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PETROLEUM GEOLOGY OF SHALLOW-WATER BASINS AROUND VITI LEVU, FIJI

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ABSTRACT

Most petroleum exploration in Fiji has been directed towards the shallow-water sedimentary basins around Viti Levu - the Bligh Water and Bau Waters Basins. A large amount of commercial multi-channel seismic-reflection data acquired across these basins from 1971 to 1979 show thick, extensive and relatively undeformed bedded sediments. This evidence for sedimentary basins and the presence of thick Lower to Middle Miocene shallow-water limestones at outcrop on Viti Levu encouraged the drilling of five deep petroleum exploration wells offshore and on Viti Levu from 1980 to 1982. All the wells were dry, although some had minor shows of gas and oil fluorescence. The wells penetrated over 2500 m of sedimentary rocks largely of Miocene and younger age, but some Oligocene or older volcanislastic rocks were also intersected. Most of the well sections comprise volcaniclastics and terrigenous clastic sediments, and no Lower to Middle Miocene shallow-water limestone targets were encountered.

A large amount of recently released commercial seismic data from around Viti Levu has been interpreted and a reassessment of petroleum potential made. Early Pliocene and pre-Early Pliocene seismic marker horizons have been mapped and these locally are significant unconformities. A Late Pliocene unconformity is also indicated by seismic profiles. Up to about 4 km and 2 km of Late Miocene and younger strata are interpreted to occur in the Bligh Water and Bau Waters Basins, respectively, but pre-Late Miocene sediments are not seismically resolved and thus the total sedimentary thickness is unknown. The sedimentary sequences off Viti Levu are cut by large faults and pre-Pliocene rocks are affected by folding which locally is quite intense.

No source-rocks have been identified in the deep wells nor in tests of outcrop and stratigraphic borehole material from Viti Levu and Vanua Levu, but anomalous amounts of pentane in sea bed sediments off northern Viti Levu suggest that some thermogenic hydrocarbons have been generated. Limestones are generally considered to have better reservoir potential than coarse volcaniclastics and these are the more desirable targets.

Because of the limited seismic resolution, no traps with Lower to Middle Miocene shallow-water limestone facies can presently be identified in the basins offshore Viti Levu. Trial seismic reprocessing to improve trap identification is recommended. Late Miocene and younger sequences contain numerous structurally formed potential traps, and several Plio-cene reef-like seismic mounds also occur in the western Bligh Water Basin. Mudstones are widespread in the offshore basins and seals are likely to be good, although some relatively recent faulting may have breached some potential traps.

ACKNOWLEDGEMENTS

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PLATE TECTONIC SETTING

Fiji is located near the edge of the Indo-Australia Plate in an area of the Pacific Ocean that has formed during the Tertiary through the growth of marginal basins and island arcs (Figure 1). Many plate tectonic reconstructions for the SW Pacific during the Middle/Late Miocene show Fiji within a continuous NE facing volcanic arc, the Vitiaz which extended through the New Hebrides and Fiji to the then united Lau and Tonga Ridges. Subduction of the Pacific Plate beneath this arc is thought to have occurred at the Vitiaz Trench (Figures 1 and 2), inactive fragments of which still exist north of Fiji. The growth of marginal backarc basins by sea floor spreading, initiated in the Late Miocene apparently as a result of the breakup of the Vitiaz Arc, resulted in clockwise rotation of the New Hebrides Arc and anti-clockwise rotation of the Fiji Platform. The exact spreading history is uncertain, but a sketch of the present plate tectonic setting is shown in Figure 2.

GEOLOGY OF VITI LEVU

The geology of Viti Levu is summarised in Figure 3. The oldest known rocks in Fiji crop out in SW Viti Levu and are small limestone bodies of Late Eocene to Early Oligocene age. The limestone bodies are associated with basaltic lavas and volcaniclastic rudites (Yavuna Group).

There is evidence for a mid-Oligocene hiatus following which thick Upper Oligocene to Middle Miocene volcaniclastic rudites of basic to acidic andesite compo-sition, pillow basalts, shallow-water carbonates and volcaniclastic sandstones and mudstones and tuff accumulated (Wainimala Group). The Wainimala Group extends over a large part of southern and central Viti Levu (Figure 3). The sequence generally becomes finer grained and thinner to the north and the facies associations have been interpreted to represent a volcanic arc, intermittently fringed by shallow-water limestones and flanked to the north by a deep-water sedimentary basin (Figure 4).

Regional metamorphism up to greenschist facies affects most rocks of the Wainimala Group, with higher grade contact rocks close to plutonic stocks of the Middle to Late Miocene Colo Plutonic Suite. The plutonic stocks appear to occupy the crest of an anticlinorium which trends approximately ENE across the islands (Figure 5) and it has been suggested that the plutons were intruded synorogenically (Colo Orogeny). However, the extent of compressive tectonism during the Colo Orogeny is unknown. The Colo Orogeny corresponds to a gap of about 5 Ma in the stratigraphic record between about 13 Ma and 8 Ma. This hiatus has been termed the Colo Unconformity and it may be related to a general emergence of the island.

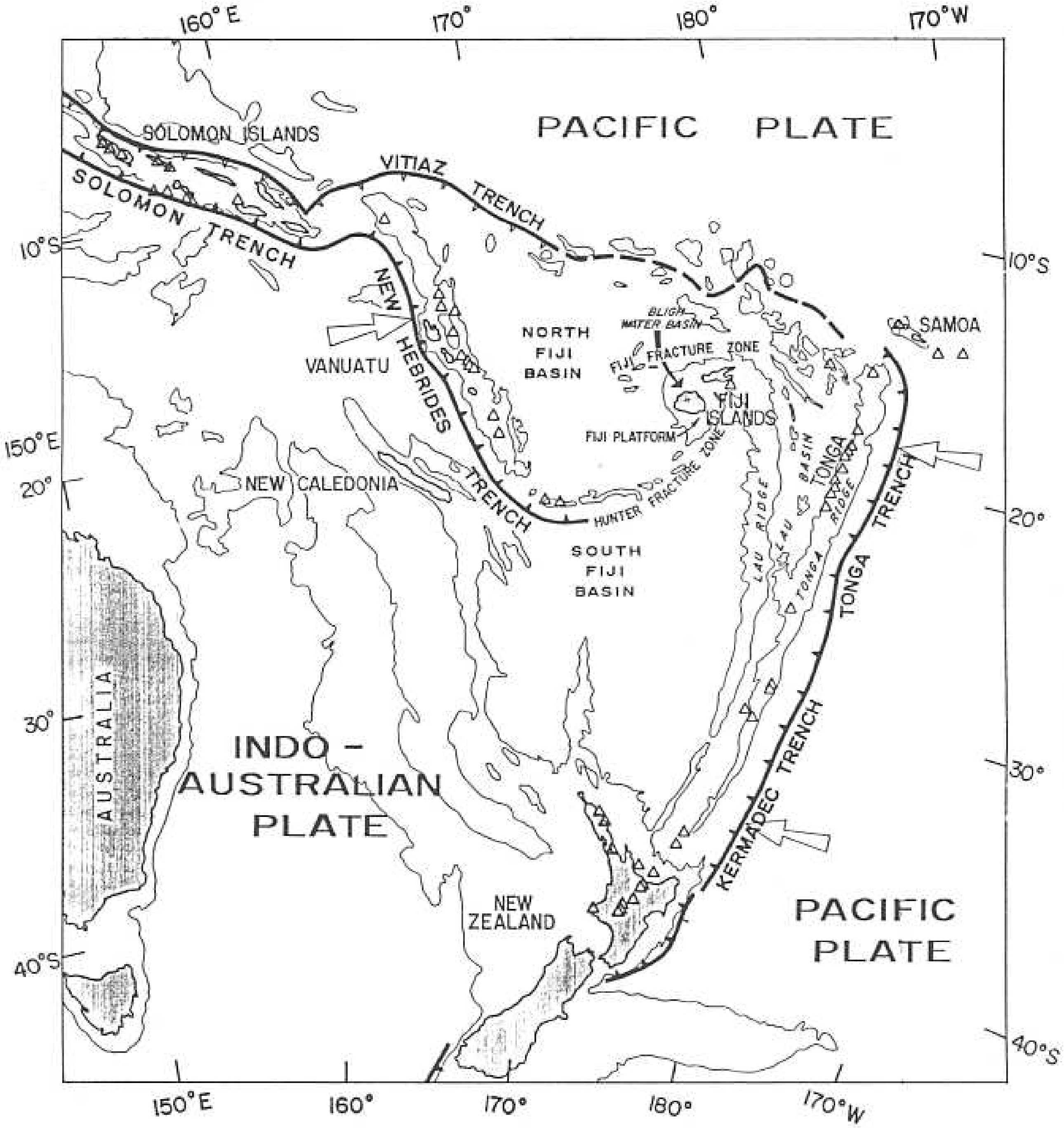

Figure 1. Tectonic and morphological features of the Pacific/Indo-Australian plate boundary. Open arrows indicate direction of relative plate convergence. Contour line shows 2-km isobath. Holocene volcanoes are indicated by open triangles. Solid and open barbed lines indicate active and relic convergent plate boundaries, respectively. Dashed line indicates possible eastward extension of the Vitiaz Trench.

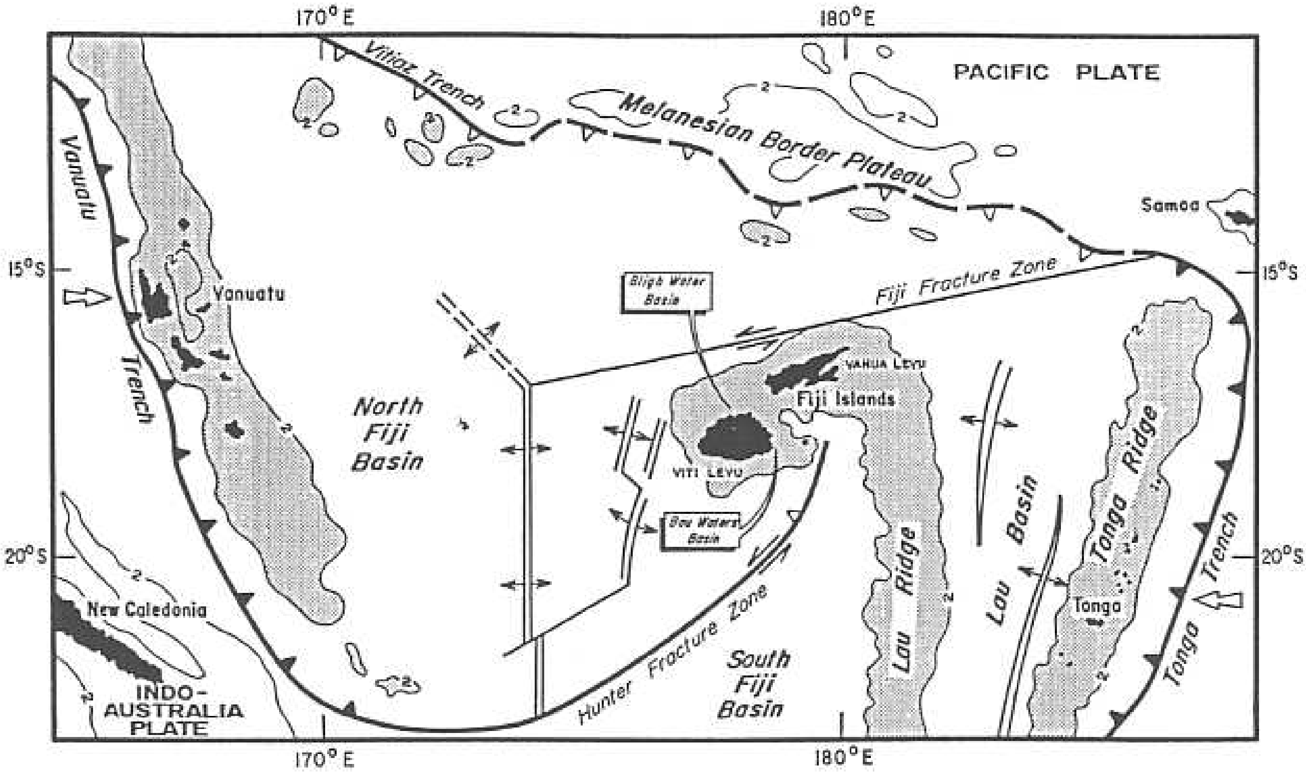

Figure 2. Sketch map showing the regional tectonic setting of the Fiji islands. Active and remnant island arcs are shaded. Contour line shows 2-km isobath. Solid and open barbed lines indicate active and relic convergent plate boundaries, respectively. Dashed line indicates possible eastward extension of the Vitiaz Trench. Open arrows indicate direction of subduction. Parallel lines and divergent arrows indicate spreading centres.

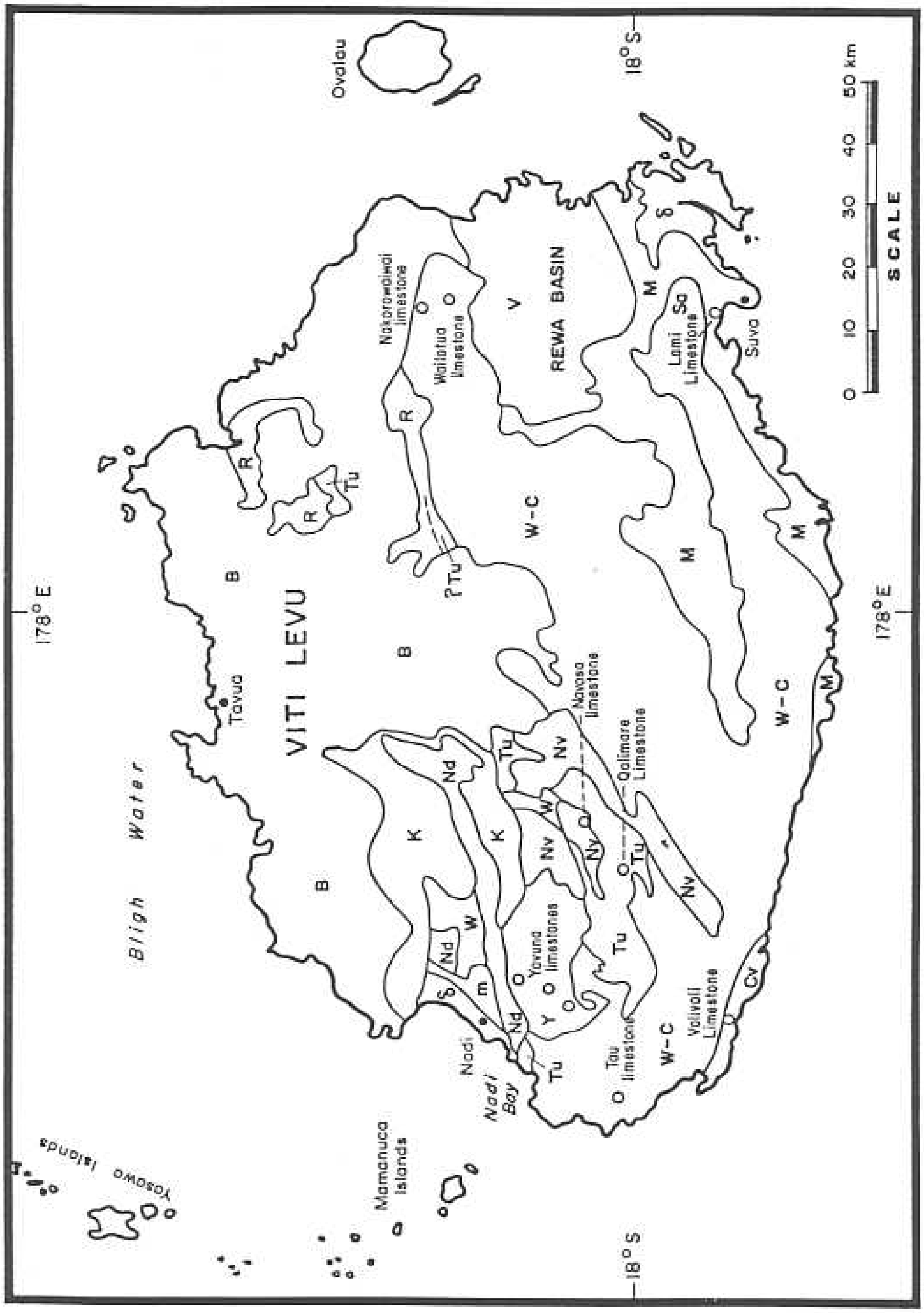

Figure 3. Generalized outcrop of lithostratigraphic groups on Viti Levu. Abbreviations: d, Delta; m, Meigunyah beds; B, Ba Volcanic Group; Cv, Cuvu Sedimentary Group; K, Koroimavua Volcanic Group; V, Verata Sedimentary Group; Nv, Navosa Sedimentary Group; R, Ra Sedimentary Group Tu, Tuva Group; C, Colo Plutonic Suite; W, Wainimala Group; Sa, Savura Volcanic Group; Y, Yavuna Group. Major limestone outcrops are indicated by open circles.

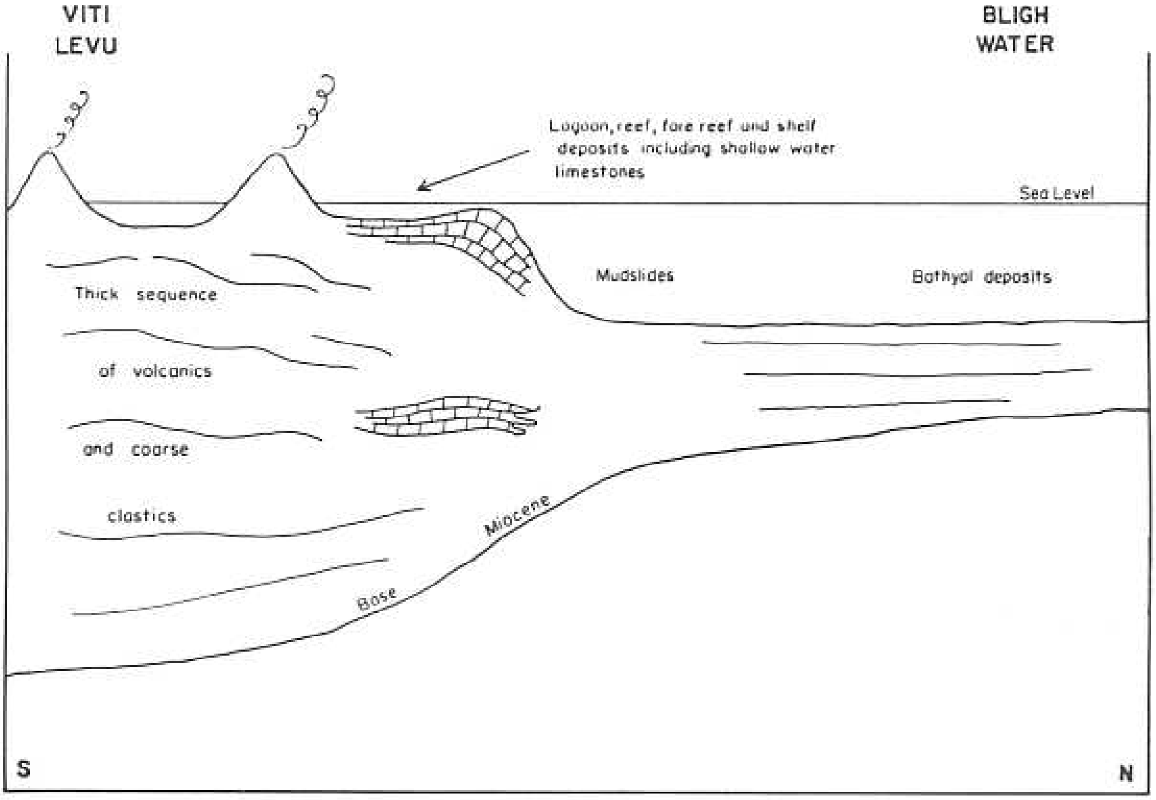

Figure 4. Model for Early/Middle Miocene deposition (after Eden and Smith, 1984).

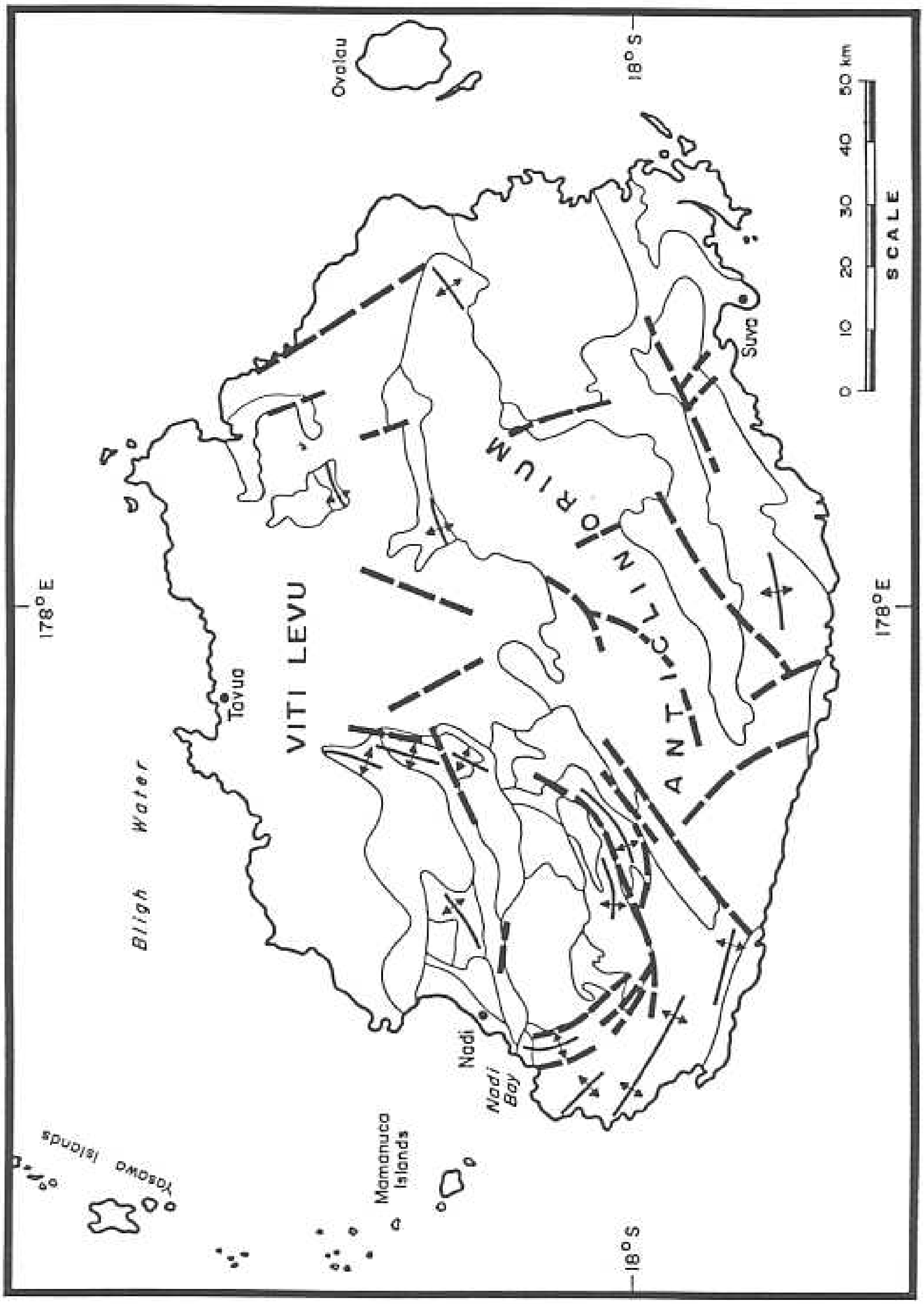

Figure 5. Location of selected anticlinal fold axes (lines with arrows) and major faults (thick dashed lines) on Viti Levu. Outlines of lithostratigraphic groups are shown. Geology is simplified and sketched.

Late Miocene breccias, conglomerates and sandstones with minor mudstones and locally abundant terrigenous plant debris (Tuva Group) overlie the Wainimala Group with no angular unconformity, but are strongly folded and faulted. The full extent of deformation affecting Tuva and other age equivalent rocks is unknown. It has been suggested this strong Late Miocene deformation may relate to the breakup of the earlier Vitiaz Arc, now separated into New Hebrides-Fiji-Lau /Tonga segments. Folds generally are restricted to pre-Pliocene rocks, but large faults cut Pliocene and Quaternary strata (Figure 5).

Tuva rocks are overlain with angular unconformity in the west by coarse grained volcaniclastics and mudstones of the Late Miocene Nadi and Navosa Sedimentary Groups and in the NE by strata of the Ra Sedimentary Group and younger rocks.

In the Early Pliocene submarine and subaerial basaltic and andesitic volcanism produced volcanic edifices across the northern half of the island (Ba and Koroimavua Volcanic Groups), but sedimentation of several hundred metres of rudites, sandy turbidites, limestones and deep-water mals continued away from the volcanic centres (eg. Medrausucu Group, Verata Group, Cuvu Sedimentary Group).

A general emergence due to prolonged tectonic uplift interrupted Pliocene sedimentation on Viti Levu from about 3-2 Ma and Late Miocene shallow-water limestone has been raised to more than 1000 m elevation. To the NE, Vanua Levu was formed by the merging and coalescing of volcanic centres in the Late Miocene and Pliocene.

BLIGH WATER BASIN

The Bligh Water Basin (Figure 6) extends for about 60 km north of Viti Levu and is about 150 km across. Water depth is commonly less than 100 m but locally up to 1000 m (Figure 6). In 1980 Chevron drilled two deep wells, Bligh Water No. 1 and Great Sea Reefs No. **1.** The wells penetrated over 2000 m and 2400 m of Upper Oligocene to Recent sediments overlying volcanic rocks described as Oligocene or older (Figure 7). The Upper Oligocene to Lower Miocene rocks are up to about 900 m thick and are considered to be age and facies equivalents of the Wainimala Group in SW Viti Levu. Much of the sedimentary sequence appears to have been deposited in deep water, and intended shallow-water Middle Miocene limestone targets were not intersected.

The wells were drilled on structural highs where sedimentary sequences are cut by significant unconformities. An Early Pliocene (?) unconformity in Bligh Water No. 1 corresponds to a large

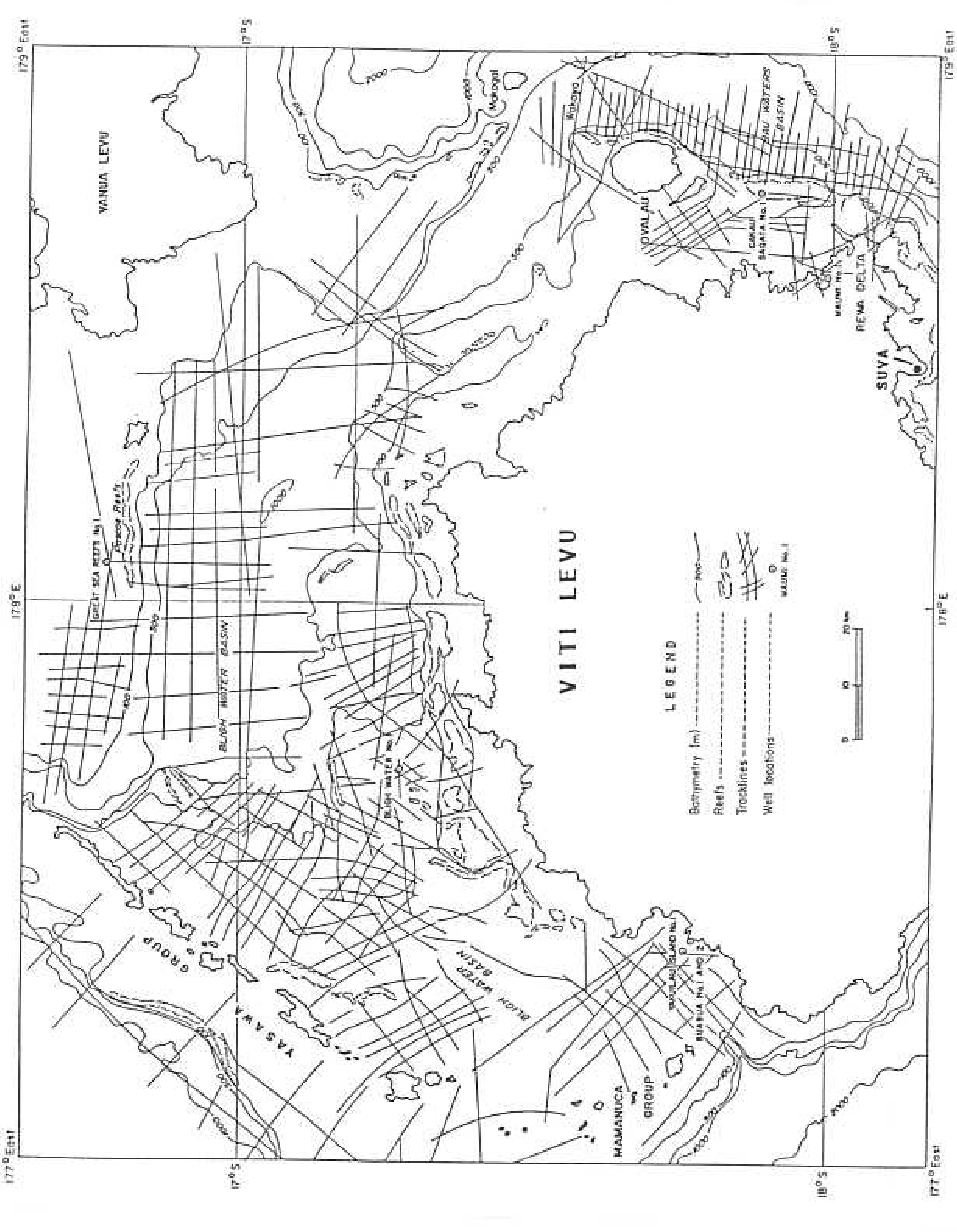

Figure 6. Outline bathymetric map of shallow-water shelf surrounding Viti Levu showing the location of deep wells and tracklines of commercial seismic surveys used in this study.

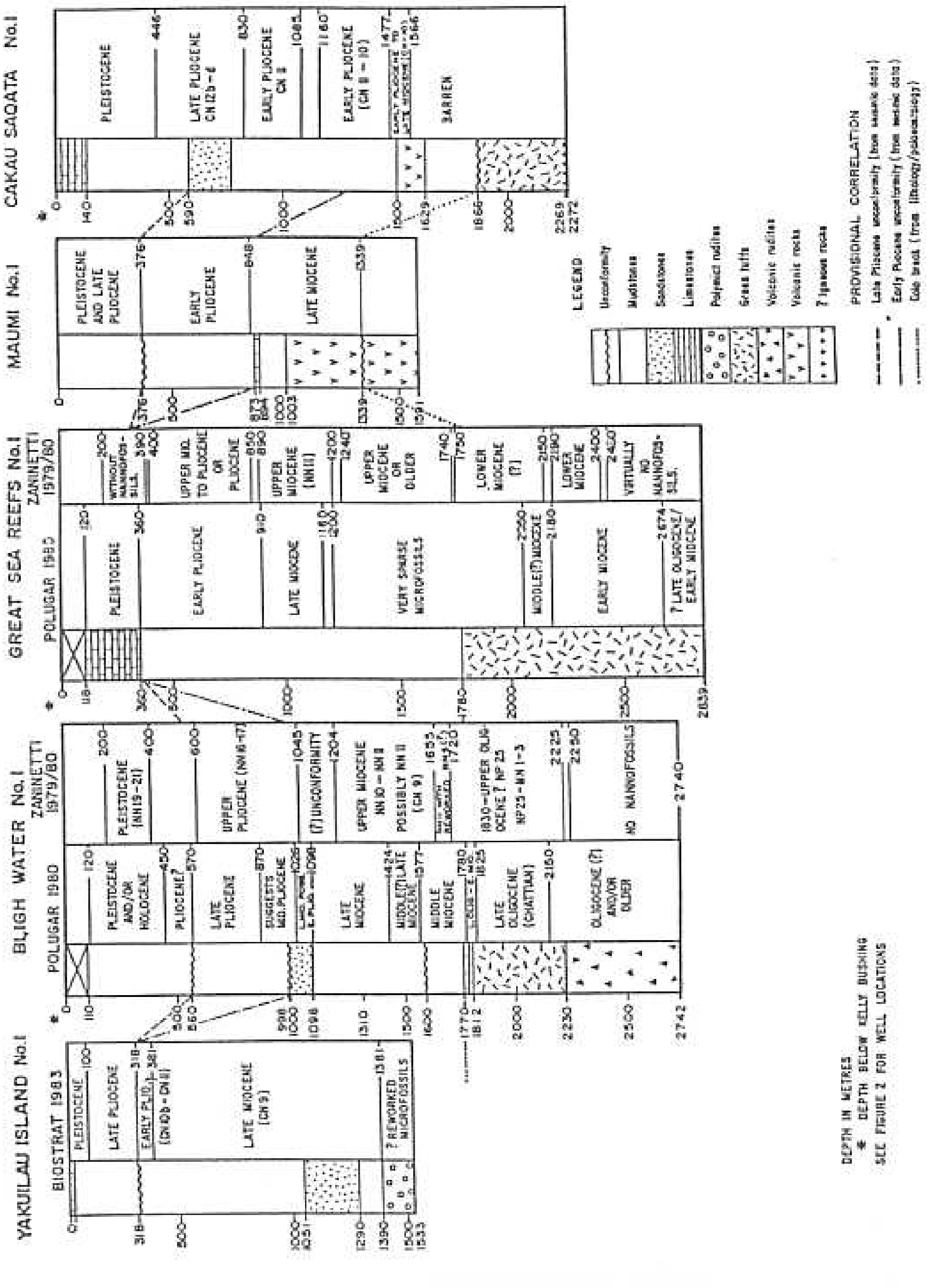

Figure 7. Generalized sections of deep oil exploration wells in Fiji.

downward increase in sonic velocity and correlates with a seismic marker horizon (Figure 8). Structure contours on this horizon are shown in Figure 9. Seismic resolution below the horizon is rather poor, but around Bligh Water No. 1 and near the NW margin of the basin it appears to mark an angular unconformity with tilted rocks truncated by it and onlapped above by less deformed layered strata (Figure 8).

In the eastern part of the basin no angular unconformity is generally apparent at the Early Pliocene seismic marker. The underlying layered sequence is thick and its lower boundary is a high amplitude reflector which defines an angular unconformity (LM, Figure 10) deformed by folds and faults. The unformity was not drilled. Structure contours on this surface, believed to be pre-Early Pliocene, are shown in Figure 11. Overlying strata onlap the folded unconformity surface and seismic data indicate that the folds grew syndepositionally. The fold axes and faults are discontinuous and generally trend ENE (Figure 11).

Seismic data suggest that both normal and reverse faults cut the pre-Early Pliocene unconformity, and a fractured ridge-lie feature in the centre of the basin has been tentatively interpreted as a positive flower structure, thus suggesting strike-slip fault movement (Figure 12). Folded strata, possibly including the unconformity, also occur near the western margin of the basin adjacent to the southern end of the Yasawa chain, where folds trend north to NNE, that is, parallel to the Yasawa islands (Figure 11).

The age of the deep unconformity in the eastern part of the Bligh Water Basin is uncertain, but it is probably pre-Pliocene and may even correlate with the Late Miocene angular unconformity on Viti Levu above the Tuva Group. The intense deformation which has locally affected the angular unconformity and the immediately overlying seismic sequence in the Bligh Water Basin would then correspond to a similar tectonic event which affected rocks on both Viti Levu and the Yasawa Islands.

Alternatively the pre-Early Pliocene unconformity might correlate with the Colo Unconformity on Viti Levu and the associated intrusion of plutonic stocks in the Middle and Late Miocene. In either case, it is unlikely that the pre-Early Pliocene angular unconformity forms the base of the sedimentary sequence in the basin.

The intensity of structural deformation decreases substantially above the Early Pliocene reflector. This seismic marker is locally gently folded, but in general folding appears to be largely pre-Pliocene, just as on the Fiji islands themselves. However, signifcant faults cut the Early Pliocene marker, and the seismic data suggest that most of these have normal throws.

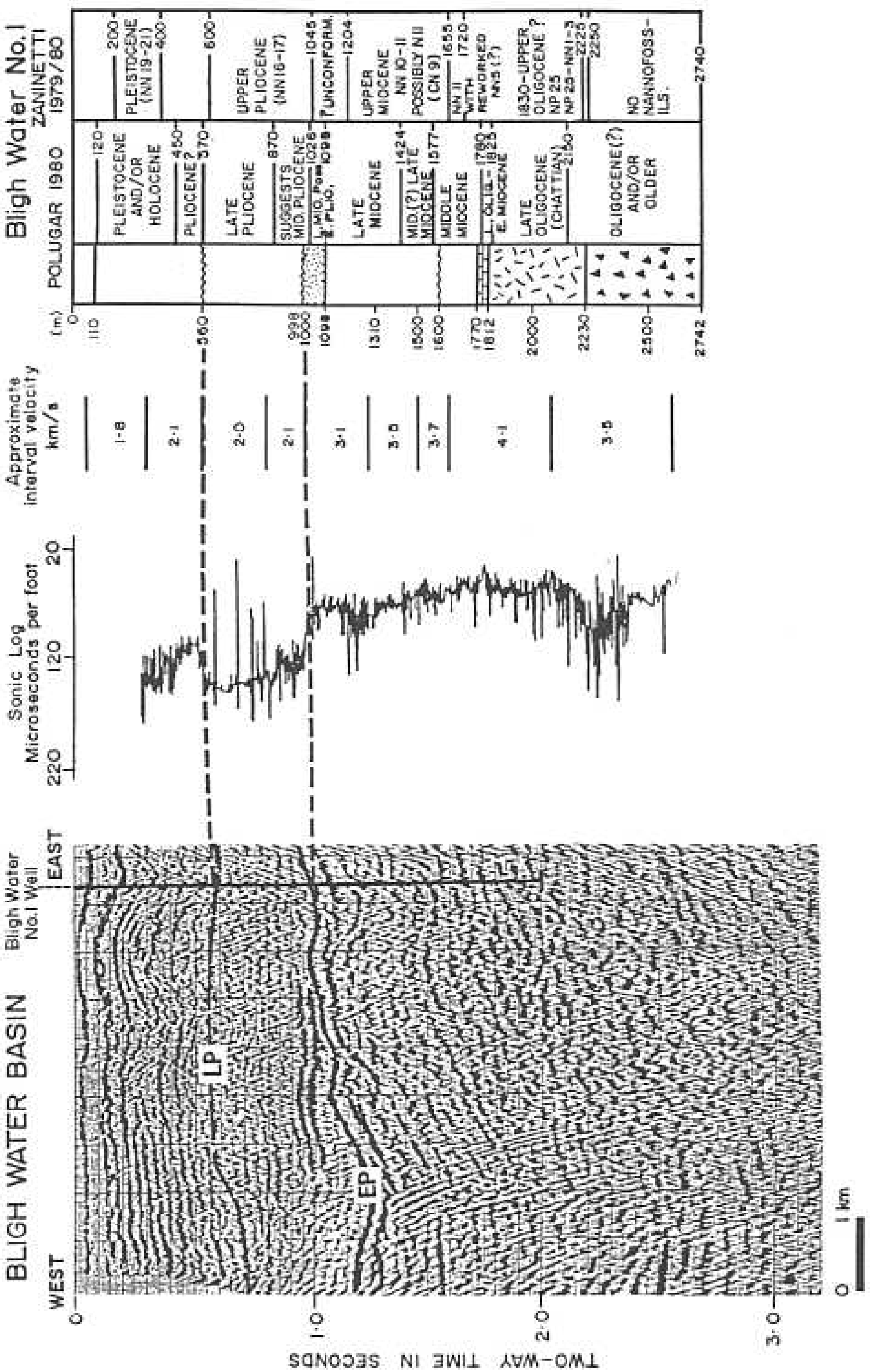

Figure 8. Sonic log for Bligh Water No. 1 showing correlation with seismic profile. EP=Early Pliocene seismic marker, LP=Late Pliocene seismic marker. For location, see Figures 9 and 11. For explanation of lithological ornaments, see Figure 7.

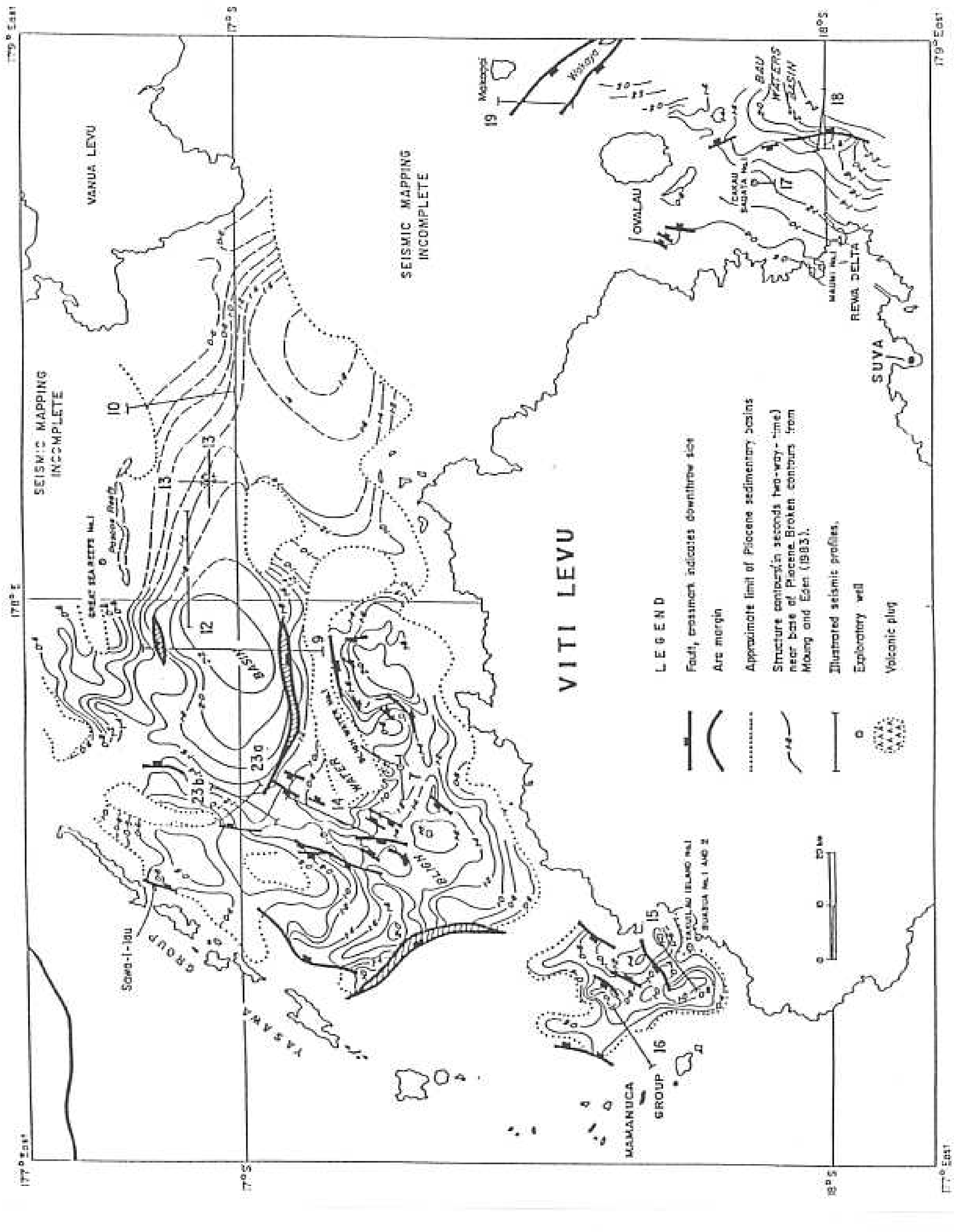

Figure 9. Structure contours in two-way reflection time on Early Pliocene seismic marker (EP in Figures 8, 10, 12, 13 and 17), Bligh Water and Bau Waters Basins.

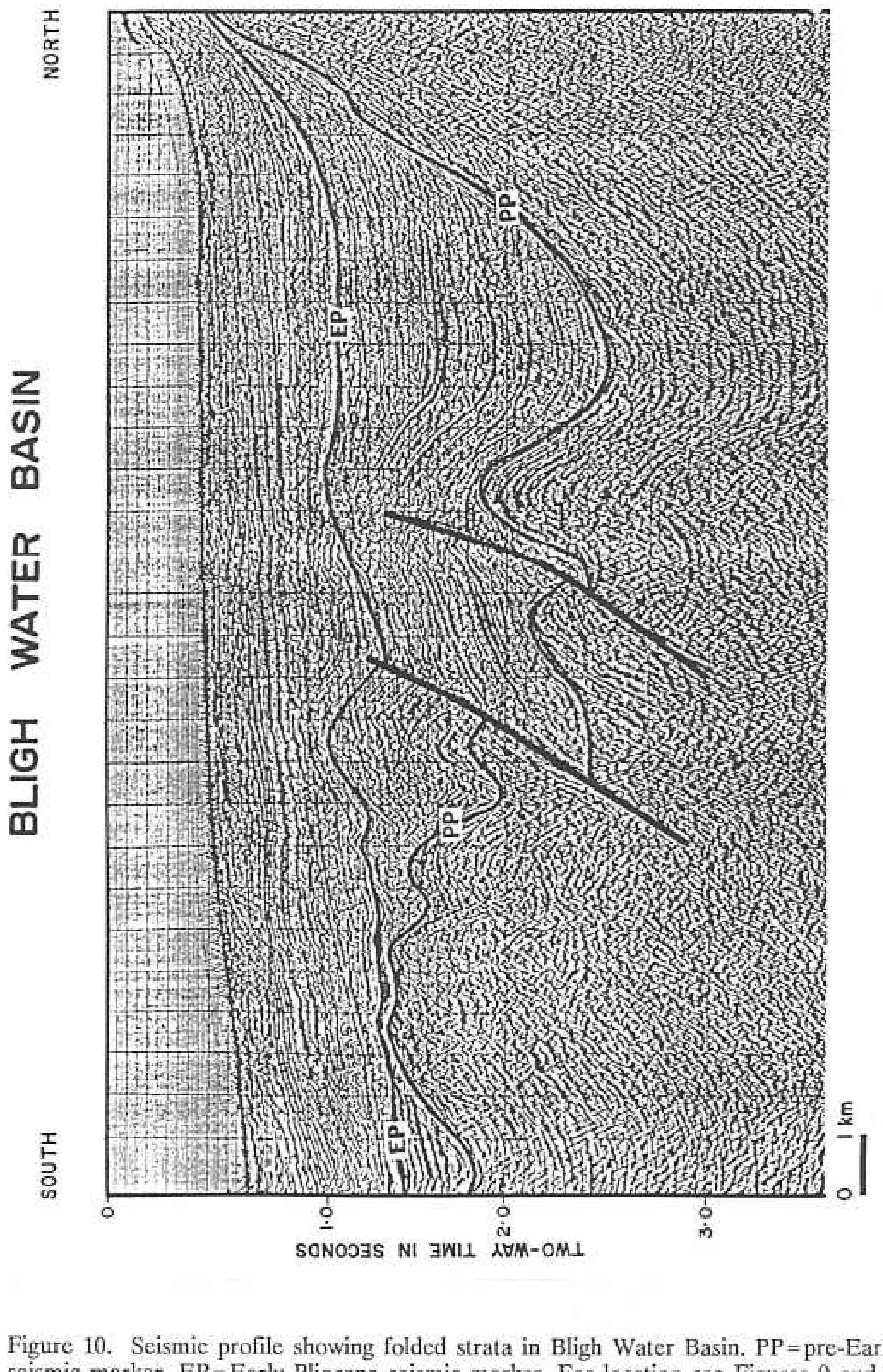

Figure 10. Seismic profile showing folded strata in Bligh Water Basin. PP=pre-Early Pliocene seismic marker, EP=Early Pliocene seismic marker. For location see Figures 9 and 11.

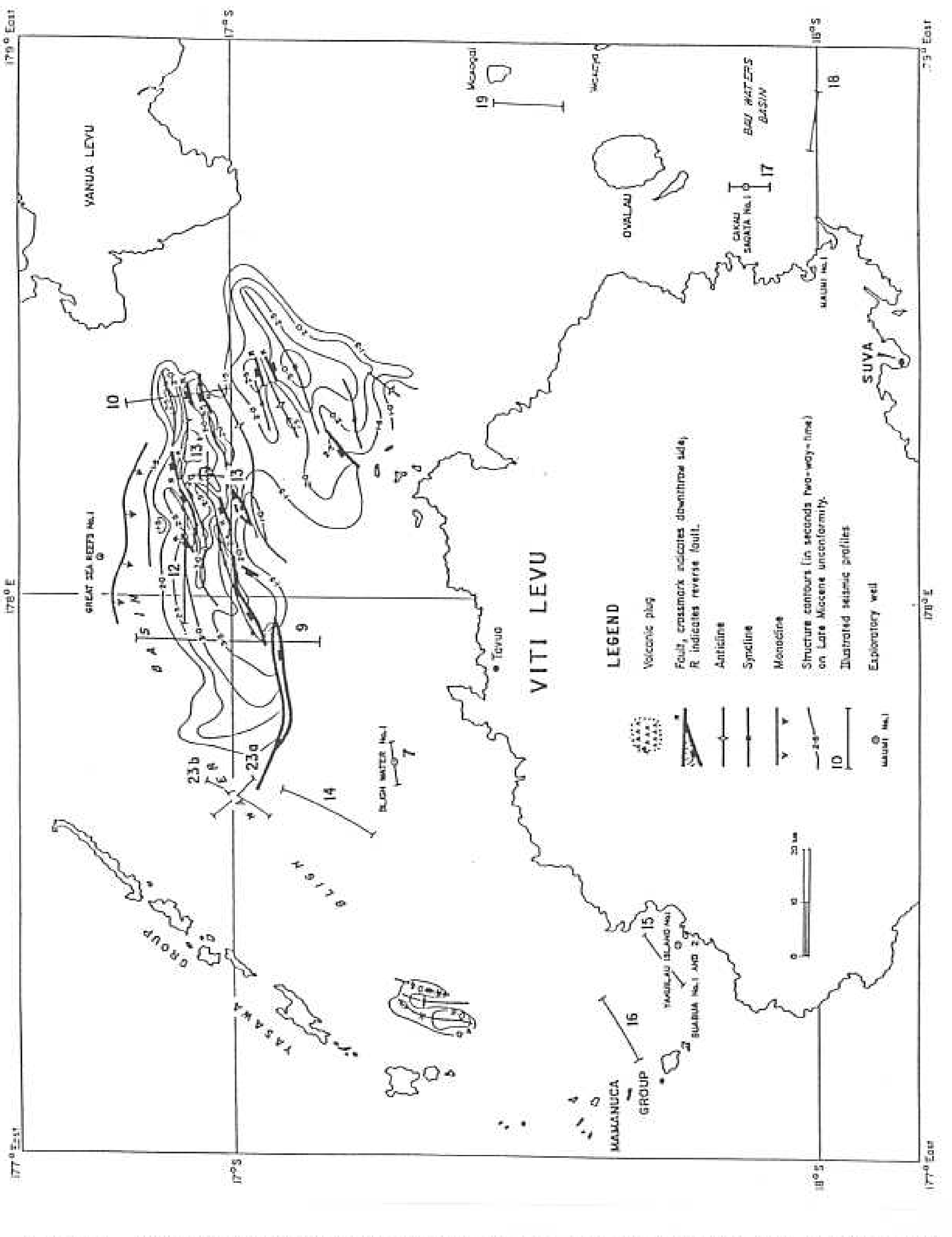

Figure 11. Structure contours in two-way reflection time on a pre-Early Pliocene seismic marker, (PP in Figures 10 and 12) Bligh Water Basin.

BAU WATERS BASIN

In the Bau Waters area, east of Viti Levu (Figures 9 and 11), water depth is less than 100 m landward of the reefs bordering Viti Levu and the small offshore islands, but commonly over 500 m elsewhere (Figure 4). Two deep wells, Maumi No.1 and Cakau Saqata No.1 were drilled in 1982 for Bennett Petroleum Corporation. Maumi No.1 was drilled on the SE coast of Viti Levu (Figures 9 and 11) and penetrated to 1591m (Figure 7). It intersected 1003 m of mudstones with thin sandstone and limestone beds of Late Miocene to Plio-Pleistocene age. The lower third of the well penetrated an igneous complex with spilites, volcanic breccia and glass, but also included some fossiliferous beds of Late to (?) Middle Miocene age.

Cakau Saqata No.1 penetrated about 1500 m of Plio-Pleistocene mudstones and sandstones which particularly in the lower part are mainly volcaniclastic and/or tuffaceous (Figure 7). A layer of basalt was intersected near the base of the Plio-Pleistocene sequence. The pre-basalt sequence consists of tuff and tuffaceous sandstones and mudstones and is of Late to Middle Miocene age and possibly older.

Early Pliocene and Late Pliocene seismic marker horizons have been correlated with the deep wells (Figure 12) and these have been mapped across most of the western shallower water part of the Bau Waters Basin. Only structure contours on the Early Pliocene seismic marker are illustrated here (Figure 9). In the deep water area between Ovalau island and Wakaya island only the Late Pliocene seismic reflector is resolved on seismic data. The exact relationship between the Early Pliocene and Late Pliocene reflectors in the Bligh Water and Bau Waters Basins is uncertain.

The Early Pliocene marker is locally a slight angular unconformity showing minor tilting erosion and onlap, but commonly no angular discordance is apparent. It displays good lateral continuity in the shallow water part of the basin and commonly forms the top of a group of laterally continuous high amplitude reflectors (Figure 13). This reflective interval commonly spans about 0.2 seconds reflection time and generally marks the lower limit of seismic resolution.

The Late Pliocene reflector also commonly marks the top of a group of laterally continuous, parallel, high amplitude reflectors (Figures 12 and 14). In much of the shallow-water shelf area east of Viti Levu no angular discordance is apparent across the Late Pliocene reflector, which is assigned to the CN12b nannozone (2.6-2.4 Ma) in Cakau Saqata No.1. In the deeper water areas further NE, however, this horizon is strongly onlapped by a wedge-shaped seismic sequence bounded by NW-trending normal faults which downthrow to the SW (Figure 14). This wedge-shaped Pliocene to Recent sequence is up to 1.8 seconds two-way reflection time thick, and a Plio-Pleistocene seismic

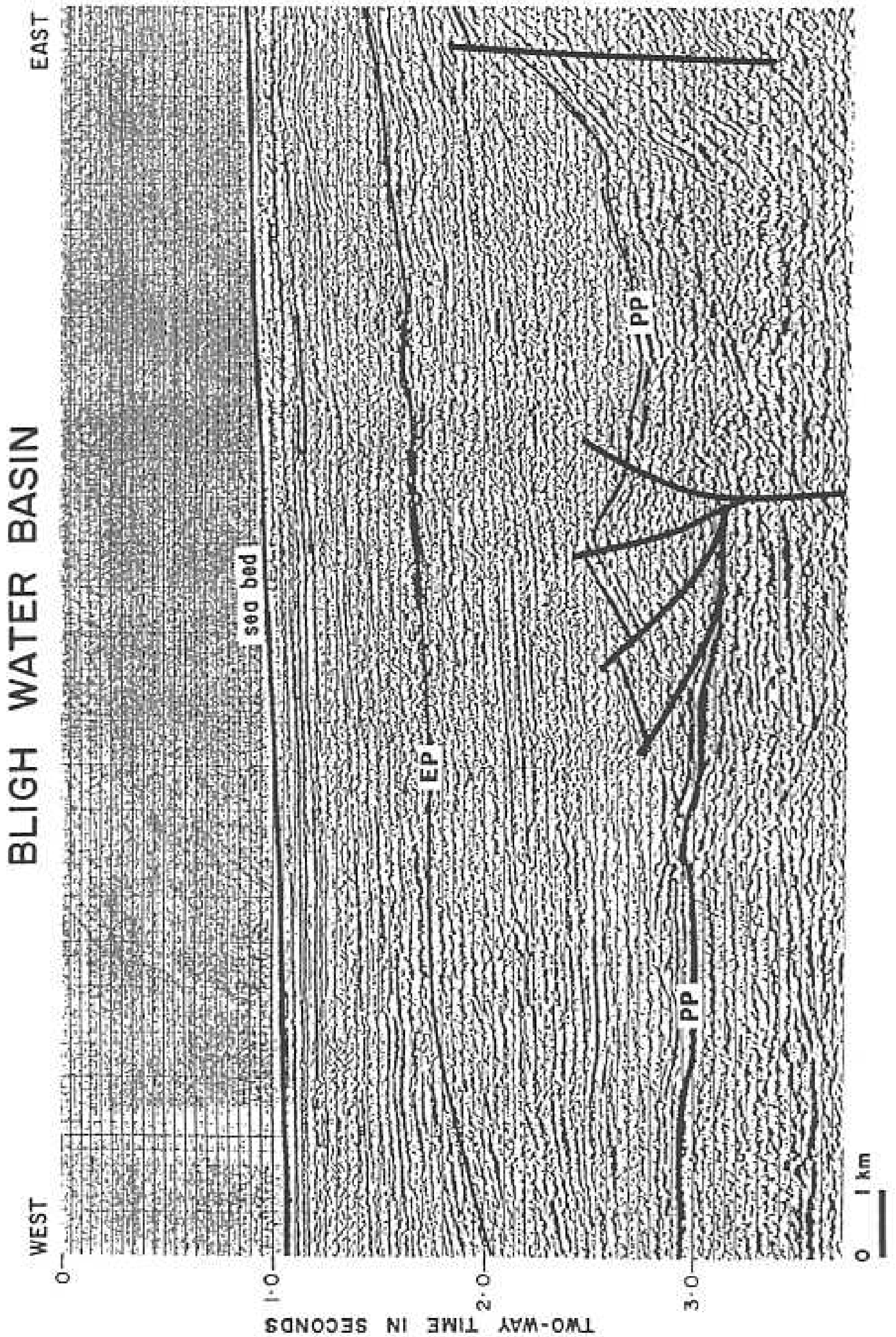

Figure 12. Seismic profile showing a possible positive flower structure in the Bligh Water Basin. PP=pre-Early Pliocene seismic marker, EP=Early Pliocene seismic marker. For location, see Figures 9 and 11.

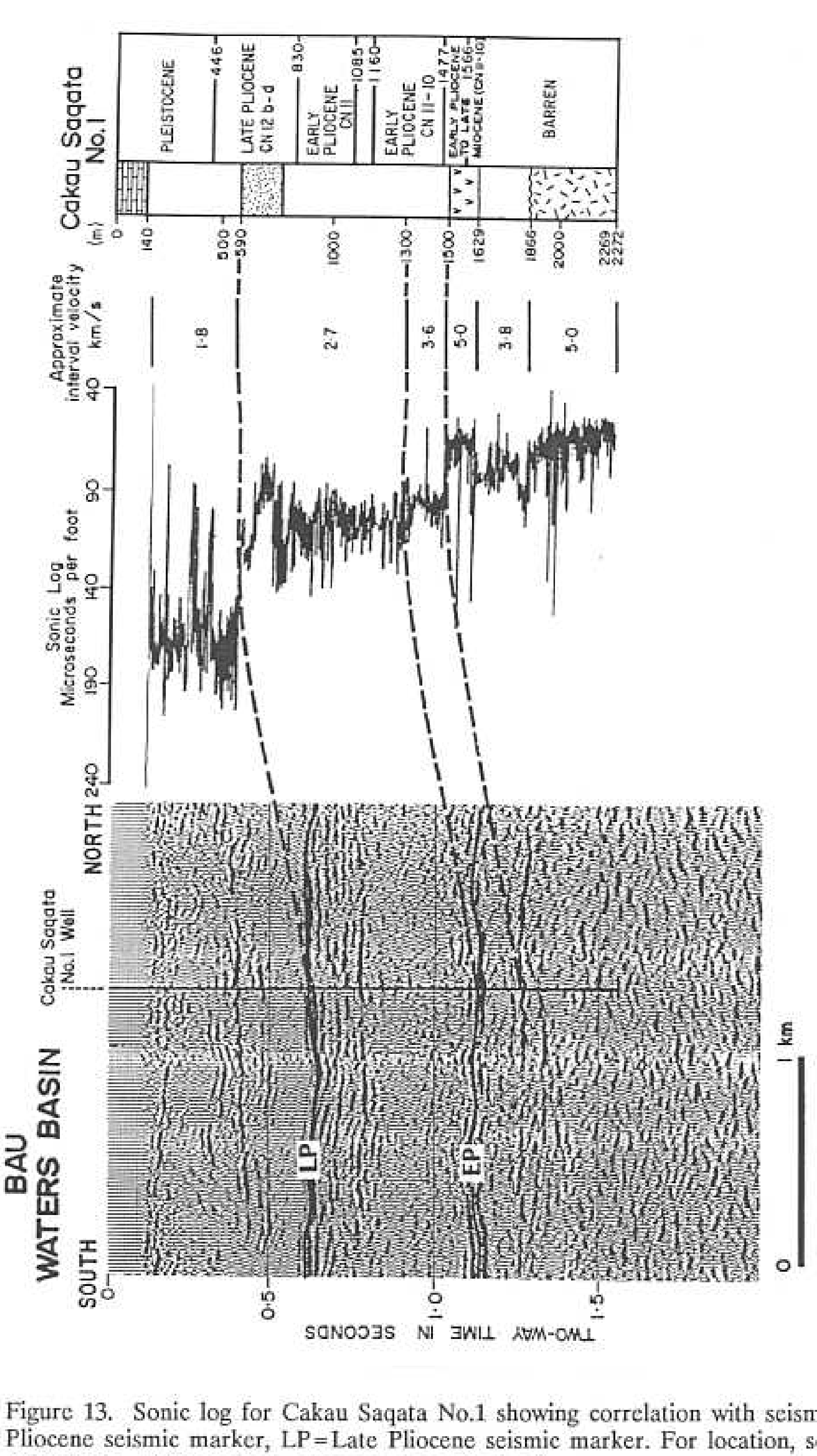

Figure 13. Sonic log for Cakau Saqata No.1 showing correlation with seismic profile. EP=Early Pliocene seismic marker, LP=Late Pliocene seismic marker. For location, see Figures 9 and 11. For explanation of lithological ornaments, see Figure 7.

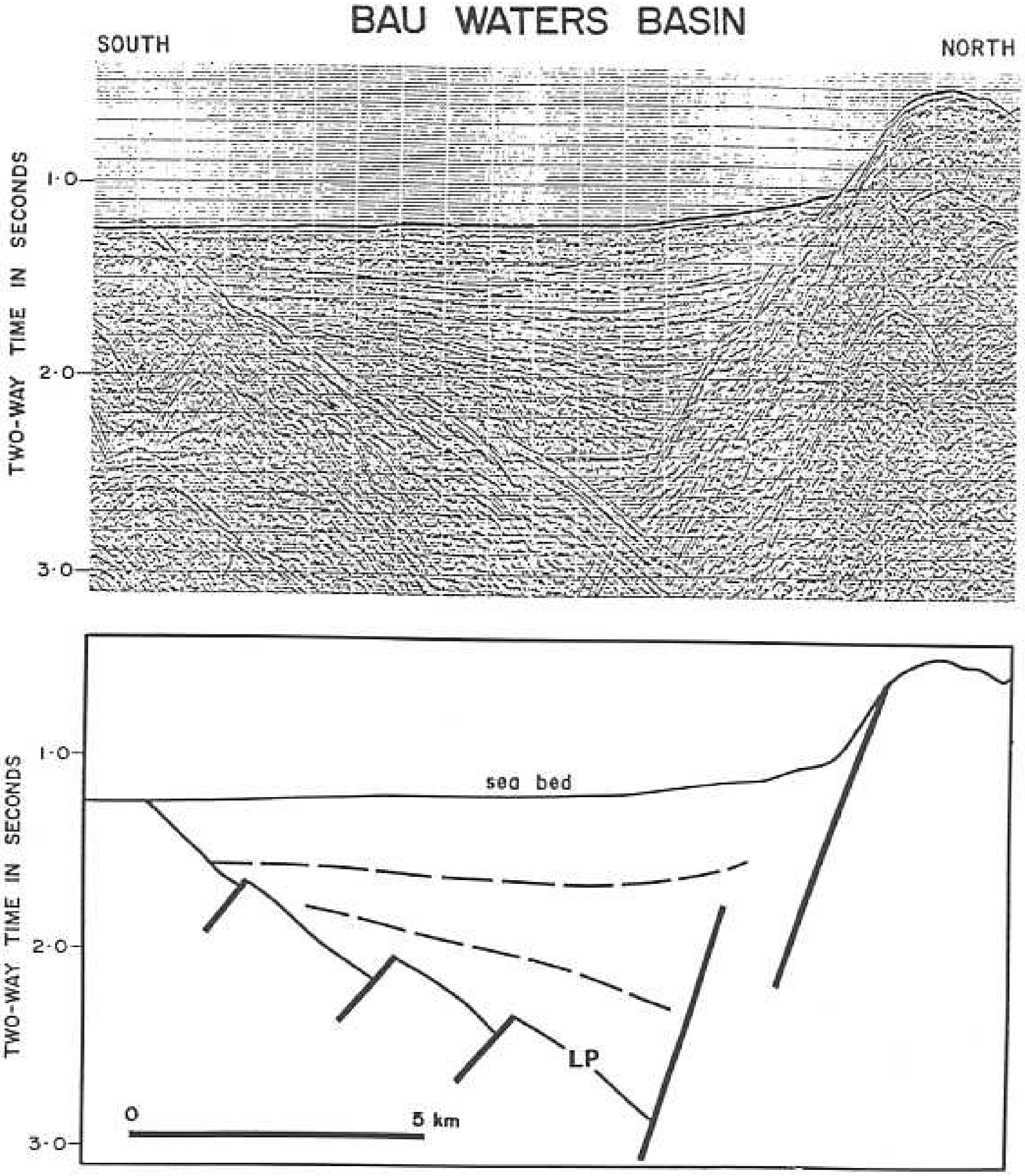

Figure 14. Seismic profile showing a wedge-shaped, probably fault bounded Late Pliocene and younger seismic sequence in Bau Waters Basin. LP=Late Pliocene seismic marker. For location, see Figures 9 and 11.

interval velocity of about 1.8 km per second from Cakau Saqata No.1 suggests that this equates to about 1.6 km. To the NE of the faults bounding this sequence are the uplifted volcanic islands of Wakaya and Makogai. Some internal reflector divergence near the base of the wedge shaped seismic sequence suggests syndepositional faulting (Figure 14). Because of the limited seismic resolution the total sedimentary thickness in the Bau Waters Basin is unknown.

SOURCE ROCKS

To date, no source-rocks have been identified in Fiji. It has been suggested that the most likely potential source-rocks would be associated with reef complexes, because of the high organic productivity of such environments and the possibility of stagnant back-reef and fore-reef environments. The Fiji island geology suggests that reef complexes were best developed in the Early to Middle Miocene, however none of the deep wells have penetrated such rocks.

Bligh Water No.1 and Great Sea Reefs No.1 are the only deep wells to have penetrated a significant thickness of Middle Miocene and older sedimentary rock, but deep-water facies were intersected with no reef-complexes. Total organic carbon (TOC) content rarely exceeds 1% in the well sections. The carbon is of gas-prone or non-source character. Vitrinite reflectance data indicate the top of the oil window to be about 2400 m in Bligh Water No.1. In contrast vitrinite reflectance tests an material from Maumi No.1 well in eastern Viti Levu suggest that the top of the oil window lies at only 1060 m. Thermal gradients and depositional/uplift rates have certainly varied greatly with geological time and with location within the Fiji arc platform. A consequence of the complex thermal history of the sedimentary basins is that the timing of thermal maturation of organic matter enclosed in the sediments is difficult to predict.

Source-rock tests on over 150 samples from outcrop on Viti Levu and from stratigraphic boreholes on Viti Levu and Vanua Levu indicated low TOC contents (generally less than 1% TOC). Furthermore, Rock-Eval pyrolysis analysis of drill-core samples indicated that Hydrogen Index values are low and gave a type lll character for enclosed kerogen. Thus the potential for generation of liquid hydrocarbons is low although gas generation may be expected.

Field studies indicate that much of the finer grained sedimentary rock sequence on Viti Levu is intensely bioturbated thus indicating well-oxygenated palaeo-bottom conditions and a generally poor preservation potential for enclosed organic matter.

Although source-rock tests have been disappointing minor shows of hydrocarbon gases have been recorded in Maumi No.1, Cakau Saqata No.1, and Yakuilau Island No.1 wells, and minor oil fluorescence was recorded between 380 and 472 m in Cakau Saqata No.1.

Detailed geochemical investigation of adsorbed hydrocarbons in over 650 shallow core samples from Bligh Water sea bed sediments have indicated an area about 20 km north of Tavua with anomalously high values of methane, ethane and pentane (Figure 15). The presence of appreciable amounts of pentane suggests that liquid hydrocarbons are present in the potential subsurface. reservoirs. The results of carbon-isotope analysis of 10 samples from the anomalous area tend to confirm the view that the anomaly reflects a subsurface deposit, probably oil.

RESERVOIR ROCKS

From the start of petroleum exploration in Fiji, carbonates have been considered to be the primary targets rather than coarse volcaniclastics. This is because the volcaniclastics generally are quartz-deficient and texturally and mineralogically immature. Their unstable mineral assemblages are prone to secondary alteration, diagenesis and compaction and thus would generally be tight.

Detailed information is scarce on subsurface reservoirs in Fiji. Most of the deep wells penetrated sections dominated by mudstones and tuff. The following porosity and permeability values were measured from Early Pliocene and ?Late Miocene sandstones from outcrop on Viti Levu however, they are unlikely to be representative of material at depth.

Formation	Age	Porosity %	Permeability millidarcys
Waidina Sandstone	E.Pliocene (Verata Sedimentary Group)	44	59
Waidina Sandstone	E.Pliocene	50.8	1,118
Clastics of Ba	E.Pliocene Volcanic Group	33.8	10
Nacua Standstone	E.Pliocene (Verata Sedimentary Group)	47.1	672
Barotu Sandstone (Ra Sedimentary Group)	L.Miocene	25.5	0.7

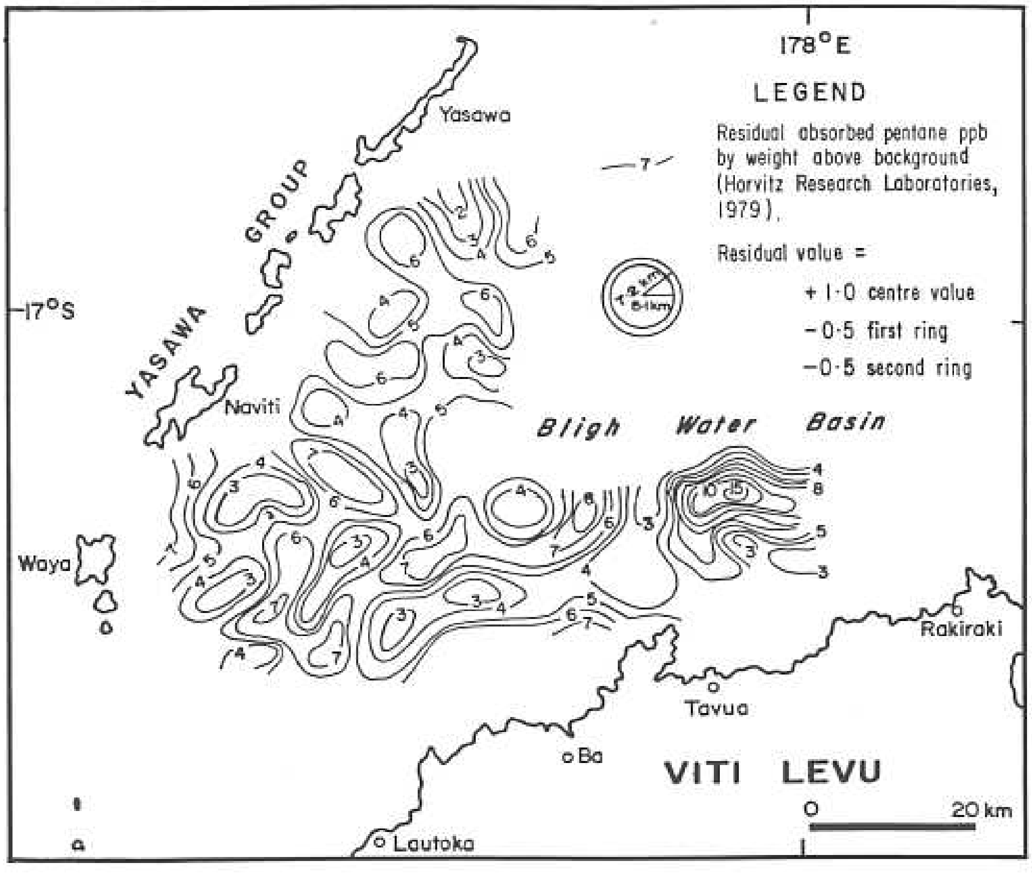

Figure 15. Map showing amounts of adsorbed pentane (parts per billion by weight above background) in sea bed sediments, Bligh Water Basin. Note anomalously high amounts about 20 km north of Tavua.

The most sought-after reservoirs have been shallow-water and locally reefal Early to Middle Miocene limestones equivalent to the clean limestones that crop out on Viti Levu and the Yasawa islands. For example, the Sawai-i-lau limestone in the Yasawa islands (Figures 9 and 11) forms an upstanding mass just less than 150 m thick and covering an area of about 2 by 1 km.

In fact most of the limestones are tight in hand specimen, but may well have fracture porosity. The degree to which buried limestone masses may have developed secondary porosity due to subaerial karstification is largely unknown. There is evidence of Early/Middle Miocene emergence and erosion of the Qalimare Limestone (Wainimala Group) in SW Viti Levu (Figure 3), and secondary solution porosity could have formed during the period of uplift.

PETROLEUM PROSPECTS

It has been suggested that the most likely potential source-rocks and reservoirs in Fiji are to be found in shallow-water facies of pre-Late Miocene age, particularly in Lower and Middle Miocene reef complexes. Since such reef targets must be located in areas of shallow palaeo-bathy-metry, they are probably related to, and controlled by, the location of the main volcanic island arc. In Viti Levu the location of the Early to Middle Miocene volcanic arc is marked by the ENE-trending outcrop of Wainimala Group volcaniclastic rudites and massive dacites in the southern and central parts of the island (Figure 3). This former volcanic axis is, indeed, flanked to the north by outcrops of Early to Middle Miocene shallow-water limestones (eg Qalimare Limestone Figure 3). Outside of Viti Levu, however Early to Middle Miocene rocks are poorly exposed and the location of the Early to Middle Miocene volcanic axis is open to speculation.

Seismic interpretation suggests that, in general, only Late Miocene and younger strata are resolved on seismic reflection profiles. Thus, the recognition of Early and Middle Miocene drilling targets is problematical, and trial reprocessing of seismic data has been suggested to determine if deeper data can be resolved with more recent processing techniques.

It is interesting to note that the pentane anomaly in Bligh Water occurs near Bligh Water No. 1 well in an area where a bathyal facies of the Lower to Middle Miocene might be expected. In view of the lack of evidence for widespread reservoir layers, migration routes for hydrocarbons might be expected to be short, so long-distance migration from possible source beds to the south appears unlikely. The location of the geochemical anomaly if sourced from a Lower to Middle Miocene reef complex, therefore is problematic. A potentially significant, but unknown factor is the location of possible Eocene source beds. In fact the geochemical anomaly is adjacent to a large structural high (Figure 9) which, speculatively, may bring Eocene rocks to near the sea bed.

Although it is not possible at this time to identify pre-Late Miocene drilling targets there are numerous styles of potential traps in Late Miocene and younger deposits in the Bligh Water and Bau Waters Basins. The location of such potential traps with respect to potential pre-Late Miocene source beds is, of course, speculative, but thick Late Miocene strata in depocentres of the Bligh Water Basin may have undergone sufficient heating to attain thermal maturation, and they might also contain sufficient organic matter (mainly terrigenous) to have generated some hydrocarbons, probably mainly gas.

As noted previously, the best potential traps arc buried reefs. There are several mound-like features at various stratigraphic levels in the Pliocene sequence in the western part of the Bligh Water Basin and these show some of the characteristics of buried reefs. In addition to a mound shape, these characteristics include onlap and drape of overlying sediments and lack of internal seismic reflections. Seismic profiles which intersect at 90' over one such Pliocene mound are shown in Figure 16. The mound is up to 0.25 seconds two-way reflection time in height. Since there are no associated velocity anomalies it must have a similar velocity to the surrounding rocks which in Bligh Water No. 1 well, is about 2 km per second. Thus it is up to 250 m thick. The mound is buried under about 0.55 seconds two-way reflection time of strata (about 550 m). Although it rests on a block-faulted surface the upper boundary does not appear to be cut by faults and the overlying undeformed layered strata sediments may include a fine grained seal. Water depth over this mound is about 400 m.

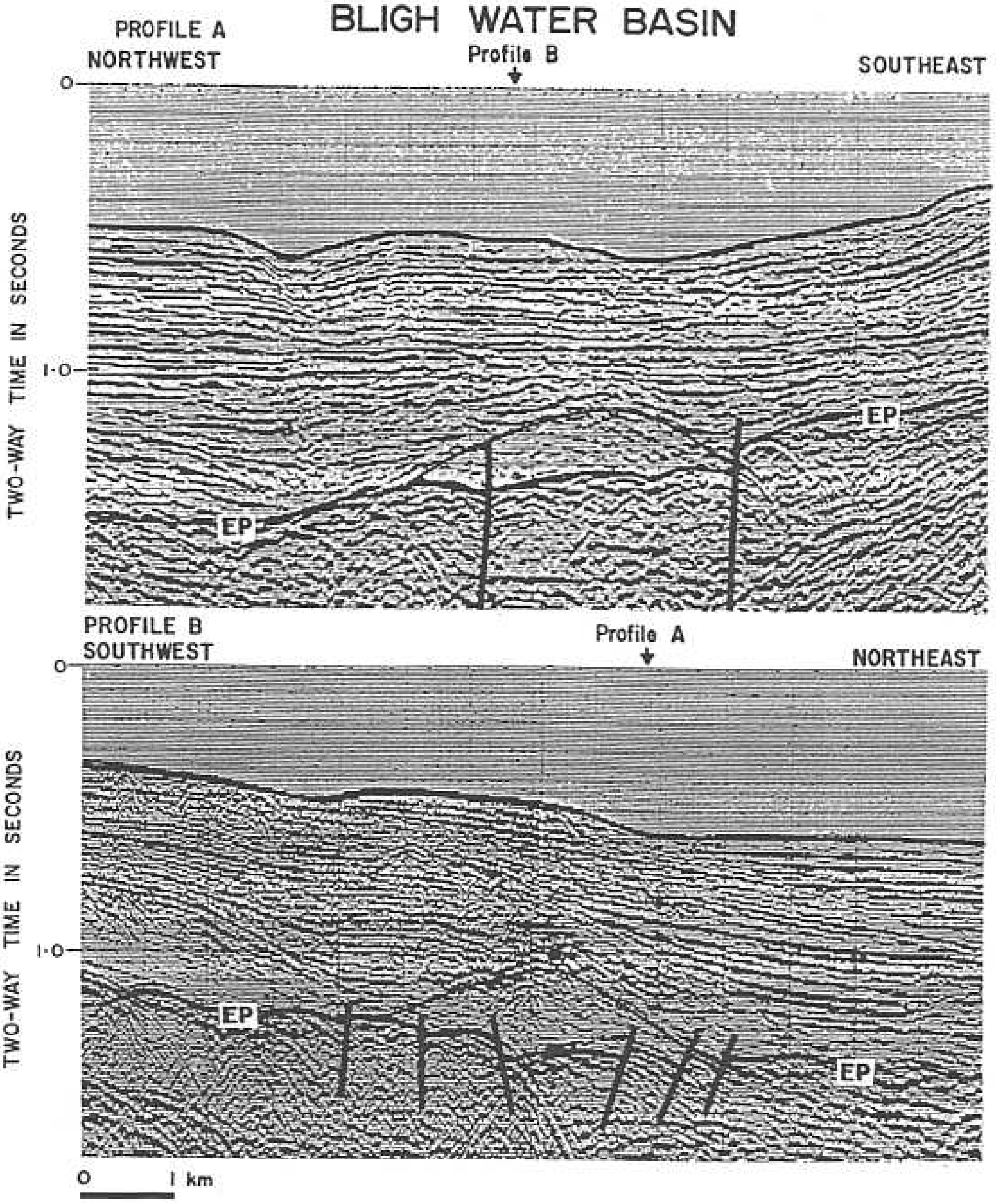

Figure 16. Orthogonal seismic profiles showing a reef-like mound in Bligh Water Basin. EP = Early Pliocene seismic marker. For location, see Figures 9 and 11.

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