

# LATE METEORIC FLUSHING AND TIMING OF HYDROCARBON ENTRAPMENT IN THE KUPE SOUTH FIELD

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## Abstract

Late meteoric flushing of Paleocene reservoir sandstones in the Kupe South Field is recorded by the occurrence of abundant authigenic kaolinite in some of these sandstones. The kaolinite is a late phase, postdating co-existing authigenic chlorite/smectite, calcite and ferroan carbonate, as well as significant sandstone compaction that occurred during rapid late Miocene burial. The oxygen isotopic composition of the kaolinite ( $\delta^{18}\text{O}_{(\text{SMOW})} = 15.4$  to  $16.3\text{‰}$ ) indicates that for geologically realistic kaolinite formation temperatures, the kaolinite must have formed from porewater that was at least partly meteoric.

The presence of meteoric water in the sandstones following deep late Miocene burial is linked to meteoric ingress at the major Miocene–Pliocene unconformity that truncates the reservoir section 10 to 15 km up dip from the Kupe South Field. This implies that meteoric flushing and consequent authigenic kaolinite formation occurred during the latest Miocene to earliest Pliocene, the time when the reservoir section was subaerially exposed prior to regional Pliocene to Holocene marine sediment accumulation. Because authigenic kaolinite is abundant in the hydrocarbon-bearing sandstones, hydrocarbon entrapment must postdate kaolinite formation and thus must have occurred in the Kupe South Field during the Pliocene–Holocene burial episode.

## Introduction

Kupe South Field is an offshore gas condensate and oil field located within the South Taranaki Graben of the Taranaki Basin, New Zealand (figure 1). The discovery well, Kupe South-1, was completed in 1986, and a further four wells have since been drilled, with the most recent being Kupe South-5, which was completed in 1990. Hydrocarbon accumulations in the field occur in fluvial sandstones of Paleocene age within a fault-bounded, north-plunging anticline.

A comprehensive diagenetic study was carried out on reservoir sandstones in the Kupe South Field, providing information on the fluid flow history of the sandstones during burial diagenesis (Martin et al., 1994). Based on some of the results of this study, the present paper focuses on the significance of the oxygen isotopic composition of authigenic kaolinite in the reservoir sandstones as an indicator of localised late-stage meteoric flushing in the Kupe South Field. The timing of the meteoric flushing is used to constrain the timing of hydrocarbon accumulation in the Kupe South reservoirs.

## Regional Setting and Stratigraphy

The Taranaki Basin is situated along the southwestern side of the North Island of New Zealand, mainly beneath the present-day continental shelf and slope. It contains up to about 9000 m of marine and non-marine, mostly terrigenous sedimentary rocks of Late Cretaceous to Holocene age that

accumulated in an active regional tectonic setting characterised by seafloor spreading followed by plate convergence (Thrasher, 1992; King and Thrasher, 1992).

Reservoir sandstones in the Kupe South Field constitute part of the Paleocene Farewell Formation (Schmidt and Robinson, 1990) (figure 2). In the Kupe South area, this unit is about 1000 m thick and consists mainly of stacked fluvial sandstones. The Farewell Formation is underlain by the Upper Cretaceous Pakawau Group, which constitutes the basal unit of the Taranaki Basin fill. The lower 2000 m of the Pakawau Group accumulated in non-marine lower coastal plain to alluvial fan environments (Rakopi Formation), whereas the upper 1000 m accumulated in lower shoreface to nearshore marine environments (North Cape Formation) (Thrasher, 1992). Oligocene marine mudrocks of the Otaraoa Formation unconformably overlie the Farewell Formation in the Kupe South area, and are overlain by Neogene marine mudrock units. These units are unconformably overlain by marine, Pliocene to Holocene mudrocks, sandstones and unconsolidated sediments.

## Burial and Thermal History of the Kupe South Area

The Kupe South area has undergone three episodes of subsidence and two episodes of uplift since the inception of the Taranaki Basin during the Late Cretaceous (figure 3). The first subsidence episode occurred during the early Late Cretaceous to latest Paleocene, and led to rapid accumulation of the Pakawau Group and Farewell Formation.

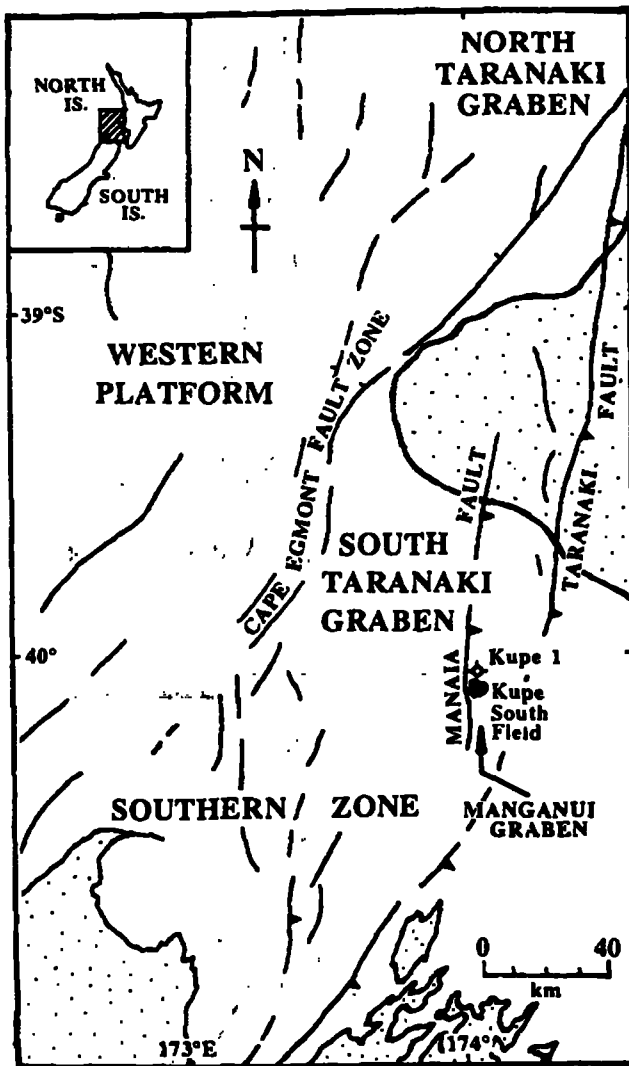


Fig. 1. Location and major structural elements of the Taranaki basin (after Schmidt and Robinson, 1990, and Kamp and Green, 1990).

Following latest Paleocene to Eocene uplift and erosion (Schmidt and Robinson, 1990), sediment accumulation resumed over the Kupe South area during the early Oligocene. By the late Miocene, the Farewell Formation was overlain by about 3000 m of mainly argillaceous sediments of the Otaraoa Formation and higher Miocene units.

Late Miocene structural inversion, the second and most significant uplift episode, led to the removal of about 2000 m of upper Miocene section in the area. Increased uplift southward resulted in deeper erosion and exposure of the Farewell Formation about 10 to 15 km south of the Kupe South Field (Thrasher, 1992).

The third subsidence episode commenced during the early Pliocene, and has continued to the present day. Subsidence was rapid during this period, and resulted in burial of the Farewell Formation to depths slightly greater than those attained at the end of the second burial episode (Kamp and Green, 1990). Over the Kupe South Field, the Paleocene reservoir sandstones are presently buried to a depth of about 3000 to 3200 m, and are at their maximum burial temperature of about 85°C.

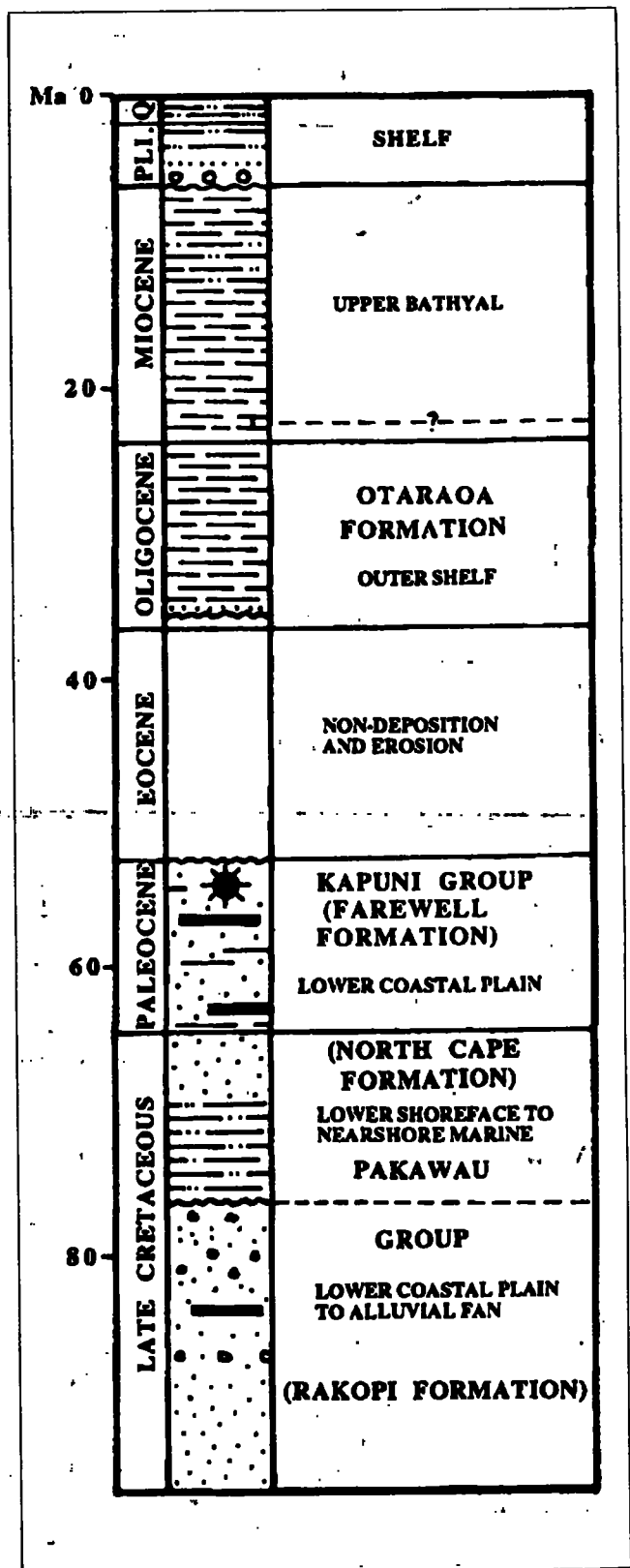


Fig. 2. Stratigraphy of the Kupe South area (modified from Schmidt and Robinson, 1990). Stratigraphic subdivision of the Pakawau Group based on Thrasher (1992).

### Methods

Over 200 sandstone samples were taken from whole and sidewall cores of the Farewell Formation at depths between 3000 and 3200 m in Kupe South 1 to Kupe South-5. The samples were routinely examined by thin section, X-ray diffraction (XRD) analysis. Selected samples were also

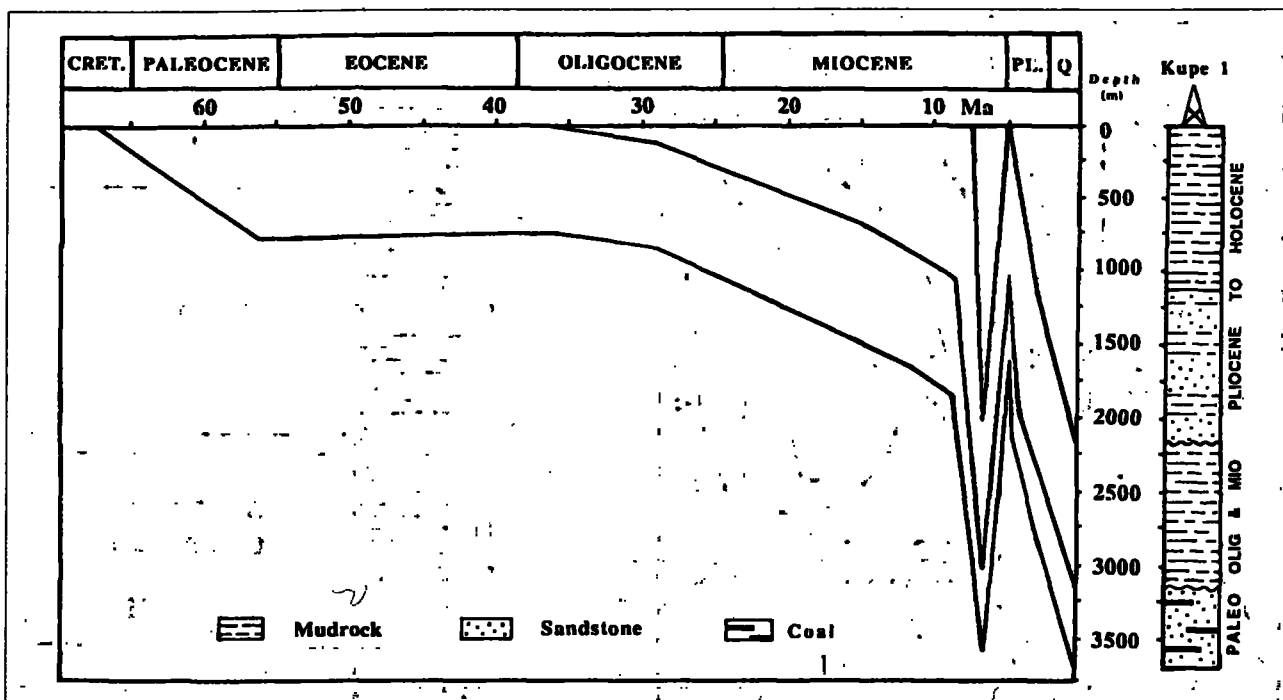


Fig. 3. Burial history diagram for the location of Kupe 1 (modified from Kamp and Green, 1990 on the basis of data in Schmidt and Robinson, 1990). Lower curve corresponds to the lower Farewell Formation.

examined by electron microprobe, scanning and transmission electron microscope, and stable isotopic analysis.

Oxygen isotope compositions were determined for authigenic kaolinite extracted from three samples, using the standard isotopic analytical techniques of Clayton and Mayeda (1963). The samples are all from Kupe South-4, with suitable samples for kaolinite isotope analysis being unavailable from the other wells. XRD analysis of the separated kaolinites prior to isotopic analysis verified that they contained less than 10% impurities. Oxygen isotopic data are presented in per mil (‰) with respect to standard mean ocean water (SMOW) (Craig, 1961). The reproducibility of standard  $\delta^{18}\text{O}$  values was  $\pm 0.2\text{‰}$  or better.

## Results

### Sandstone petrology

Samples are mainly medium to coarse-grained, moderately to well-sorted arenites. In addition to quartz, they contain large amounts of feldspar and rock fragments, and can be classified as arkoses, lithic arkoses, feldspathic litharenites and litharenites (Folk et al., 1970) (figure 4). Biotite abundance commonly exceeds 10% of the bulk rock. Heavy minerals include epidote, sphene, zircon, tourmaline, hornblende, apatite and ilmenite. Major authigenic minerals are chlorite/smectite, kaolinite, calcite, siderite and ankerite.

In some of the wells, there is a consistent vertical change in sandstone detrital mineralogy that allows the drilled reservoir interval to be divided into two intervals, which will be referred to in this paper as the upper and lower sands. This change is coincident with changes in authigenic mineralogy, and occurs at depths approximating those of the A-B sand boundary as seismically defined by Schmidt and Robinson (1990). The A-B terminology of Schmidt and Robinson (1990) is not used here as this implies a depositional origin for the petrological differences.

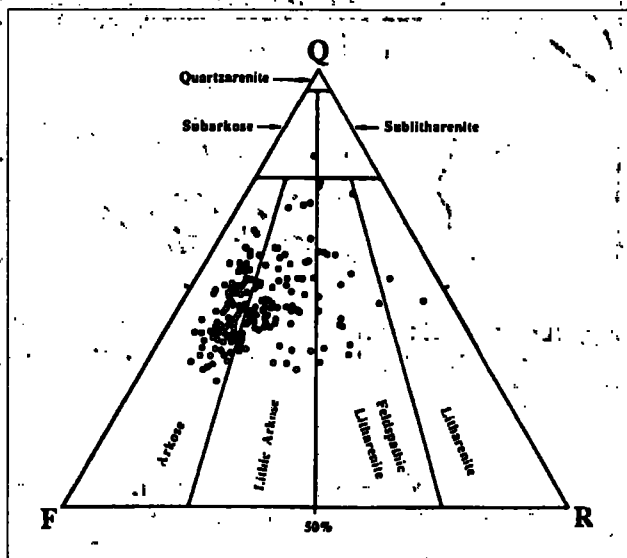


Fig. 4. QFR compositions (after Folk et al., 1970) of reservoir sandstones of the Farewell Formation. Filled circles show upper sands; open circles show lower sands.

The lower sands are more feldspathic than the upper sands (figure 4) as a result of a significantly higher plagioclase content at the expense of quartz and rock fragments. The lower sands also have much higher biotite contents, and contain epidote and sphene, which are absent in the upper sands. In addition, chlorite/smectite is the typical authigenic mineral of the lower sands, whereas the presence of authigenic ferroan carbonate and kaolinite characterises the upper sands. This contrast in authigenic mineralogy depends on whether unstable grains, particularly biotite and plagioclase, have decomposed to chlorite/smectite, or instead, reflecting more advanced alteration, to ferroan carbonate and kaolinite. Accordingly, rather than reflecting a change in provenance, the mineralogical difference between the lower and upper

sands is considered to be a diagenetic effect (Martin et al., 1994).

Authigenic kaolinite abundance in the upper sands commonly exceeds 10% and ranges up to 26% of the bulk rock. The kaolinite occurs mainly as randomly oriented or vermiform stacks of 2.0 to 10.0  $\mu\text{m}$  wide, pseudohexagonal crystals that form a loosely packed and erratically distributed pore infilling. In addition, where biotite has decomposed to kaolinite and ferroan carbonate, the kaolinite commonly retains the original morphology of the precursor biotite grain. Precursor grains for kaolinite in the sandstones, besides biotite, include feldspars and a variety of unstable rock fragments.

#### Kaolinite stable isotope data

Oxygen isotopic data for the authigenic kaolinite in Kupe South-4 are presented in table 1. Isotopic analysis of the three kaolinite samples gave  $\delta^{18}\text{O}_{(\text{SMOW})}$  values that lie in the narrow range of 15.4 to 16.3‰.

#### Kaolinite relative timing

Kaolinite is bounded by chlorite/smectite grain rims, is partly engulfed by rare quartz overgrowths and appears to occur within secondary pores created by dissolution of late (post compaction) calcite and ferroan carbonate. These textural relationships indicate that the kaolinite is a relatively late-stage phase, postdating burial compaction as well as chlorite/smectite and carbonate formation, but predating quartz overgrowth formation. Kaolinite formation also predates hydrocarbon entrapment since kaolinite is abundant in the hydrocarbon-bearing sandstones. A summary of the interpreted diagenetic paragenesis based on these and other textural relationships (described in Martin et al., 1994) is given in figure 5.

## Discussion

### Meteoric flushing

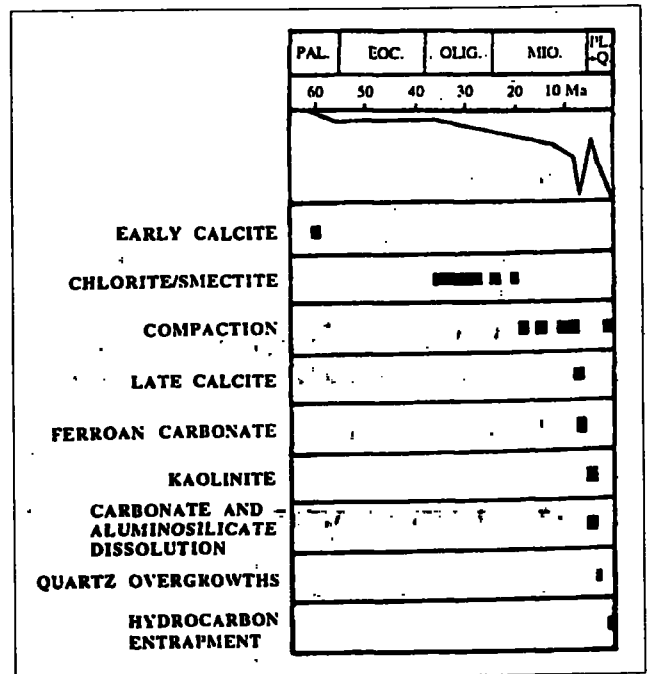
Evidence for late meteoric flushing in the reservoir sandstones is provided by the timing and oxygen isotopic composition of authigenic kaolinite in the sandstones, together with stratigraphic relationships in the Kupe South area.

As noted previously, kaolinite postdates sandstone compaction, implying that the kaolinite must have formed during or after the late Miocene, the likely time of significant sandstone compaction. Following the rapid late Miocene burial phase, the Farewell Formation remained buried beneath at least 1000 m of mudrocks in the Kupe South Field. Hence, the kaolinite could not have formed at a temperature below about 35°C (assuming present day geothermal gradient of 23°C/km). The present day formation temperature of 85°C is the maximum burial temperature, and is thus the upper temperature limit at which the kaolinite could have formed.

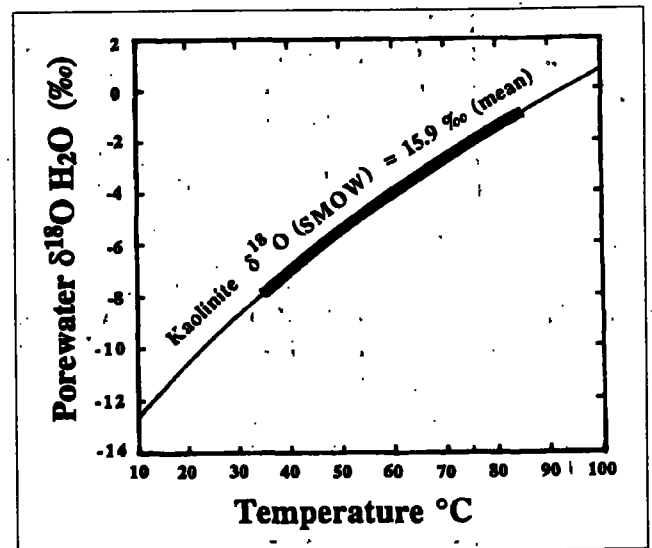
The oxygen isotope data for the kaolinite indicate that for a temperature range of 35° to 85°C, the kaolinite must have formed from water with a  $\delta^{18}\text{O}_{(\text{SMOW})}$  value ranging from -7.6 to -0.7‰ (figure 6). The fact that 1) the kaolinite postdates overgrowths, and 2) hydrocarbon entrapment followed the formation of the kaolinite, indicates that the kaolinite is not the latest diagenetic effect, and thus probably formed at temperatures below the present-day maximum of 85°C. Accordingly, on this basis, the  $\delta^{18}\text{O}$  value of the water involved in the formation of the kaolinite must have been well below 0‰ (figure 6), implying that during deep (>1000 m) burial, meteoric waters were present in the reservoir sandstones (meteoric water has  $\delta^{18}\text{O}$  values less than 0‰).

**Table 1.** Authigenic kaolinite oxygen isotopic compositions.

Well	Depth (m)	$\delta^{18}\text{O}$ (‰ SMOW)
KS4	3059.4	16.3
KS4	3071.3	15.4
KS4	3095.9	15.9



**Fig. 5.** Paragenetic sequence of diagenetic events in the Farewell Formation at Kupe South. A generalized burial curve for the reservoir sandstones at Kupe South is also shown.



**Fig. 6.** Porewater water  $\delta^{18}\text{O}$  value vs. temperature for authigenic kaolinite in the Farewell Formation. Precipitation temperatures based on likely kaolinite timing within reconstructed burial-temperature history. Curve is for the mean kaolinite  $\delta^{18}\text{O}$  value, and was calculated using the mineral-water fractionation equation,  $10^3 \ln \alpha (\text{kaolinite-water}) = 2.50 \times 10^6 T^{-2} - 2.87$  (Land and Dutton, 1978), (temperature in kelvins).

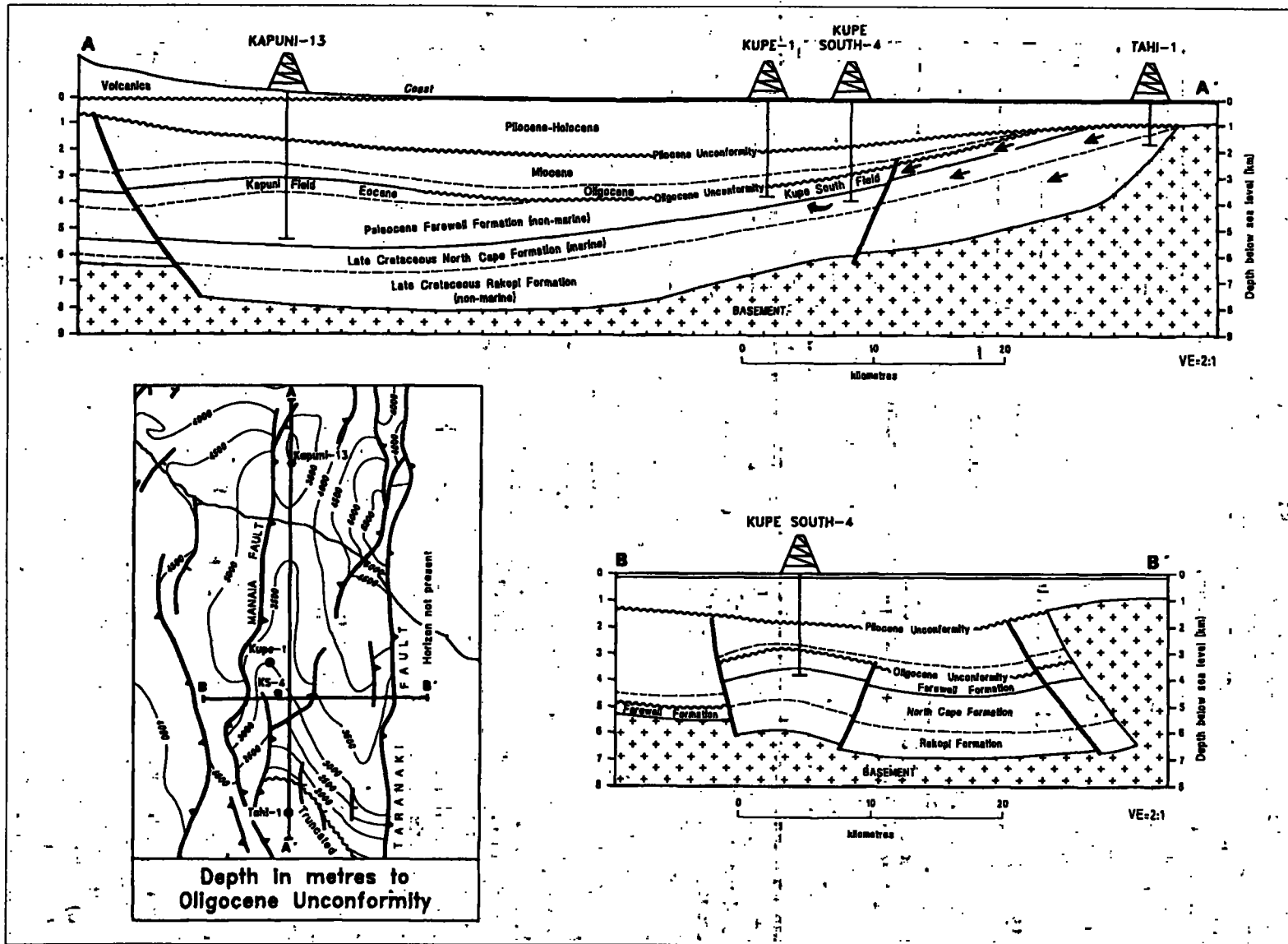


Fig. 7. Structural cross-sections over part of the South Taranaki Graben showing configuration of the Kupe South Field. Arrows indicate probable northward flow of meteoric water into the Kupe South reservoirs during latest Miocene to earliest Pliocene exposure of the Cretaceous-Paleocene sequence. Vertical exaggeration of cross-sections is approximately 2:1. Cross-sections adapted from King et al. (1991); map adapted from Thrasher and Cahill (1990).

The presence of meteoric water in the reservoir sandstones during deep burial is most easily explained by meteoric water ingress at the major Miocene–Pliocene unconformity. Although this unconformity occurs about 1000 m above the Farewell Formation in the Kupe South Field, seismic and well data show that only 10 to 15 km south of the field, the entire Paleocene and Cretaceous sequence subcrops beneath the unconformity due to deep Miocene–Pliocene erosion up the plunge of the north-plunging anticline that forms the Kupe South structure (figure 7). Hence, prior to onset of Pliocene sediment accumulation, meteoric waters could have directly entered the reservoir sandstones exposed at the top of the breached anticline during the latest Miocene to earliest Pliocene, and moved down-dip into the Kupe South Field.

Another possible late-stage meteoric water source is the Cretaceous section (Pakawau Group), which, in the Kupe South area, includes over 2000 m of non-marine sandstones, conglomerates, mudrocks and coals of the Rakopi Formation (Schmidt and Robinson, 1990). Upward expulsion of high-latitude (75°S; Veevers et al., 1991), hence originally very <sup>18</sup>O-depleted connate meteoric waters in these rocks could have occurred during the late Miocene, when the Cretaceous section, which previously had not been buried below about 2000 m, was rapidly buried to depths exceeding 4000 m.

Meteoric water ingress at the top of the breached anticline is the preferred scenario for the formation of the kaolinite in the Kupe South reservoirs, given the well-known relationship between meteoric flushing and deep authigenic kaolinite formation (e.g. Ayalon and Longstaffe, 1988; Glasmann et al., 1989; Baker and Golding, 1992). This scenario implies that the kaolinite formed at temperatures well below the maximum burial temperature of 85°C, which in turn indicates that the meteoric water involved in kaolinite formation was, as expected given a situation of meteoric influx from a nearby recharge area, isotopically unmodified (since it was very depleted in <sup>18</sup>O) (figure 6). Another important implication of the meteoric influx scenario is that the kaolinite and associated secondary porosity formed during the latest Miocene to earliest Pliocene, the time of subaerial exposure of the reservoir section.

#### Hydrocarbon entrapment

Hydrocarbon entrapment postdates kaolinite formation (since kaolinite is abundant in the hydrocarbon-bearing sandstones), and thus, based on the arguments presented in the preceding section, occurred during the Pliocene to Holocene, when about 2150 m of sediments accumulated and reservoir temperatures were increased by about 55°C in the Kupe South area (Kamp and Green, 1990). Hydrocarbons in the Kupe South Field are likely to be derived from source rocks in the underlying Cretaceous section, since temperatures in the overlying section have not been sufficient for significant hydrocarbon generation (Schmidt and Robinson, 1990; Kamp and Green, 1990), implying upward fluid movement in the Cretaceous–Paleocene sequence during the Pliocene to Holocene burial phase. Any hydrocarbons generated during the Miocene burial phase would have been lost due to meteoric flushing associated with late Miocene to early Pliocene uplift and erosion of the reservoir section.

#### Conclusions

Kaolinite is a late authigenic phase in Paleocene reservoir sandstones of the Farewell Formation, Kupe South Field. It

has an oxygen isotopic composition that indicates that for all geologically realistic kaolinite formation temperatures, the water involved in kaolinite formation was at least partly meteoric.

The presence of late-stage meteoric waters reflected by the kaolinite is linked to meteoric ingress at the major Miocene–Pliocene unconformity that truncates the reservoir interval 10 to 15 km updip (south) from the Kupe South Field. This implies that the timing of meteoric inflow and consequent kaolinite formation in the reservoirs was latest Miocene to earliest Pliocene, the time of subaerial exposure of the reservoir prior to regional Pliocene to Recent marine sediment accumulation.

The authigenic kaolinite is abundant in hydrocarbon-bearing sandstones in Kupe South Field, suggesting that the hydrocarbons accumulated following kaolinite formation. Accordingly, hydrocarbon accumulation must have occurred in the Kupe South Field during the Pliocene to Holocene burial episode.

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## Acknowledgements

Petrological study of the Kupe South Field was initiated by the previous operators of the permit, TCPL Resources, whose continued assistance and cooperation we acknowledge. We also thank the present operators, Western Mining Corporation and its joint venture partners for permission to publish this paper. Sylvie Llorca, Anita Andrew, Andrew Bryce and Andrew Todd are thanked for their assistance with stable isotope analysis. JCB acknowledges the support of ARC grant AB9130015.

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