Hay, 1967; King, 1988). Following a Late Oligocene–Early Miocene period of low sedimentation rates and a reduced supply of terrigenous sediment, Taranaki Basin became a depocentre for mid-bathyal siltstones and claystones of the lower Manganui Formation. The Moki Formation comprises fine to very fine-grained, argillaceous, lithic sandstones interbedded with siltstone, silty claystone and minor limestone, and overlies the Lower Manganui Formation. It is interpreted as a sequence of submarine fans and associated turbidite deposits. Their deposition began in the southern part of the basin in the Middle Miocene and progressed in a northwestward and later northward direction of progradation ahead of an advancing slope and shelf system (Hayward, 1990). The Moki sands are time transgressive over the basin, with the North Taranaki Graben experiencing turbidite sand deposition as late as Pliocene. Moki sands are not clearly differentiated from the Manganui Formation on the Western Platform and were not deposited on the southeastern basin margin. Onshore, the Moki Formation does not crop out as the same sequence observed in the Maui wells, however King et al. (1993) considered the Tirua Formation exposed in northernmost Taranaki (Nodder et al., 1990) to be equivalent to the offshore "lower Moki Formation", while the Waikaretu Formation (Nodder et al., 1990) and Ferry Sandstone Member (Hay, 1967; King et al., 1993) were correlated with the "upper Moki Formation". These north Taranaki exposures include interbedded volcaniclastic beds incorporated in the Mohakatino Group which is partly age equivalent with the Moki sequence at Maui. Volcaniclastic material has not been recognised in the Moki sequence in the Maui Petroleum Mining Licence (PML). Moki Formation deposition marked the beginning

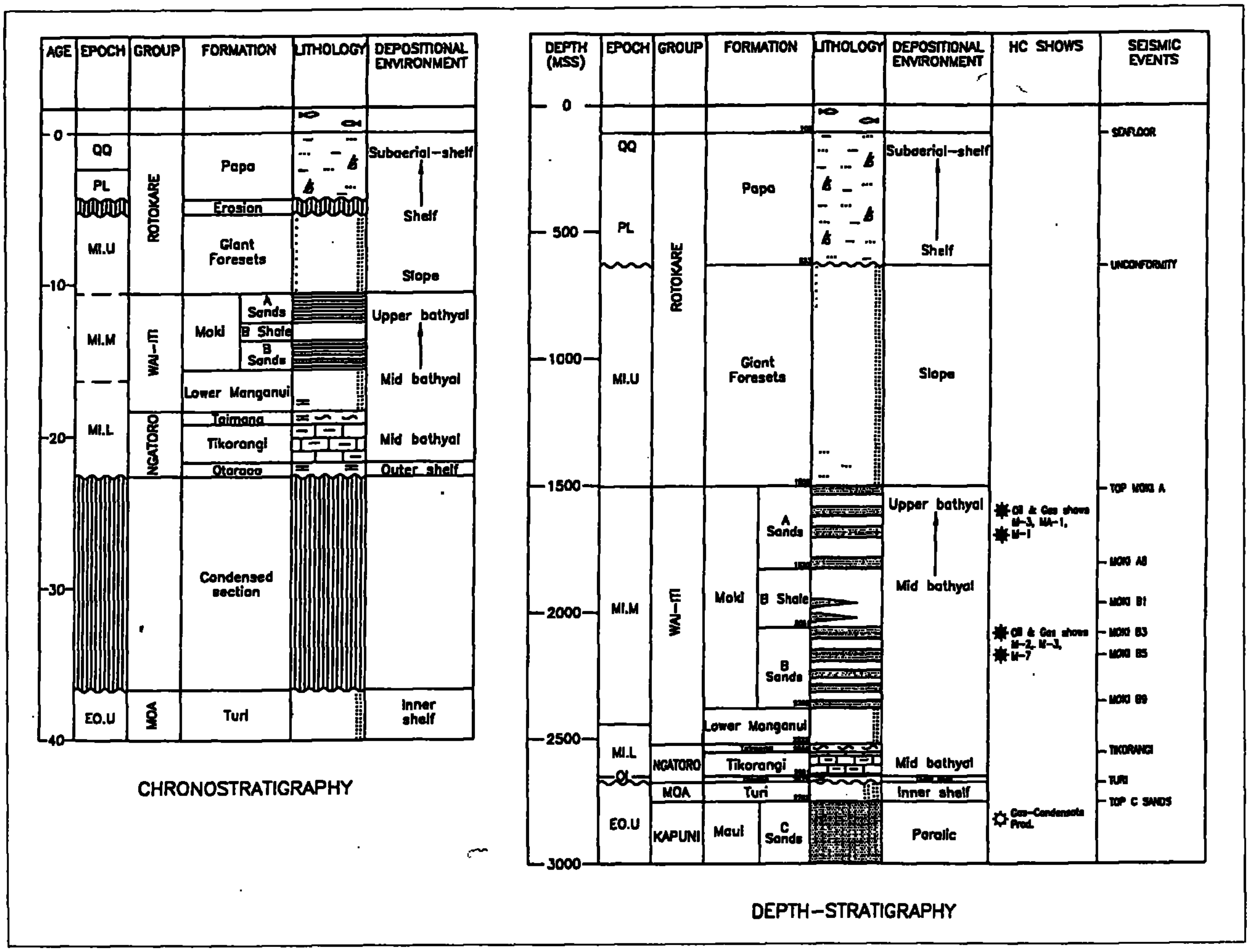

Fig. 2. Stratigraphic summary of the post-Eocene sequence in the Maui PML.

of an overall regressive phase of sedimentation that occurred in response to uplift of sediment source regions (considered to be predominantly the South Island) when convergence on the Pacific-Australian plate increased (King, 1990).

The Mt Messenger Formation crops out along the North Taranaki coast and is present in wells in the eastern basin subsurface (King et al., 1993) but is not found over the Maui Field. Sands in the Mt Messenger sequence are similar to the Moki sands; but are generally more thinly bedded and were deposited as turbidites at shallower water depths close to the slope.

Miocene turbidite sands of the Mt Messenger and Moki formations have more recently been successfully targeted onshore at the Kaimiro and Ngatoro fields (both still under appraisal) where oil and some gas-condensate have been discovered (figure 1).

In the Maui PML, seven vertical appraisal/development wells targeting Eocene objectives penetrated the Middle Miocene Moki Formation sequence prior to Maui B development well drilling and prior to acquisition of the Maui 3D seismic survey. Oil and gas shows were observed in Moki sands in several wells and low hydrocarbon saturations (typically 20-40%) have been petrophysically determined in some cases. A wireline formation test in the top Moki B Sand at 2097 mbdf in Maui-2 produced 0.3 litres of condensate and 1.9 m^3 of gas from a sand determined to have a hydrocarbon saturation of 60%. These observations at Maui and the results of drilling Miocene sediments elsewhere in Taranaki Basin, raised interest in seismic mapping and interpretation of the Moki sequence on the Maui 3D seismic survey. Figure 2 shows the stratigraphy of the Moki sequence in the Maui PML.

Maui 3D seismic survey

The Maui 3D seismic survey was acquired and processed in 1991/1992. It covers the entire Maui PML area and extends into adjacent exploration acreage, with a full-fold coverage of c. 1000 km^2 and a 25 m x 25 m bin size (figure 1). Acquisition was by GECO using the "Quad-Quad" technique (Bukovics & Alsop, 1992). The survey data were split into western and eastern parts and processed separately at Compagnie Generale de Geophysique's (CGG) processing centre in Massey, France and Shell's (SIPM) processing centre in The Hague. The western processed data were received for interpretation in late 1991 and the eastern data in mid 1992. Zero-phase data were loaded onto a Landmark trace interpretation system built around a Sun workstation and supported by Seiko and versatec colour plotters.

The Maui 3D seismic survey was acquired with several objectives:

1. to optimally target Maui B development wells to their Eocene C and/or D sand reservoir objectives
2. to aid Maui reservoir management, optimising production from the A and B platforms, and assist in development of a reservoir model
3. to identify potential exploration prospects in the Maui PML.

The following results from seismic interpretation and mapping of the Moki Formation on the Maui 3D seismic

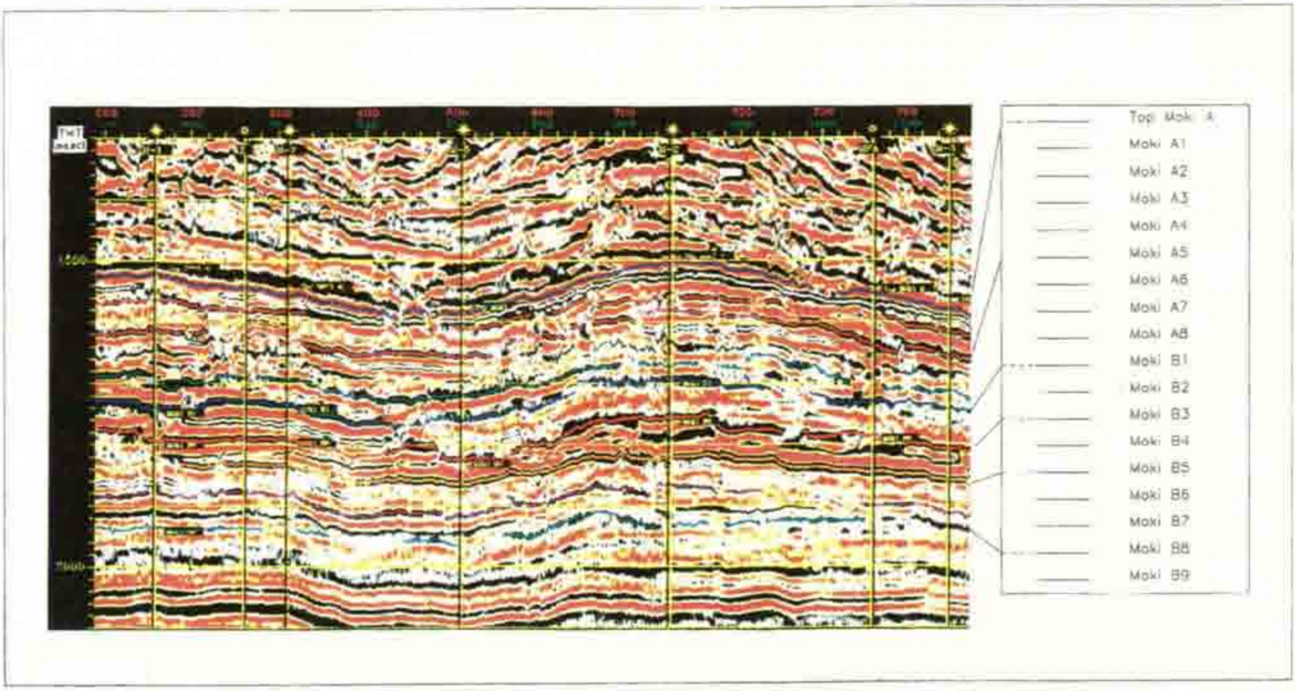

Fig. 3. Seismic-well tie line showing the mapped Moki Formation events.

survey, concentrate on new insights into the depositional setting and structure of these turbiditic sands.

Seismic Interpretation and Mapping

Interpretation of the Moki Formation has been performed using Landmark Seisworks 3D software on a Sun Sparc workstation. Every softkick (black positive loop) in the Moki sequence was mapped using seismic event nomenclature shown in figure 3.

Well synthetics were produced at 50 cm/sec for all the Maui vertical wells over the Moki interval using Sierra Quiklog software to tie the Moki seismic events to the well stratigraphy (e.g. MB-11 (Z), figure 4).

Each event was mapped using a seedline grid of at least every 16th in- and cross-line over the entire survey area west of the Cape Egmont Fault Zone (CEFZ). Arbitrary diagonal and zig-zag lines were utilised when required and at times a more closely spaced seedline grid was mapped.

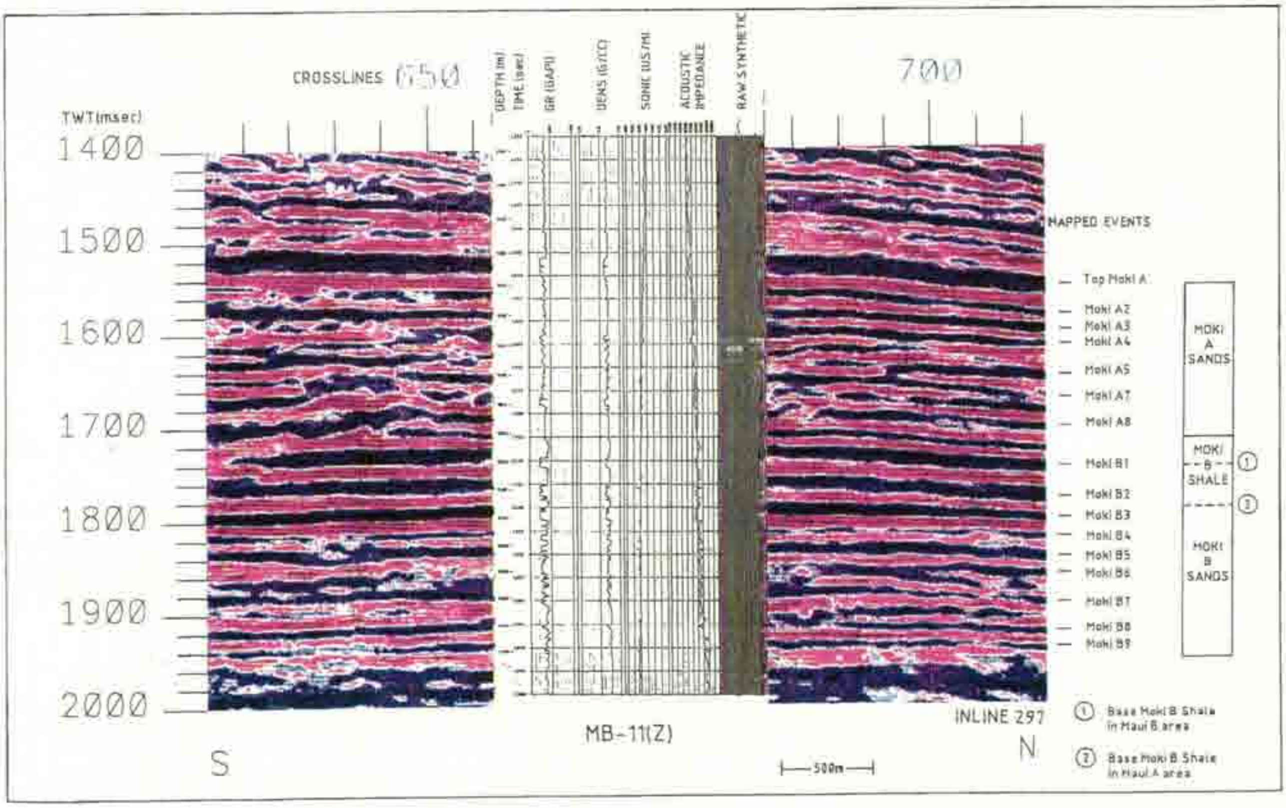

Fig. 4. Well synthetic-seismic tie for MB-11(Z) Moki Formation.

The Moki Formation is considerably downthrown on the eastern hanging wall of the CEFZ and is unlikely to contain a commercial reservoir in that setting, therefore no detailed seismic mapping was performed in that area.

Mapping events in the Moki Formation was not straightforward. Only at the Moki B5 (intra Moki B Sands) level is there a strong softkick well-developed across most of the survey area with few channels cutting the event. Most Moki events suffer from being cut by channels in several locations and from pinchout due to either tuning effects as sand bodies thin out or interference effects from overlying sands and shales. Numerous faults offset events in the eastern half of the survey and in some cases seismic character changes across fault blocks with extra events being present on one side of the fault at some levels. Channels often coincide with fault planes also, which make correct correlation across the faults difficult and generally require tying the data around from further afield. This was particularly the case with correlation across the Whitiki Fault/Fold (figure 1). In places the mapped event shows a progradational depositional character with downlapping terminations. As the objective of the study was to identify potential exploration leads, the event mapping was generally forced through such areas, if warranted, to allow mapping of that level over as much of the survey as possible.

After a seedline grid was mapped as far as possible across the survey, a control file was set up and Landmark's autotracking software was run overnight accessing the 16-bit 3D seismic data on disk. Initial runs incorporated autotracking which resulted in clear recognition of younger channel complexes cutting the picked event, however, this method caused common incorrect picks. The best results which did not track away from the interpreted event were achieved by producing an interpolated horizon from the seedline grid and then snapping this horizon to the correct softkick maximum without tracking, using a confining window of c. 6 m/sec. The autotracking produced TWT structure maps and amplitude extracts for each mapped event.

Stratigraphy

Lithostratigraphy

The Moki Formation in the Maui PML has been divided into three members, in descending order, the Moki A Sands, the Moki B Shale, and the Moki B Sands (figure 2). The top Moki A is defined by the highest sand body of submarine fan origin below the slope deposits of the Giant Foresets. As lithologies within the Moki Formation only include sandstones, siltstones, silty claystones and thin limestones (calcified sands) of limited areal extent, there are no distinctive PML-wide marker beds to allow constrained lithostratigraphic correlation between wells. Individual Moki sand bodies vary in thickness from <1 m to c. 25 m and thickness variations are typical even between closely spaced wells. Therefore, correlation of individual sand bodies between widely spaced Maui wells cannot be made with confidence.

Seismic interpretation of the Maui 3D Moki sequence offers the opportunity for the first time to constrain well-to-well Moki correlations using well synthetic to seismic matching of mapped events and arbitrary seismic lines tying the Maui wells. Results indicate the thicker development and higher nett to gross ratio of the Moki A Sands over the Maui B area compared with the Maui A area and areas to the north. However, it should be noted that seismic amplitude displays from the upper Moki A Sands may suggest thick nett sand development in areas NE of Maui A where no well calibration is available.

The top Moki B Shale lies below the Moki A8 seismic event and is not a consistent regional lithostratigraphic pick, as this shale unit is time transgressive and thickens to the E and NE. The regional top Moki B Sands member is closely related to the Moki B3 seismic event, however, over Maui B, two other prominent sand units overlie the sands corresponding to the Moki B3 event and are mapped as the Moki B1 and B2 events. It is recommended here that the sand bodies corresponding to the Moki B3 event be accepted as the regional top Moki B Sands Member.

The Moki B5 event corresponds to a prominent sand unit, *c.* 20 m thick, that appears to be one of the most persistent correlatable intra-Moki units mappable across the Maui PML. The Moki B5 event is certainly the most readily mappable seismic event in the Maui 3D Moki sequence.

The base Moki Formation (base Moki B Sands) occurs at the base of the sands corresponding to the Moki B9 event, however, this event becomes difficult to map in the vicinity of Maui-3 to Maui-6. The base Moki Formation is defined by a change from high to low sand to shale nett to gross ratio.

The Lower Manganui Formation underlies the Moki Formation and comprises mid-bathyal claystones, marls, concretionary layers and occasional thin sandstones and siltstones.

Age

The Moki sequence over the Maui PML was deposited in the Middle Miocene. Deposition of the lower Moki B Sands began in the lower Lillburnian Stage (c. 14.5–15.0 Myr) and the upper Moki A Sands were deposited at the end of the Middle Miocene Waiauan Stage (c. 11 Myr ago) (Scott, 1985). Thus some 900 m of Moki sediments were deposited over the Maui PML in c. 3.5 Myr; a depositional rate of c. 250 m/Myr.

Seismic stratigraphy

Figure 3 shows a seismic-well tie line with all the main mapped Moki Formation events. Figure 5 shows the seismo-stratigraphic character of the Moki Formation along regional lines oriented SW-NE and S-N. The Moki A Sands comprise a strongly banded reflective package of seismic events compared with the blander seismic facies of the Moki B Sands. An overall much higher reflective Moki sequence is found in the SW and S of the Maui PML than in the NE and N, corresponding with the higher proportion of turbidite sands deposited close to the Cape Egmont Fault Zone.

For interpretation and mapping purposes, the Moki sequence has been subdivided into main softkick (black) events starting with the top Moki A event and down the stratigraphy, based on the Maui B area seismic sequence, with the Moki A2, A3 ... to A8 events. The A8 event corresponds to the lowest Moki A Sand in the Maui B area. The next softkick below Moki A8 is the Moki B1 event, then the Moki B2, B3 ... to B9 events. As discussed above, the Moki B3 event corresponds to the regional top Moki B Sands pick across the Maui PML and the Moki B9 event is the lowest Moki B Sand. In some areas of the survey extra softkick loops were developed and in most cases these were mapped as separate events.

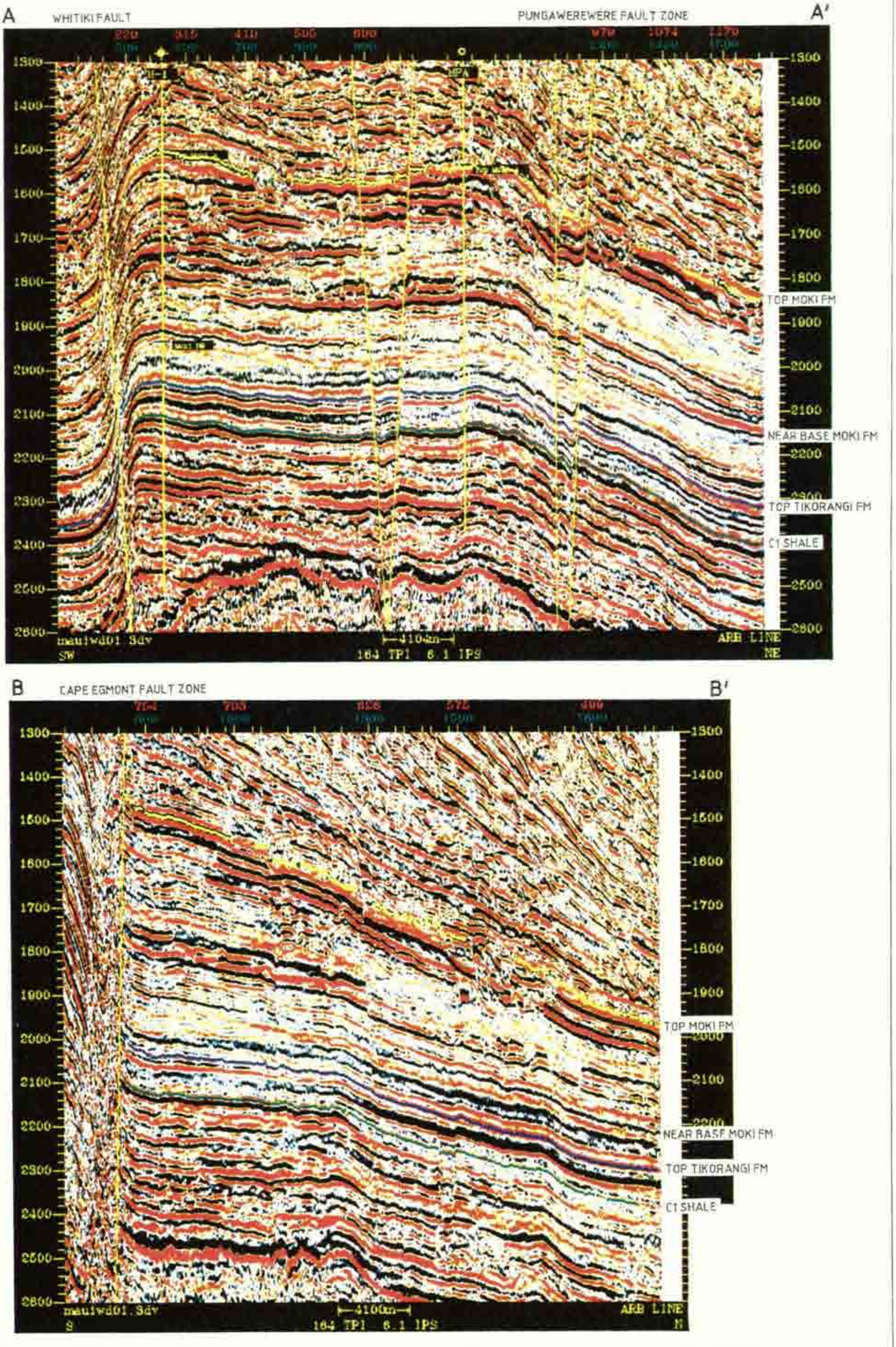

Fig. 5. Regional seismic lines across the Maui PML showing the seismic facies character and thinning of Moki sequence to the northwest.

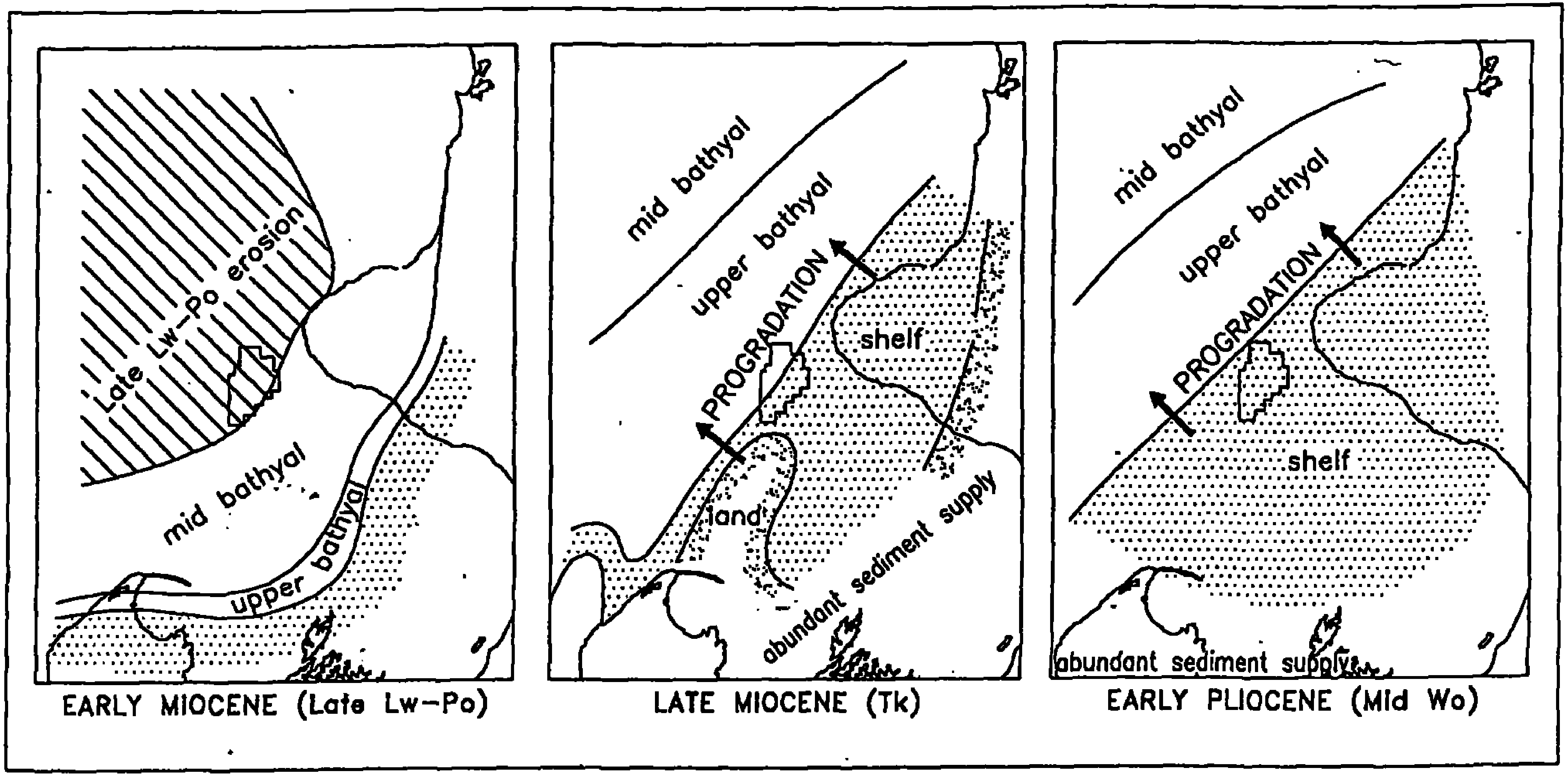

Fig. 6. Early Miocene to Early Pliocene paleogeography and depositional setting over Taranaki Basin (from Hayward 1990).

Depositional Setting of the Moki Formation

The Moki Formation in the Maui PML comprises a Middle Miocene sequence of turbidite sandstones interbedded with bathyal claystones cut by numerous submarine channel complexes. The depositional model for the Moki Formation involves progradation of the slope across southern offshore Taranaki from the Middle Miocene to Pliocene which produced a regressional Neogene sequence. By the early Pliocene the slope break was northwest of the Maui PML (figure 6; Hayward, 1990) and uplift and erosion took place to produce an unconformity which separates the underlying Late Miocene Giant Foresets slope deposits from the overlying Plio-Pleistocene shelfal sediments (figure 2).

Initial movement on the Cape Egmont Fault Zone (CEFZ) was downthrow to the east, however, in the Miocene structural inversion resulted in downthrow to the west and a thicker Oligocene – Miocene sequence was deposited across the Maui PML than east of the fault zone (Thrasher, 1992). In the Late Miocene–Early Pliocene, however, structural inversion again occurred in the South Taranaki Graben resulting in the CEFZ becoming substantially downthrown to the east.

Isochore mapping, as a result of the Maui 3D Moki interpretation, shows progressive thinning of the Moki sequence to the NW away from the CEFZ (figures 5 & 7). The thickest Moki sequence is in the SW corner of the Maui PML.

In detail, the depositional pattern of the Moki Formation is rather complex, involving individual fan lobes of sand being rapidly deposited by turbidity currents, probably under the influence of sea-level lowering. Following one depositional event, further turbidites resulted in stacked composite sands at one location or, due to a different fan lobe configuration to previously, the earlier fan was by-passed and bathyal claystones were deposited by suspended sedimentation on the bathyal plain, resulting in one sand bed sandwiched between claystones.

Because individual seismic events are, in most cases, not able to resolve individual Moki sand beds, it is extremely difficult to confidently correlate every sand bed between wells, even if the wells are closely spaced. Seismic tuning effects start to occur when bed thicknesses of less then 35 m are present and Moki Formation sand beds over the Maui PML are typically 15–20 m thick but often include thin shaley units.

The lower part of the Moki Formation (the Moki B Sands) was deposited on a mid-bathyal plain (Scott, 1985; Hayward, 1990) well in front of the approaching slope front located to the SE. The frequent occurrence of turbidity currents resulted in a relatively high nett to gross sequence of sands to shale in this interval of up to 275 m gross thickness deposited in the lower - middle Lillburnian Stage (15 to 13.5 Myr).

This was followed by a period when fewer turbidites were deposited over the Maui-5, Maui A and northern areas of the Maui PML but sands were continuing to be deposited over parts of the Maui B area. This period of quieter sedimentation was of dominantly bathyal claystones and has been incorporated in the Moki B Shale unit and is interpreted as a time of sand by-passing in the Maui A region, however the overall depositional setting or water depth did not significantly change.

In the late Lillburnian to early Waiauan Stages (13–11 Myr) the depositional setting had progressively shallowed to upper bathyal depths (Scott, 1985) and base of slope turbidites were deposited as the Moki A Sands. The depositional setting for the Moki A Sands is the same as that described for the lower Mt Messenger Formation in eastern Taranaki (King et al., 1993). The Moki A Sands have a lower sand to shale nett to gross ratio than the Moki B Sands and in some locations only a few well developed sands were deposited during this period, e.g. Maui-2, -3 and -6.

It seems likely that sea-level changes had an influence on Moki Formation deposition, with the turbidite sands being related to times of sea-level lowering. These low sea-level stands would have been a lower order signature upon the

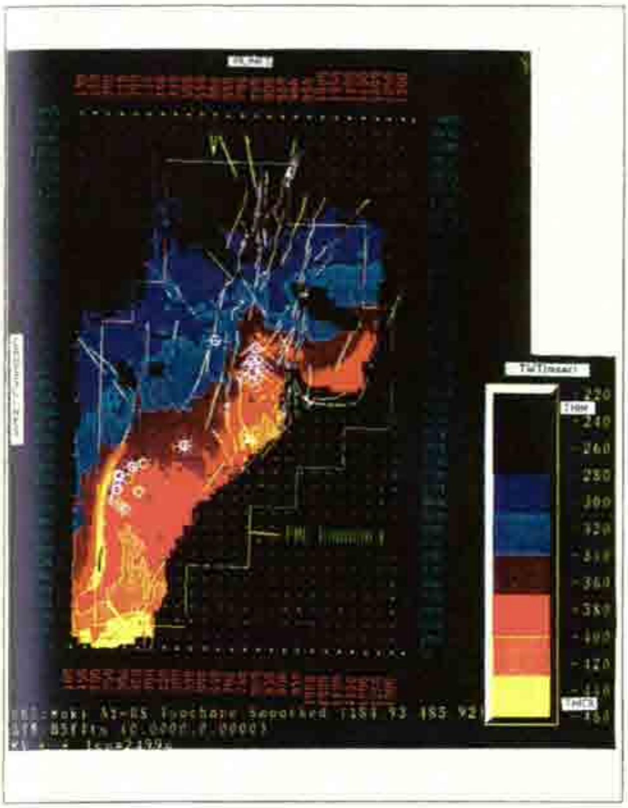

Fig. 7. Isochore map of the Moki Formation over the Maui PML.

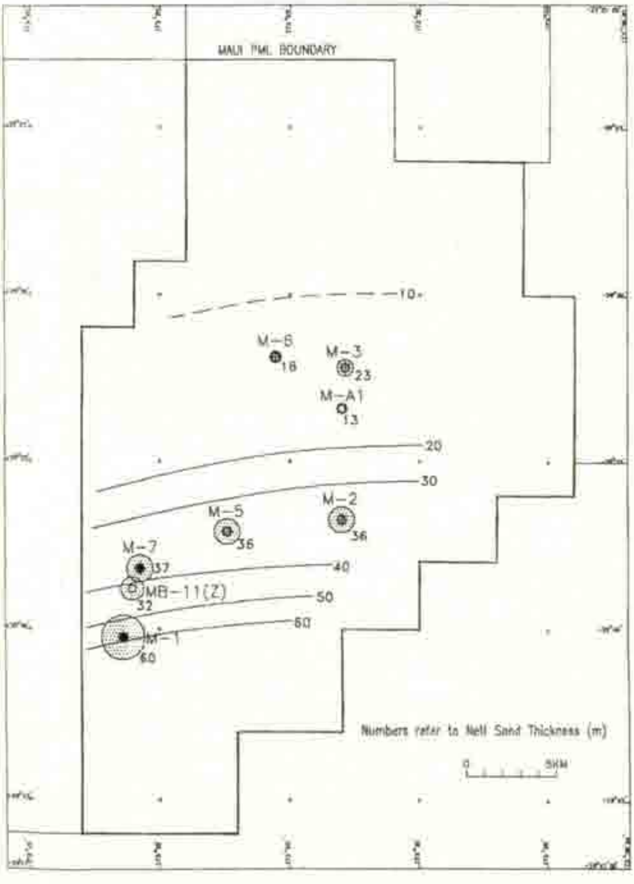

Fig. 8. Nett sand thickness distribution for the lower Moki B Sands sequence between the mapped Moki B7 and B8 seismic events over the Maui PML.

overall Mid to Late Miocene shallowing trend. Paleontological data from the Moki sands typically indicate the presence of shelfal taxa which are interpreted as reworked by transport down the slope to bathyal depths. Paleo-depth resolution of foraminifera and other fossils do not allow determination of minor changes in water depositional depths for the mid-bathyal environment, therefore magnitude of the sea-level changes during Moki deposition cannot be resolved from the Maui data.

Comparison of the time of Moki Formation deposition with the Haq et al. (1988) global sea-level curve indicates there may be a coincidence between a period of global sea-level lowering at c. 10 Myr ago and Moki A Sand deposition, however a similar magnitude global sea-level lowering is not indicated for the time of Moki B Sand deposition. Such eustatic falls most likely caused instability on the slope with a resulting reworking of shelf and slope sediments into the bathyal environment.

Nett sand counts can be determined for intervals between the mapped Moki seismic events based on well synthetic to seismic ties and using density or gamma-ray cut-offs to determine nett sand. Only in some instances was it possible to interpolate contour lines of nett sand thickness for each interval (e.g. figure 8). This is a result of:

i) the small number of widely spaced wells to calibrate nett sand thickness

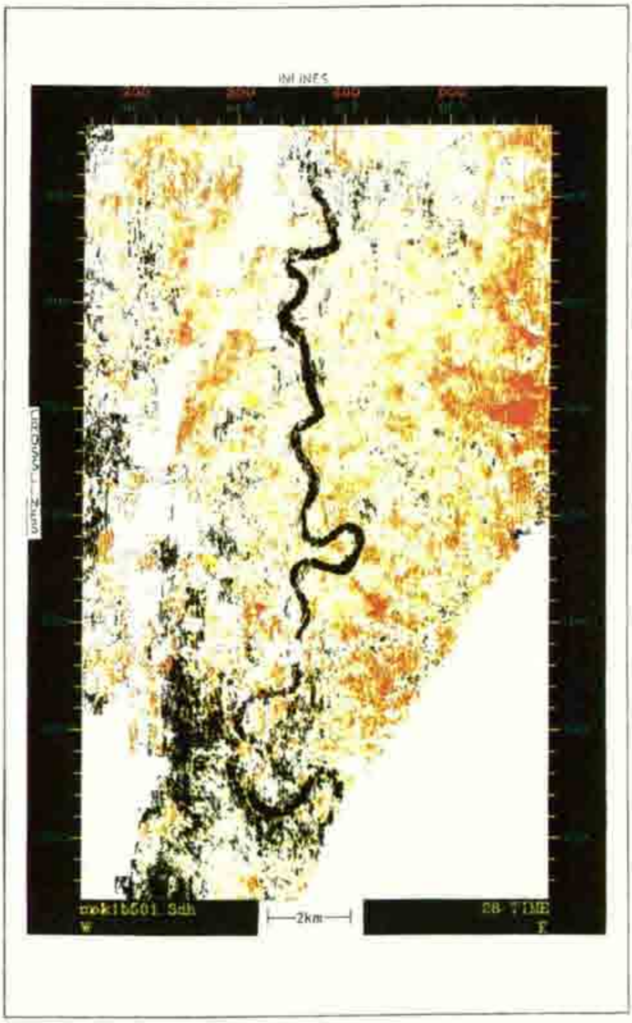

Fig. 9. Seiscrop display below the mapped Moki B5 event showing a meandering channel in the intra-Moki B sequence (detail over Maui B area).

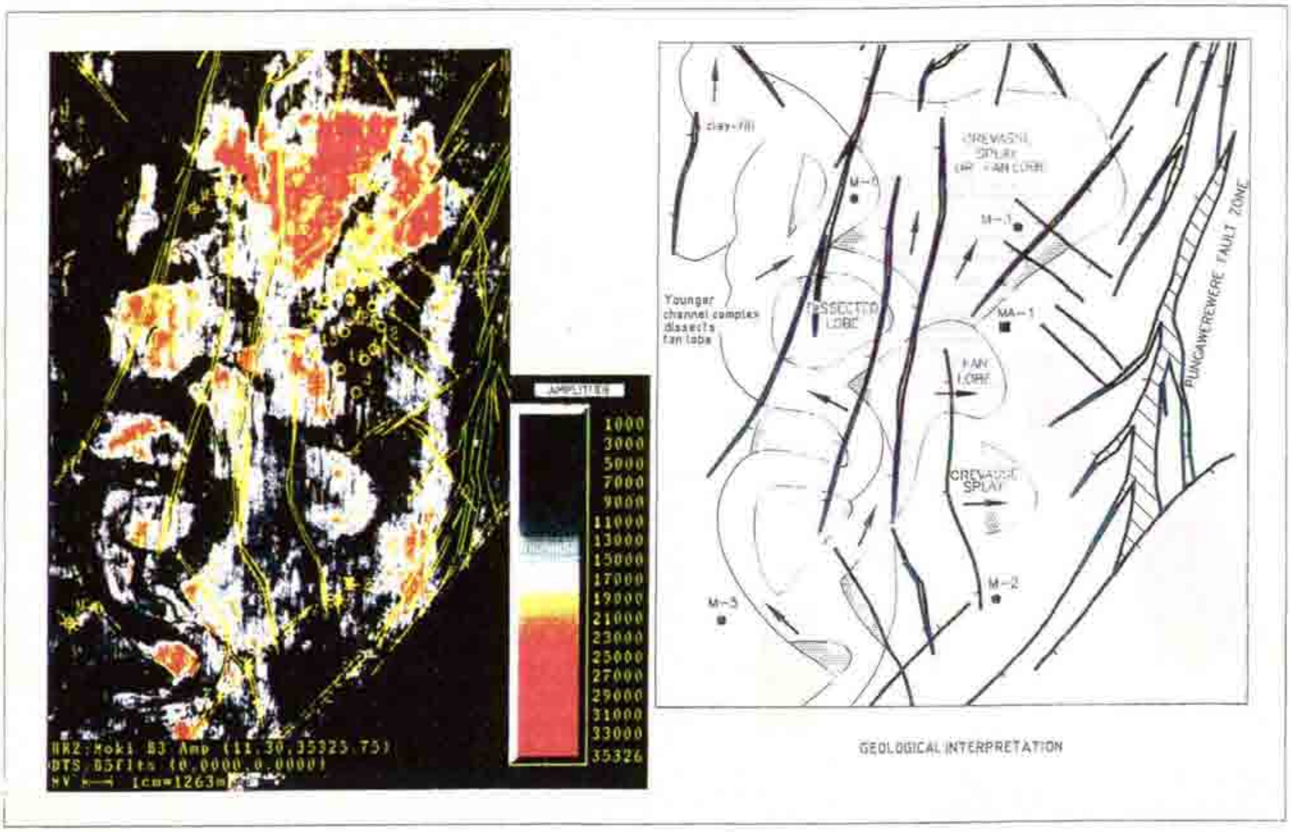

Fig. 10. Amplitude extract of the top Moki B Sand event in the Maui A area and geological interpretation.

Fig. 11. Seiscrop display above the mapped Moki B5 event showing a meandering channel complex at top Moki B Sand level (detail from northern Maui PML).

ii) the interval represented comprises several separate sands deposited at different times and probably with different geometries

iii) there are likely multiple feeder channels in different locations around the Maui PML delivering sand to separate loci of sedimentation

Where nett sand isopach lines could be interpreted from the data they do confirm an overall thinning of the sequence to the north or northwest.

Amplitude displays of mapped events in the Moki Formation have provided considerable new insights into the configuration and complexity of submarine turbidite channels across the Maui PML. In the lower Moki B sequence, channels appear to be rare and seismic events are laterally continuous. Channels that do occur tend to be isolated, narrow, and surprisingly, meander in a morphology similar to a large river on a low-lying floodplain, e.g. Moki B6 event (figure 9). Further up the Moki B sequence, these narrow channels become more common, e.g. Moki B5 event. At the Moki B3 event level, amplitude displays show the configuration of fan and channel complexes in some detail (figures 10 & 11). Above the Moki B3 event level, SE-NW trending channel complexes are present at every mapped level. Amplitude imaging of these complexes show the presence of valleys within which channels have meandered back and forth producing scrolling patterns. Within the Moki A sequence the valleys become more pronounced and persist through a longer period of time at the same location (figure 12); thus one channel complex may cut down through several Moki A events. This pattern of change in channel appearance from base Moki B to top Moki A is consistent with a model of progradation of the slope and overall regression of the sequence. The presence of

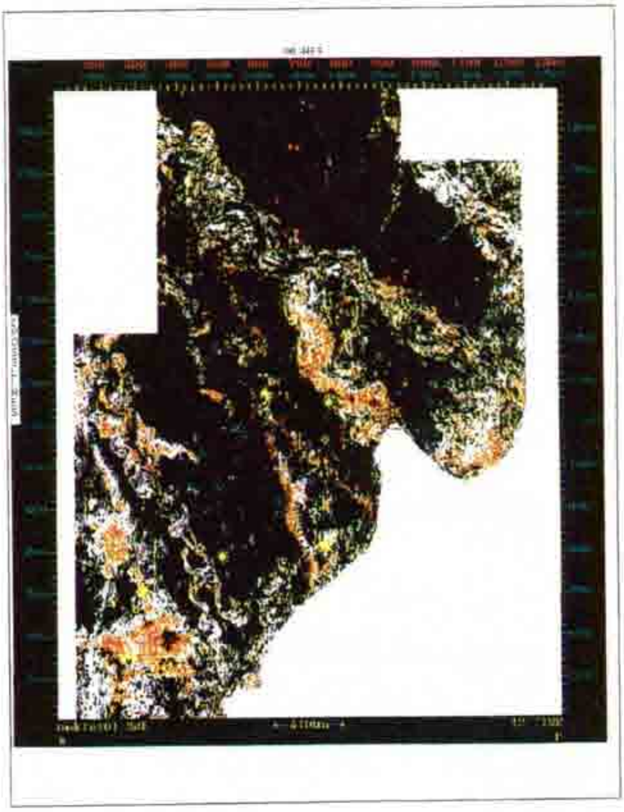

Fig. 12. Seiscrop below the Moki A1 mapped event showing major channel complexes trending NW-SE across the Maui PML.

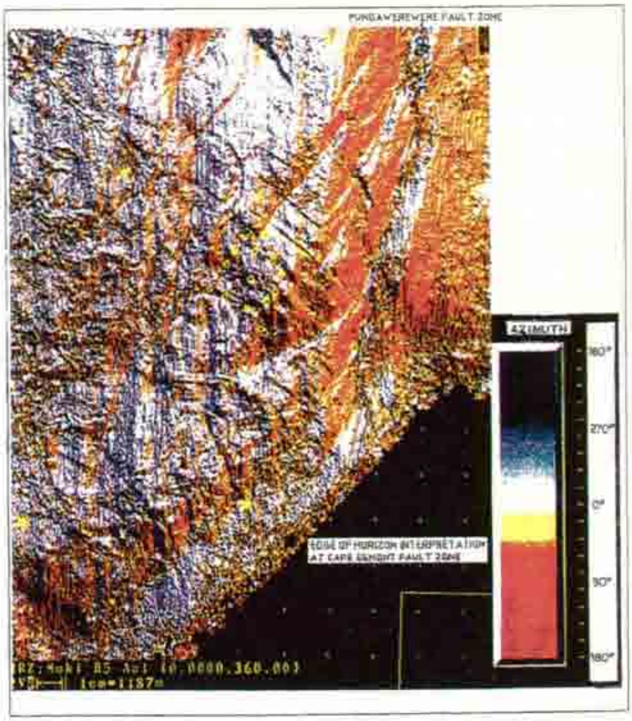

Fig. 14. Azimuth map of the Moki B5 event over the Maui A area showing fault trends and some channels within the Moki B Sands.

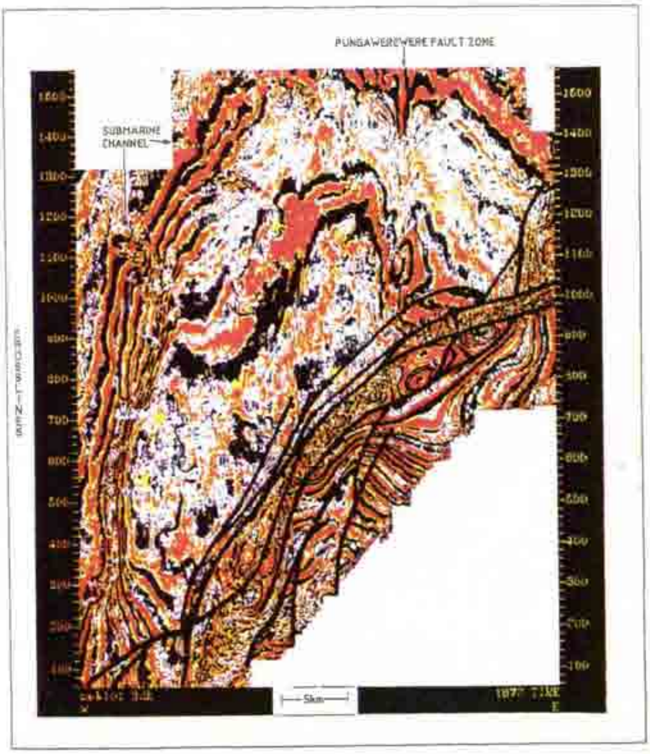

Fig. 13. Timeslice at 1872ms showing intra-Moki B structure in the northwest and an interpretation of fault branches in the Cape Egmont Fault Zone in the southeast. (WFZ = Whitiki Fault/Fold Zone).

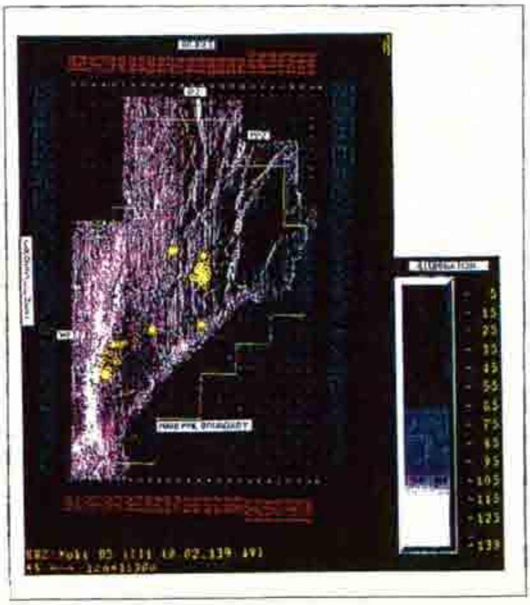

Fig. 15. Illumination map of the Moki B5 event over the Maui PML showing fault trends. Light source azimuth = 270°, inclination = 40°. (WFZ = Whitiki Fault/Fold Zone, IFZ = Ihi Fault Zone, PFZ = Pungawerewere Fault Zone).

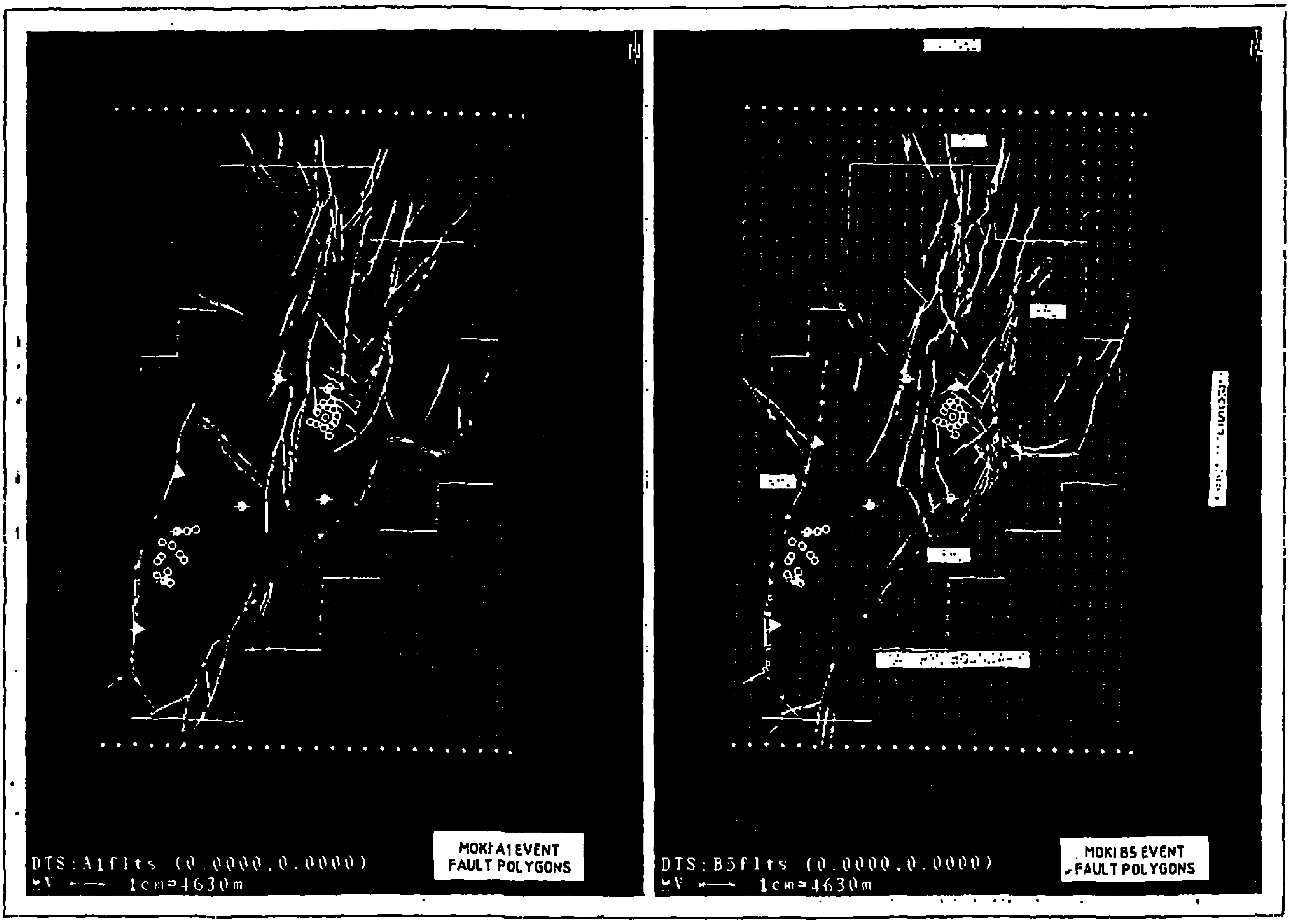

Fig. 16. Fault polygon maps for the top Moki A and Moki B5 (intra Moki B Sands) events, Maui PML. (WFZ = Whitiki Fault/Fold Zone, IFZ = Ihi Fault Zone, PFZ = Pungawerewere Fault Zone, CEFZ = Cape Egmont Fault Zone).

downlapping terminations observed in some areas also supports this model of progradational deposition. In the lower Moki B sequence, channels coming off the slope may only occasionally have reached the Maui PML. As the slope approached from the SE, channels became more common across the Maui PML and began to get more deeply entrenched and hence persisted in one location for longer. Close to the slope these Moki A submarine channel complexes were up to 4 km wide entrenched valleys within which individual channels meandered. In distal regions, sediment transport may have been confined to individual narrower channels.

Submarine fan channels have long been known to follow moderately sinuous courses, however, it is rare to observe such highly sinuous deep-sea fan channels with intricate, tight, looping meanders along their entire length. One modern example comes from the Amazon deep-sea fan (Damuth et al., 1988) where side-scan sonar techniques have imaged numerous meandering channels between 2000–5000 m water depth. This morphology suggests the channels had a large suspended load with little bed load (Schumm, 1981) and is considered a viable depositional analogue for similar Moki channels.

Structure

Faulting

Figure 1 shows some of the main regional structural features in the greater Maui PML area. The principal structural feature of the Maui area is the SW–NE trending Cape Egmont Fault Zone (CEFZ). This has been a persistent fault during Taranaki Basin's evolution with relative amount and direction of throw varying along its length and varying with time (see above). The trace of the CEFZ can be mapped offsetting the seafloor, indicating it remains presently active (Nodder, 1993). Time slices at various depths from the Maui 3D survey show the complexity of the Fault Zone and allow an interpretation of the main branches (figure 13).

The Whitiki Fault is a reverse fault trending N-S, west of Maui B (figure 1). Paleocene to Lower Miocene sediments are offset by the fault but Middle and Upper Miocene sediments, including the Moki Formation, display mainly prominent folding from the Maui high in the east, to the west with steep westerly dips (figure 5).

The Pungawerewere and Ihi Fault Zones comprise a series of discontinuous normal faults trending SW-NE, east and north of Maui A (figures 5 & 13–16). These faults normally offset Paleocene to Pliocene sediments and must have influenced Moki sedimentation at times because extra seismic events are present east of the fault.

Detailed fault mapping has been performed at two levels in the Moki Formation, the Moki B5 and top Moki A events, by digitising fault polygons on various seismic attribute maps, then checking these using seismic displays crossing the observed lineaments. Fault polygons were digitised off dip, azimuth (figure 14), difference, edge and illumination maps (figure 15) of the two events; the resulting fault polygons from this mapping are shown in figure 16.

Faulting is common in the eastern half of the Maui PML where all faults offsetting the Moki Formation are normal,

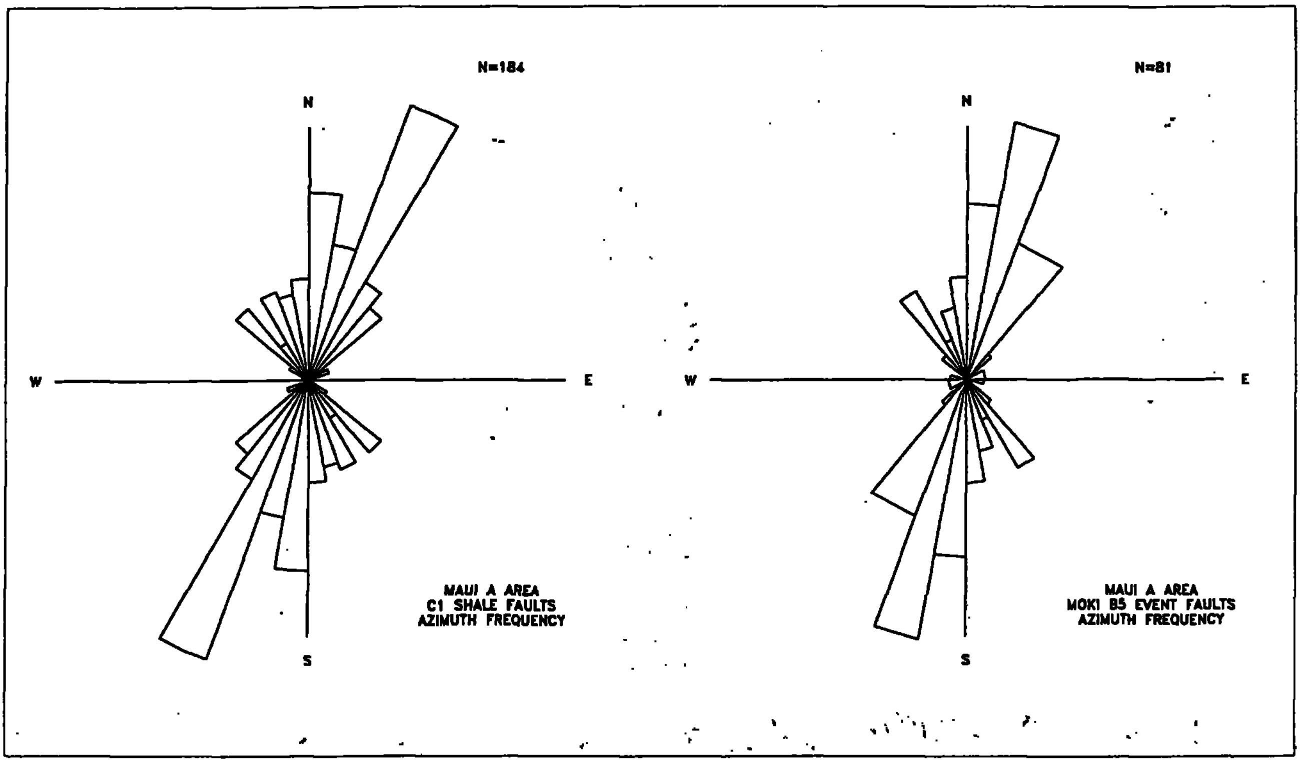

Fig. 17. Rose diagrams comparing direction and frequency of fault trends over eastern Maui PML for the C1 Shale (Eocene) and Moki B5 (Miocene) events.

steeply dipping and deep-seated. In contrast the western area over Maui B has few significant Moki faults and the main structural features are the prominent folding over the deeper Whitiki Fault and the major normal offset to the south at the CEFZ. Some attribute map displays clearly show that numerous other small scale faults are present over the Maui PML, but these tend to be not mappable on conventional vertical seismic line displays and are not included in this analysis.

Figure 17 presents a rose diagram analysing the frequency and orientation of the Moki B5 level faults and comparing these with faults at top C Shale (Eocene) level. The prominent fault trend is SSW-NNE and there is good agreement between fault trends observed at top Eocene and middle Miocene levels. Along the strike of some faults it was observed that direction of throw changes from one side to the other. Also, a flower structure was observed along the Pungawerewere Fault Zone, where at shallow level, the main normal fault has several antithetic branches. These features suggest some degree of transcurrent offset along at least the main faults. However, there is no observed lateral offset of features such as channels (at both Eocene and Miocene levels) that run perpendicular to the main fault trends and thus the amount of lateral movement must be minor (<100 m?).

Depth structure

Time-to-depth conversion over the entire Maui PML has only been performed for one Miocene level, the Moki B5 event. This seismic softkick corresponds to the top of a regionally correlatable sand interval and forms the best mappable seismic event in the Moki sequence. Figures 18 and 19 show the depth and TWT structures for the Moki B5 event. The depth map has been made by using a layer cake T-Z conversion involving the seabed, top Giant Foresets (base Pliocene) and Moki B5 TWT grids.

Structure at the Moki B5 level (figures 18 & 19) shows *c.* 70 m of four-way dip closure over the Maui B area and steep folding over the Whitiki Fault. Maui-5 is located at the saddle between the Maui A and B areas. A north-trending structural nose is developed over the Maui A area and further N, while to the S the structure flattens and then dips up into the CEFZ. East of the Pungawerewere Fault Zone the Moki sediments dip monoclinally NE and form structural noses with separate fault blocks in the NE of the PML. The overall structure is similar to that of the top C Sands reservoir of the Maui field, however, there is no or slight four-way dip closure over the Maui A area at Moki level, whereas this is better developed at Eocene level.

Timeslices from the Maui 3D survey also reveal the regional structure and figure 13 shows one timeslice at intra Moki B level.

Analysis of Seismic Amplitude Variations

For each mapped Moki seismic event, an amplitude extract map was produced as part of the autotracking, using 16-bit seismic data on disk. Figure 20 is an example of amplitude mapping of the Moki B5 event. Considerable areal amplitude variation is observed over the Maui PML and these variations often define geometries consistent with certain geological depositional settings. The amplitude variations can be explained by several causes, including changes in hydrocarbon porefill, porosity, bed thickness and sand nett to gross ratio. Seismic modelling using Sierra Quiklog software assessed the likely cause of increases in amplitude of the top Moki B event. Substituting water-bearing sandstone with gas, results in an increase in seismic amplitude, however, based on both regional and local hydrocarbon habitat, oil is expected within these Moki sands. By modelling increasing

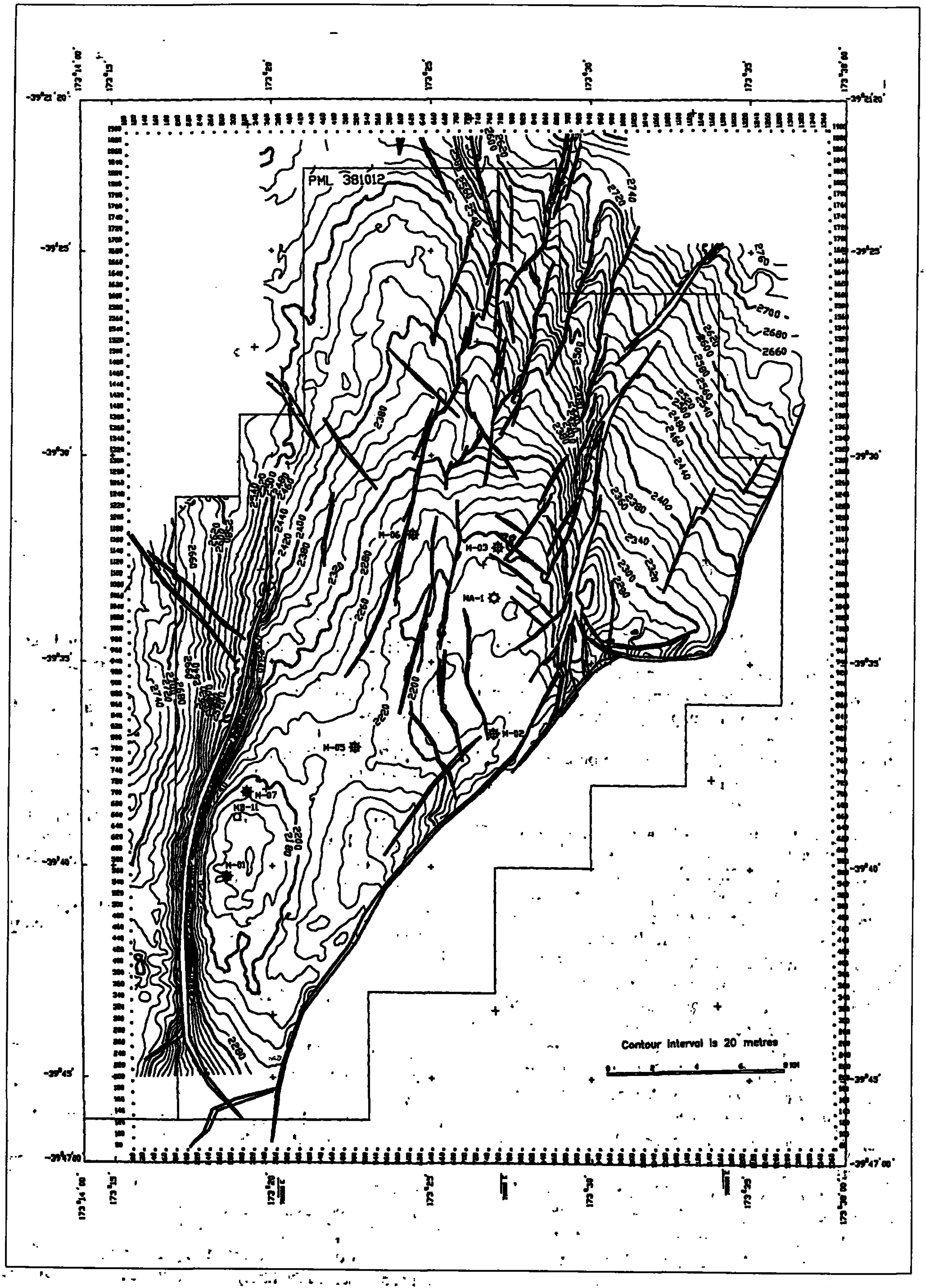

Fig. 18. Depth structure of the Moki B5 event, Maui PML.

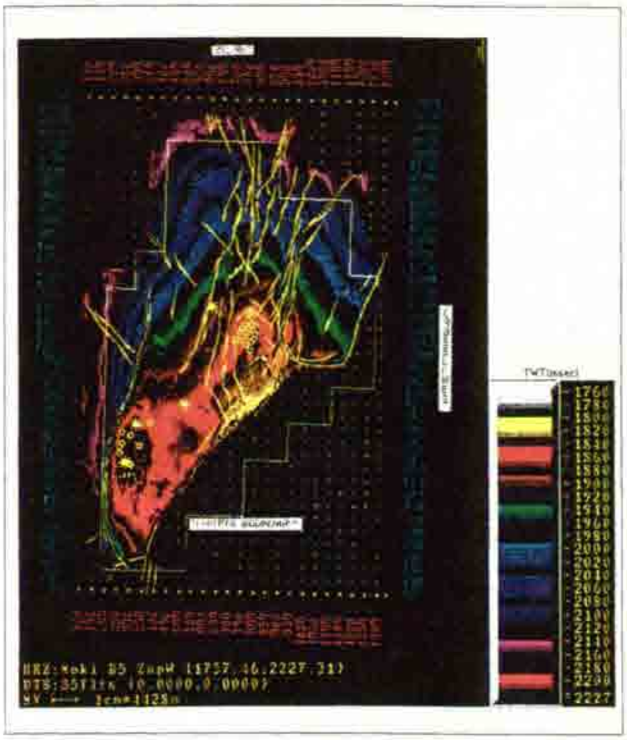

Fig. 19. TWT structure of the Moki B5 event, Maui PML.

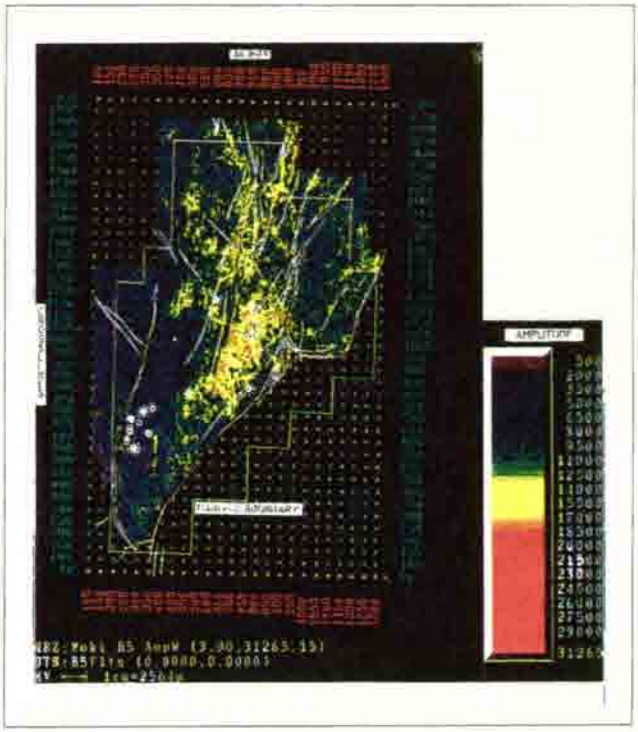

Fig. 20. Amplitude extract of the Moki B5 event, Maui PML.

oil saturation no significant increase in seismic amplitude was observed. However, by increasing sand bed thickness in one model and sand to shale nett to gross ratio in another model, increases in seismic amplitude were observed (figure 21). In the Maui B area, two vertical and several deviated development wells have wireline log coverage over the Moki Formation and allow calibration of areas with different seismic amplitudes, and where petrophysically determined hydrocarbon saturations and porosities are constant. Analysis of the top Moki B Sand reveals a correlation between increasing seismic softkick maximum amplitude with increasing nett sand thickness and increasing nett to gross ratio of sand to shale. Therefore, well data support the results of seismic modelling and suggest that high seismic amplitudes in the Moki Formation relate principally to thicker sand bed development or high sand to shale proportions. Figure 10 shows the amplitude morphology of the top Moki B seismic event in the Maui A area and clearly reveals the presence of fan lobes deposited from the south and dissected in the west by a younger submarine channel. In summary, areas of high amplitude are considered to indicate areas of better sand development, however, the presence of gas-bearing sands cannot be ruled out.

Identification of areas of perceived best reservoir development, therefore, can be derived from seismic amplitude displays which not only provide information on good sand development where high amplitude anomalies are observed, but also allow delineation of possible depositional setting by the morphology of the amplitude patterns. However, recognition of sand depositional patterns from seismic amplitudes is linked to the resolution of the seismic data and the thickness of the interbedded shale and sand packages in the Moki sequence. Seismic interference with the Moki B sequence, for example, due to the high nett to gross ratio of sands to shale, results in poor resolution of depositional patterns of sand bodies for the intra Moki B events, whereas the top Moki B is well resolved because a thick shale sequence overlies the top Moki B sand in most areas. Notwithstanding the above, interpretation of the Moki sequence on the Maui 3D seismic survey has allowed a considerable advance in our understanding of the complexities of objective Moki reservoir sand geometries which could not be determined from earlier data sets.

Conclusions

1. The Maui 3D seismic survey provides an excellent dataset for studying the depositional setting of the Moki sequence in more detail than previously possible.
2. The Moki B sequence was deposited during the Lillburnian (Middle Miocene) as mid-bathyal submarine fans and pelagic oozes distant from a slope and shelf system that was prograding from the southeast to the northwest.
3. The Moki A sequence was deposited during the Lillburnian to Waiauan (Middle Miocene) near the base of the advancing slope. Spectacular NW-SE oriented, meandering channel complexes developed in several locations and at different times during Moki deposition.
4. Individual Moki sands penetrated by wells are not considered to be laterally extensive over the Maui PML.
5. Faulting at the Moki level is similar in trend and intensity to that at the Upper Eocene level. Most faults except the Whitiki Fault/Fold are high angle, normal faults with a predominant SSW-NNE trend. There is no evidence for major lateral offset along faults west of the Cape Egmont Fault Zone.
6. Seismic amplitude variations in the Moki Formation relate to changes in nett sand thickness or sand to shale nett to gross ratio. Amplitude displays provide a powerful tool for mapping sand body development and geometry.
7. Seismic imaging of an individual sand is dependent on seismic resolution and/or interference (tuning) from seismic events directly above a particular sand unit.

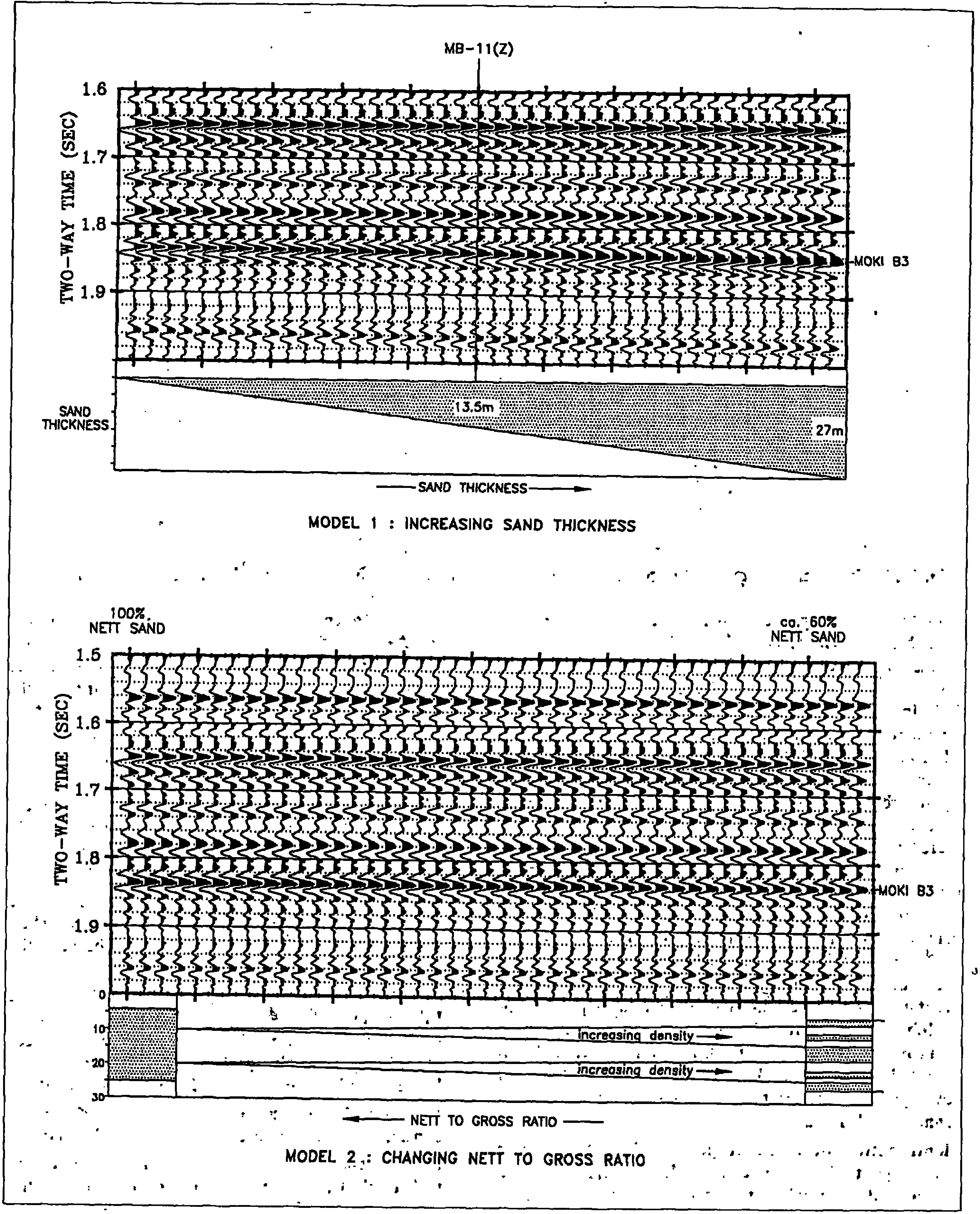

Fig. 21. Results of two seismic models for the Moki Sands investigating amplitude response to changing sand thickness (model 1) and changing sand to shale nett to gross ratio (model 2).

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