

Lithofacies, Depositional Setting, and Reservoir Characteristics of the Farewell Formation, Kupe South Field, Taranaki Basin, New Zealand

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Abstract

The Kupe Field reservoir interval is the Paleocene Farewell Formation which is up to 1200 m thick. In this study, we re-evaluate the sedimentology of these rocks based on core description, to further refine the interpretation of their depositional setting and assess the reservoir characteristics of these rocks. Over 285 m of core were examined in four of the six exploration wells in the field — Kupe South-1, -2, -4 and -5.

We recognise three relatively coarse-grained lithofacies — pebbly conglomerate, pebbly sandstone, and very fine to very coarse sandstone, and four fine-grained lithofacies — mudstone, mudstone with silty-sandy lenses, siltstone-sandstone, and organic-rich lithofacies. These lithofacies occur in fining-upward cycles in each of the cores. We interpret the coarser-grained lithofacies as mixed sandy and gravel bed, braided stream deposits. Parts of Kupe South-5 are interpreted as deposits of meandering streams. Fine-grained lithofacies mostly represent a variety of terrestrial overbank floodplain, paleosol and lacustrine depositional settings, but some containing dinoflagellates, represent marginal marine environments.

Our study indicates several encouraging reservoir attributes in the Farewell Formation. The sandstones are moderately to well sorted, with little interstitial clay or silt, and have good porosity and permeability. Permeability is typically in the range 1-1000 mD. Maximum permeability occurs in the very fine-very coarse sandstone lithofacies (maximum 1800 mD, average 800 mD), with greatest variability in the pebbly conglomerate lithofacies (maximum 330 mD, average 26 mD). Although bases of depositional cycles may be erosional and marked by pebbles, they tend not to be mud-lined, and therefore should not significantly impair communication and connectivity within the reservoir. The stacked nature of sand and conglomerate lithofacies within the reservoir favours a high net:gross ratio. Fine-grained lithofacies developed at the tops of depositional cycles are likely to relate to abandonment surfaces in channels or on floodplains, and individual units are probably of restricted lateral extent.

Introduction

Kupe South Field in offshore Taranaki Basin (Figure 1) is likely to become a major gas producing field in the next few years (Beggs 1996, Kidd 1996, Petroleum Exploration in New Zealand News 1996). In-place recoverable reserves are estimated at 65.1 MMBOE, consisting of 16.3 MMB of oil/condensate and 256 BCF of gas (King and Thrasher 1996). The timeframe for development of Kupe South Field will be dependent in part on the production life of the Maui gas field, which some predict will be depleted as early as 2006 (Kidd 1996), and on alternative gas supplies becoming available from other sources (eg the Mangahewa prospect). To optimise production from Kupe South,

comprehensive studies of the structural, depositional, and thermal histories of the field are required. Such studies are warranted now, considering that a short lead-time is probable before the full commissioning of production, and because comparatively few geological studies have been undertaken in the field. After initial research by the then licence holders TCPL Resources Ltd, following the discovery in December 1986 (Robinson 1989, Schmidt and Robinson 1990), no further geological studies of the field have been published. Three-dimensional seismic coverage of the field has been acquired during the past few years (Petroleum Exploration in New Zealand News 1996), but these data remain confidential. Thus, it is considered timely to re-evaluate the sedimentology of the reservoir

interval in the field, to further refine the depositional setting of these rocks and assess their reservoir attributes.

Six exploration wells were drilled in the region between 1975 and 1990 (Kupe-1 and Kupe South-1 to -5). Gas shows were recorded in Kupe-1 and each of the Kupe South wells was either a gas/condensate or oil/gas discovery. In each well, the petroleum is reservoirized within the Paleocene Farewell Formation. In this study, 285 m of core from Farewell Formation in Kupe South-1, -2, -4, and -5 (Kupe-1 and Kupe South-3 were not cored) are described in terms of lithofacies, their depositional environments interpreted, and reservoir attributes assessed (Figures 2, 3, 4, and 5). Seven samples of fine-grained lithologies are analysed for their palynofacies in order to corroborate lithofacies interpretations. Our aim is not to replicate the work done by Robinson (1989) and Schmidt and Robinson (1990) on some of these cores, but to add further detail. It should be noted that these two earlier papers described only Kupe South-1 and -2; the other wells were confidential at that time.

Structural and Depositional Setting

Kupe South Field covers the axial regions of a gently north-plunging anticlinal structure. It is located within the Manaia Sub-basin bounded to the west by the Manaia Fault, and is north of the Rua Fault (Figure 1). These faults were active normal structures during Late Cretaceous to Paleocene time. During Farewell Formation deposition, these faults were related to northwest-southeast directed post-rift crustal spreading associated with the opening of the Tasman Sea region (Bal 1994). The faults were reactivated during Late Oligocene to Early Miocene time producing cross-cutting northwest-southeast faults (Schmidt and Robinson 1990). During Oligocene-Miocene time inversion along the Manaia and Rua faults resulted in a faulted anticlinal closure. Uplift and folding during the late Neogene tilted the anticlinal closure causing migration of hydrocarbons toward the south (ie migration up structural dip).

Farewell Formation sedimentation occurred in numerous fault-bounded depocentres developed adjacent to the normal faults described above. Reservoirs in the Kupe South Field are in the Paleocene Farewell Formation, which comprises up to 1200 m of mostly sandstones and pebbly sandstones, and less abundant mudstones and carbonaceous mudstones (Schmidt and Robinson 1990, King and Thrasher 1996). Martin et al (1994) and King and Thrasher (1996) included all the Kupe South Paleocene strata in the Farewell Formation, though other authors have suggested that the Farewell Formation is erosionally truncated between Kupe South-4 and -5, and that some Paleocene sediments in the Kupe South-5 core are part of the older Puonga Member, North Cape Formation (Duff and Elliott 1991).

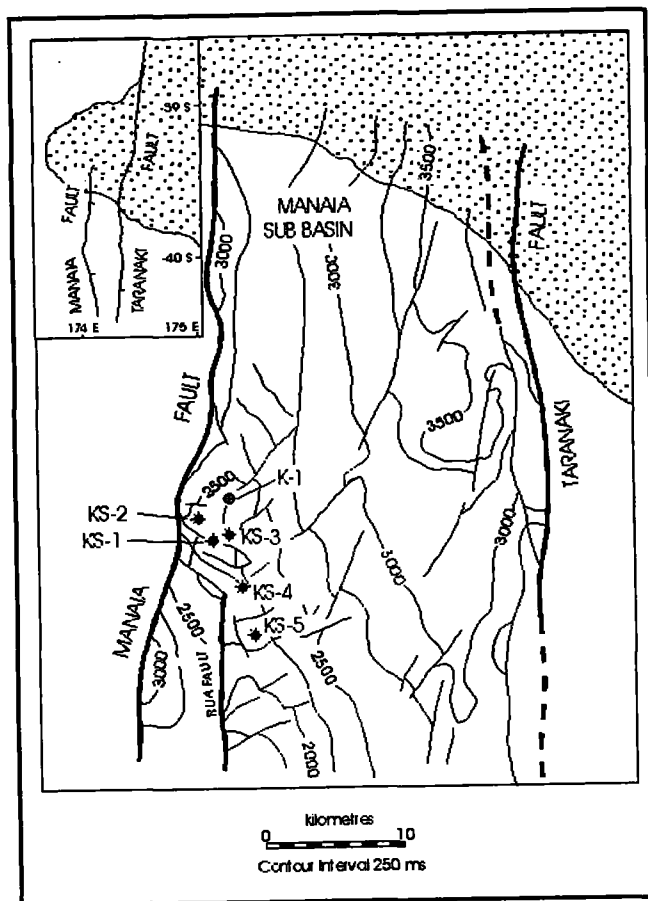


Figure 1. Map of the Kupe South Field within the Manaia Sub-basin, showing location of major faults, location of Kupe South wells, and the depth to the base of the Oligocene unconformity (in time). K-1 = Kupe-1, KS-1 = Kupe South-1, KS-2 = Kupe South-2, KS-3 = Kupe South-3, KS-4 = Kupe South-4, KS-5 = Kupe South-5. Inset map relates location of the Kupe South Field to the remainder of the Taranaki Basin. Figure modified from Schmidt and Robinson (1990).

Farewell Formation sediments have previously been interpreted as alluvial fan, braided stream, and meandering stream deposits within a coastal plain setting (Robinson 1989, Schmidt and Robinson 1990). These workers divided the formation into four sand units (A-D), the uppermost being the A sand, the lowermost, the D sand. These sands form major thinning- and fining-upward cycles on seismic reflection profiles, each about 150-200 m thick, interpreted as a series of transgressive terrestrial cycles (Schmidt and Robinson 1990). The bases of these cycles are sand-dominated, with tops characterised by mudstones up to 25 m thick.

Farewell Formation sediments were derived mainly from the south, with subordinate contributions from paleotopographic highs that flanked the Manaia sub-basin (Schmidt and Robinson 1990, King and Thrasher 1996). To the north (ie down depositional dip), the formation grades into and interfingers with marine mudstones of the Turi Formation (King and Thrasher 1996). To the south,

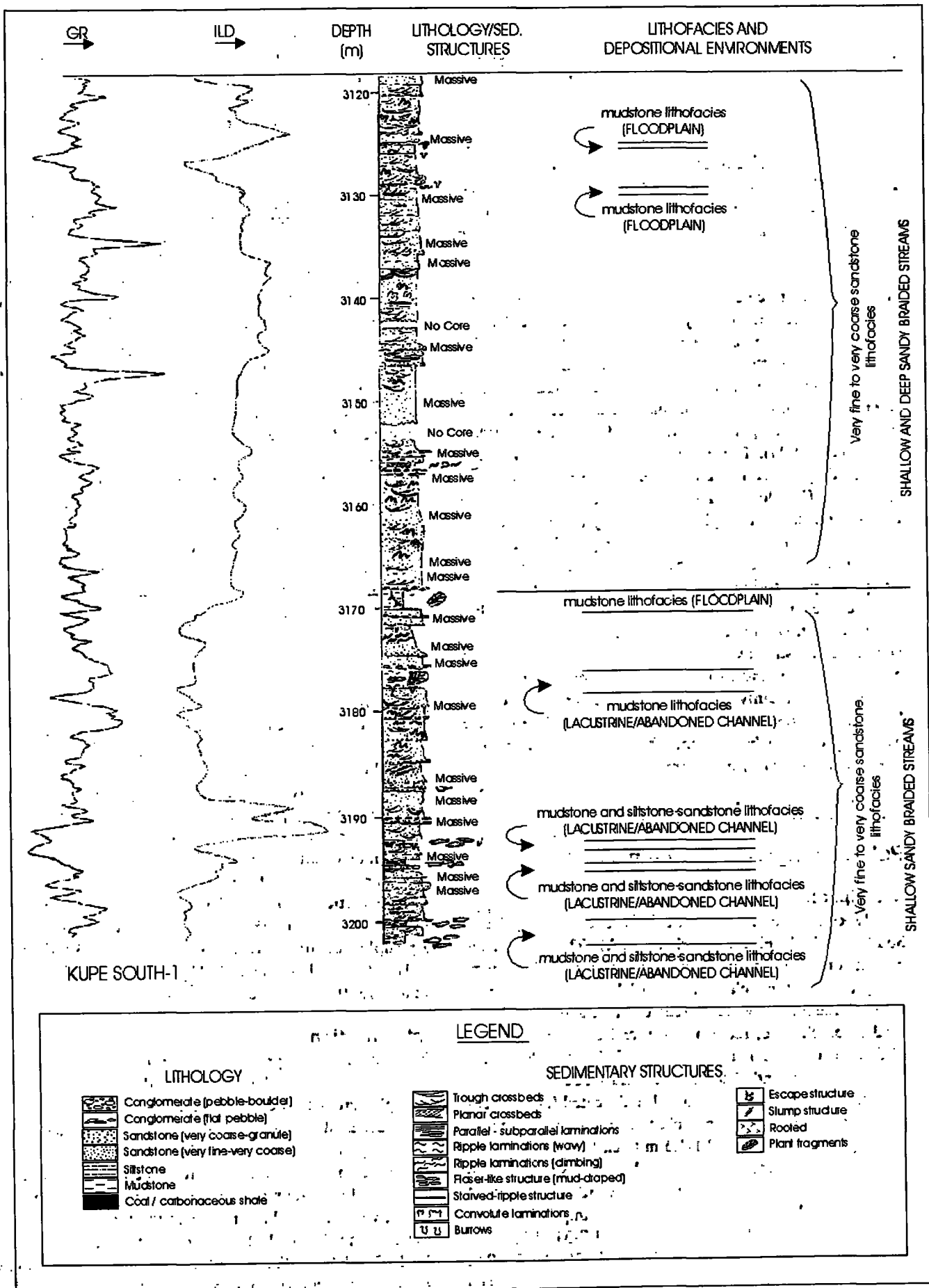


Figure 2. Lithologic, gamma, and resistivity logs for Kupe South-1.

in the northwest Nelson area, Farewell Formation comprises similar lithofacies to those in Kupe South Field, deposited in similar environmental and structural settings (Titheridge 1977, Bal 1994, Bal and Lewis 1994, Wizevich 1994, Stark 1996).

Biostratigraphic studies on each cored interval by Pocknall et al (1987), Pocknall et al (1989), and Morgans and Pocknall (1988, 1991) indicate that the majority of the Farewell Formation is terrestrial. Several dinoflagellate-bearing intervals indicate occasional marine transgressive events.

At the reservoir scale, considerable lateral continuity and vertical connectivity of pay zones are controlled by the original stratigraphic distribution of lithofacies. In addition, cross-cutting northwest-southeast trending faults strongly compartmentalise the field. At a smaller scale, reservoir quality of sandstones has been strongly influenced by diagenesis (Martin 1989, Martin 1991, Martin et al 1994). These workers recognised a lower and upper, diagenetically controlled subdivision of the reservoir. The lower zone is marked by pervasive chlorite/smectite with high microporosity (average 18.8%) and relatively high permeability (average 130 md). The upper zone is characterised by an abundance of kaolinite and partial pore-filling by ferroan carbonates that typically have reduced porosity (average 14.9%) and permeability (average 18 mD). In the lower zone, reservoir quality is controlled mostly by grain size and the presence of chlorite/smectite, and in the upper zone, reservoir quality is controlled mainly by the presence or absence of kaolinite. The reservoirs are sealed by marine shales of the overlying Otaraoa Formation, which lies above a regional erosional unconformity of Oligocene age.

Sedimentary Lithofacies

Pebbly conglomerate lithofacies

Description

Pebbly conglomerate is particularly abundant in Kupe South-2 and -4 (Figures 3, 4, and 6A). This lithofacies consists of pebble- to boulder-sized, mostly black, brown, and grey mudstone clasts up to 10-15 mm in diameter. Less abundant grey and red chert, quartz, feldspar, sandstone, siltstone, red ironstone, and coal pebble clasts (3-5 mm diameter) also occur. Mudstone clasts are commonly subrounded to rounded and blade-shaped, and commonly display a crude- to well-imbricated fabric. Beds are normal graded and both clast- and matrix-supported. Grading defines bed sets 0.1-1.5 m thick (typically 0.3-0.6 m). Several of these fining-upward sets may be stacked vertically to form a series of fining-upward units, up to 4 m thick. Basal contacts are erosional. Examples occur in Kupe South-2 (3152.5-3153.5, 3131.7-3132.7, and 3097.7-3098 m) and -4 (3097.7-3098.5, -3089.2-3089.6, 3086-3087, 3074.2-3077.8, 3064-3066, 3059-3061, and 3053-3058.6 m).

Interpretation

This lithofacies was deposited as gravel bedload in braided fluvial channels. The occurrence of normal grading and crude- to well-developed imbrication indicates traction deposition with clasts rolling on the river bed. The fining-upward trend represents waning flow strengths during deposition, with high energy and erosion at the base of these flows.

Pebbly sandstone lithofacies

Description

This lithofacies consists of fine to very coarse sandstones with interbedded granular to pebbly conglomerates in sharp to gradational contact. Pebble clasts are up to 15 mm in diameter, and dominated by black to grey mudstone, with subordinate grey and red chert, quartz, and coal fragments (Figure 6B). The clasts are typically flattened, and subangular to rounded. Beds display erosional bases and range in thickness between 0.1 and 0.5 m. Pebbly conglomerate beds are grey, massive, normally graded, imbricated, and mainly clast-supported. Fine to very coarse sandstones comprise buff to light grey, fining-upward units as much as 11 m thick. Several fining-upward units, each 0.5 to 2.0 m thick, may be stacked vertically. These fining-upward sandstones show a "salt and pepper" texture (Krynine 1950), which reflects the mixing of pale quartz and feldspar with dark rock fragments (Figure 6C). Beds are poorly to well-sorted, massive or trough cross-bedded (2-50 cm height). Subordinate sedimentary structures include wavy and climbing ripples (4-10 cm thick sets), subparallel-parallel laminae (3-40 cm thick), and convolute laminae. Trough cross-bed set thickness decreases upward, and beds are usually capped by wavy or climbing ripples. Rootlet structures consist of singular or branching tubules of carbonaceous and/or ferruginous matter, and commonly occur at the top of singular or stacked fining-upward cycles. Burrows are simple vertical tubes (1 mm wide and 5 mm long) and occur with root marks and wavy or climbing ripples. Examples occur in Kupe South-1 (3155-3200 m), -2 (3186-3197, 3174-3186, 3124.4-3131, 3116.5-3117 m), and -4 (3105-3112 and 3067-3068.5 m).

Interpretation

This lithofacies represents deposition in sandy braided streams, in which channels were floored with pebbles. Trough cross-bedded sandstones are interpreted as subaqueous dunes that were probably deposited in the deeper parts of the channels. Mudstone clasts may represent bank cave-in or reworked older overbank material. Fining-upward sandstones mark the waning of flows, with the climbing ripples at the top of these cycles, representing the final phase of deposition from suspended load. Rootlets in the top of these fining-upward cycles represent temporary to permanent stabilisation of these depositional units in a subaerial setting.

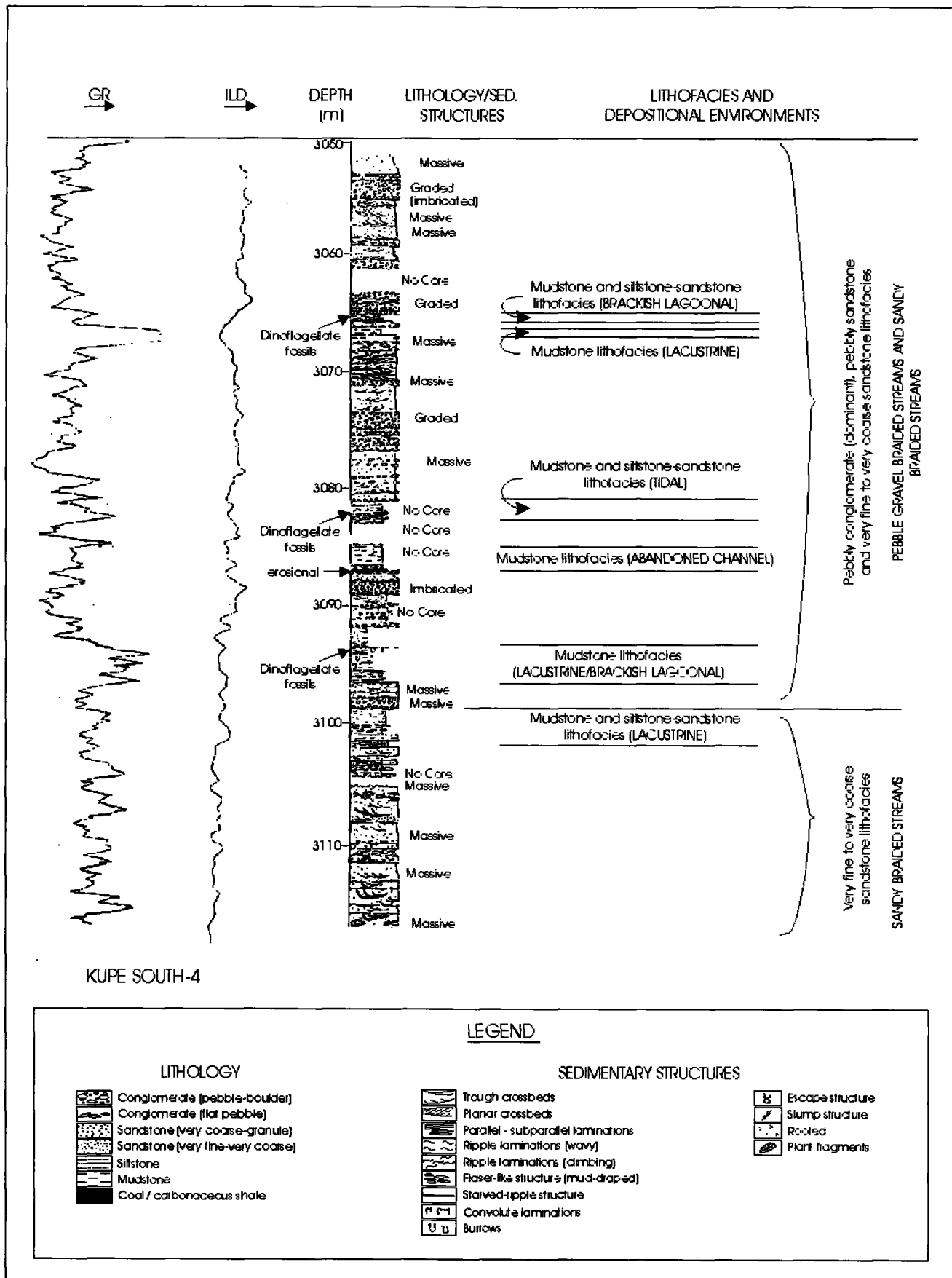


Figure 4. Lithologic, gamma, and resistivity logs for Kupe South-4.

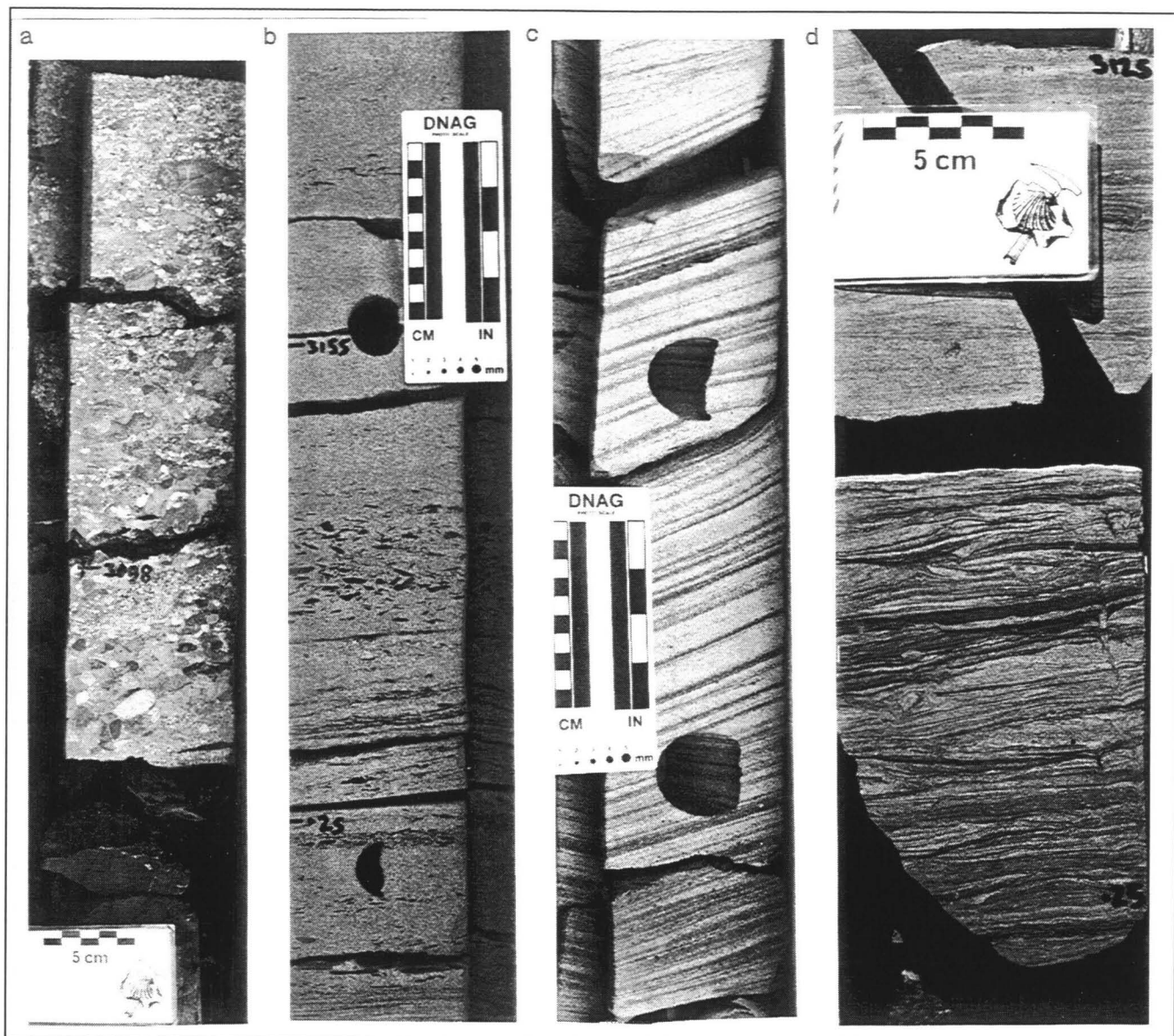


Figure 6. (a) Pebbly conglomerate lithofacies from Kupe South-2, 3098 m. Note the range of clast size, well-developed rounding for the majority of clasts, and general fining-upward trend in clast size. Scale bar is 5 cm. (b) Pebbly sandstone lithofacies in Kupe South-2, 3155 m. Note the mudclast horizon in centre of view. Scale bar in centimetres and inches. (c) Very fine to very coarse sandstone lithofacies in Kupe South-4, 3069.8 m, here showing well-developed trough cross-bedding. Scale bar is in centimetres and inches. (d) Very fine to very coarse sandstone lithofacies in Kupe South-1, 3125 m, showing ripple lamination and small-scale wavy bedding. In the lower block, vertical and near vertical tubules cut the laminae, and probably represent small-scale burrows or rootlet structures. Scale is 5 cm.

cycles. Climbing ripples are most common in the upper part of fining-upward intervals. Rootlet structures occur as single tubules, with walls lined with coaly or carbonaceous matter, and typically occur at the top of fining-upward sandstone intervals (Figure 6D). Vertical and inclined burrows, up to 7 cm long, are common in climbing ripple-laminated intervals. Open and closed (some carbonate-filled) fractures up to 15 cm long are present. Examples of this lithofacies occur in Kupe South-1 (3120-3150 m), -2 (3100-3115 m), and -5 (2891-2892 m).

Interpretation

This lithofacies represents a similar depositional setting to the pebbly sandstone lithofacies, and differs only in grain size and the presence of planar cross-beds that indicate deposition in cross-channel bars. Perhaps the presence of planar cross-beds

is the result of their greater preservation potential in the finer grained and perhaps lower energy, very fine to very coarse sandstone lithofacies. Shoaling waters promoted the formation of small wave ripples (wavy ripple laminae) and suspended deposition (climbing ripple laminae) in the upper parts of this lithofacies. Plants colonised and animals bioturbated braid bars and abandoned channels, and are prevalent at the upper parts of the fining-upward cycles.

Mudstone lithofacies

Description

The mudstone lithofacies varies in colour from light grey to greenish grey to black, depending on the amount of organic matter present. Mudstone beds are 0.1-2.0 m thick, and contain micaceous fragments (biotite and muscovite)

and finely macerated plant material. Quartz and feldspar grains occur dispersed or in discrete lenses within the mudstone. X-ray diffraction (XRD) analysis of Kupe South-2 samples (at 3171.75 and 3173.1 m) indicates a composition dominated by iron-rich chlorite and mixed layer illite/smectite, with less abundant discrete smectite and illite. The mudstone is either massively or faintly bedded, with bedding marked by plant remains, including coalified lenses 1-2 mm thick, and micaceous fragments. Massive mudstone may be sparsely to heavily rooted or burrowed. Root marks consist mainly of coalified inclined tubes and may be associated with coalified, calcareous stump-like structures. Slickensides are associated with the rooted horizons. Basal contacts are gradational or sharp and may be erosive. Examples occur in Kupe South-2 (3182-3186 and 3160.5-3173 m) and -4 (3094-3097.5 m).

Interpretation

The mudstone lithofacies occurs in the upper part of fining-upward cycles, and is interpreted as abandoned channel, floodplain, and lacustrine deposits. Erosional-based, rooted, and plant-rich mudstones (eg Kupe South-2: 3116.8-3118 m) interbedded with the coarse-grained lithofacies represent abandoned channel deposits. Sharp- and gradational-based, rooted, and plant-rich mudstones (eg Kupe South-2: 3098.5-3099.8 and 3168.3-3170.3 m) represent distal floodplain deposition in standing bodies of water (lakes). This lacustrine interpretation is supported by the presence of *Botryococcus* and well-preserved cuticle material at 3169.5 m in Kupe South-2 (J I Raine pers comm 1998). Mudstone lithofacies with root marks, tree stumps, and slickensides are interpreted as paleosols. Two paleosol types are possible; the presence of root marks and burrows suggests mollisols (Retallack 1988), while the occurrence of swelling clay giving rise to slickensided surfaces suggests development as vertisols (Retallack 1988). Abundant amorphous kerogen occurs in this lithofacies at 3171.75 m in Kupe South-2 indicating that a good source rock potential may exist for these mudstones in the Kupe South Field.

Lenticular-bedded mudstone lithofacies

Description

This lithofacies consists of grey, black, and red-brown mudstone with intercalations of silty and sandy lenses up to 25 mm thick. The lenses are horizontal to wavy and often appear as flaser-like structures. Internally these lenses are rippled, parallel-laminated, and vertically burrowed (burrows up to 10 mm wide and 25 mm long - Figure 7). A few laminae sets show bipolar ripple orientations. The mudstone is unburrowed to moderately burrowed, with vertical burrow structures 5-10 mm wide and 15-20 mm long. The mudstone is in places rooted, and contains abundant plant leaves and woody fragments. Examples of this lithofacies occur in Kupe South-1 (3194-3194.7 and 3192.4-3193 m), -2 (3182-3183, 3160.3-3173, and 3134-3141 m), -4 (3065-3066 m), and -5 (2910.8-2911.5 m). Dinoflagellates have previously been

recorded in this lithofacies in Kupe South-4 between 3081.5 and 3082.5 m (Pocknall et al 1989), and in Kupe South-5 between 2910.8 and 2911.5 m (Morgans and Pocknall 1991). Additional sampling of this lithofacies at 3065.7, 3081.3, and 3093.5 m in Kupe South-4 (Figure 3), and 2911.5 m in Kupe South-5 (Figure 5), indicates the presence of dinoflagellates (J I Raine pers comm 1998).

Interpretation

The presence of flaser-like structures, bipolar ripple laminae, vertical burrows, and dinoflagellates are consistent with an intertidal depositional setting (Nio and Yang 1991, Flores and Johnson 1995, Flores and Sykes 1996). The presence of abundant *Spinizonocolpites*

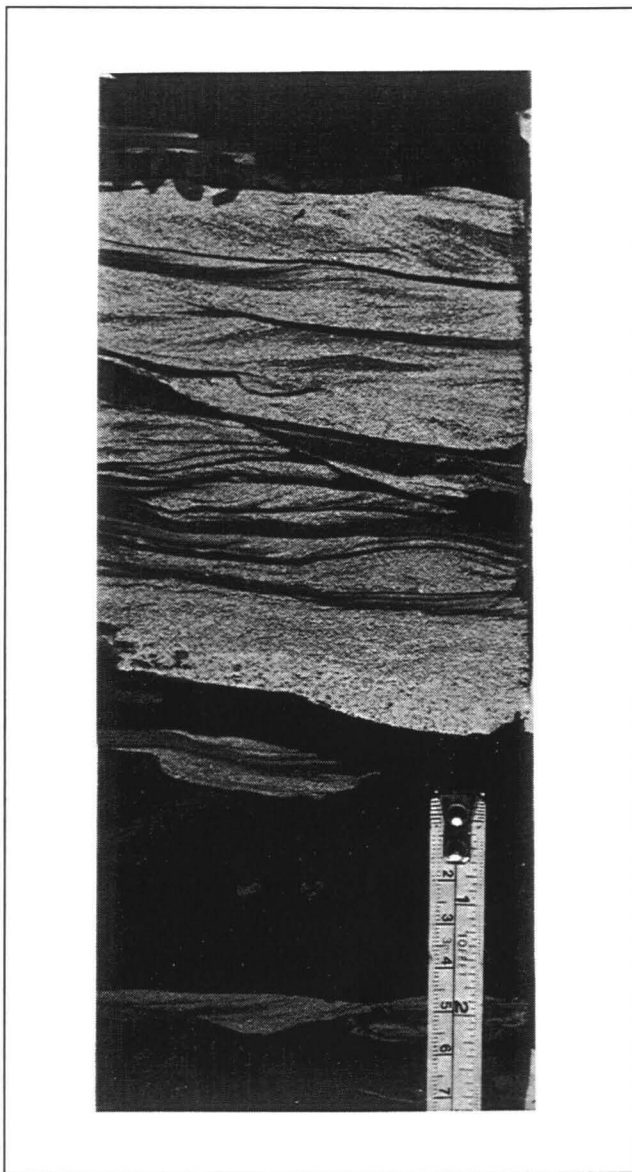


Figure 7. Lenticular-bedded mudstone lithofacies from Kupe South-2, 3065 m. Note the bi-directional ripples at the top of the core (possible herringbone cross-stratification), and the graded nature of the sandstone above the scale. Scale is in centimetres and inches.

prominatus pollen in the sample from 3065.7 m, Kupe South-4, is further evidence of marginal marine conditions,

parts of the floodplain were exposed to weathering and pedogenesis.

Kupe South-4

The lithofacies association in this well (Figure 4) is dominated by thin (0.1-1.5 m), pebbly gravel braided stream deposits. These are overlain by 0.5-2 m thick pebbly sandstone and very fine to very coarse sandstone lithofacies. This association suggests deposition within shallow, gravelly braided streams. Following abandonment, channels were filled with fines. At least one of these fine-grained intervals was tidally influenced.

Kupe South-5

The lithofacies association in the middle and upper parts of the core (Figure 5) is interpreted as meandering to braided stream deposits. The upper part, which consists of multistorey, thin- and thick-bedded, fining-upward sandstones, suggests deposition in shallow and deep sandy braided streams, respectively. The middle part of the core (Figure 5) consists of a series of fining-upward sandstone cycles, capped by lenticular-bedded mudstone lithofacies.

These cycles likely represent lateral accretion on point bars in meandering streams. The lower interval of the core (below 2910.7 m) is organic-rich, and although considered by Duff and Elliot (1991) to represent part of the coal-bearing Puponga Member, North Cape Formation, this would appear to conflict with the middle Teurian age determined by Morgans and Pocknall (1991). The Puponga Member is traditionally regarded as Late Cretaceous in age (King and Thrasher 1996). Considering both the age relationships and similar sedimentologic attributes to other Kupe South cores, we place all of the Kupe South-5 core within the Farewell Formation.

Reservoir Character

Braided stream deposits are difficult to model as hydrocarbon reservoirs (Miall 1988, Martin 1993). Problems occur because of the inherent heterogeneity of facies types, stratal architecture, lateral extent and nature of bounding surfaces, and the range of dimensions represented by the ancient braided channels. All these variables result in widely variable porosity and permeability through the reservoir. Developing reservoir models that adequately address these variables has proven problematical in fluvial depositional settings (Miall 1988, Martin 1993, Webb 1994). Any conclusions that we might draw regarding the reservoir character in Kupe South Field is limited, for we can only assess 1D well data.

Notwithstanding the difficulties of adequate reservoir prediction and modelling, our core-based study has revealed several encouraging reservoir attributes of the Farewell Formation:

1. The sediments are moderately to well sorted, with little interstitial clay or silt. Sorting and lack of mud promote favourable porosity and permeability. The range of sorting and grain size contributes to the wide variation in permeability noted by Mathews and Bennett (1987). Typically, permeabilities range from 1-1000 md, with an average of 100 md (Figure 8; Mathews and Bennett 1987). In Figure 8, average permeabilities for each of the four Kupe South wells studied are presented for the three coarsest lithofacies described in this paper. These data exclude very low permeability values from calcareous concretions. The highest recorded permeability of 1750 mD occurs in the very fine to very coarse sandstone lithofacies, which in most wells has the highest permeability, averaging 800 mD. The pebbly conglomerate lithofacies has the most variable permeability, and has the lowest overall permeability (average = 26 mD) of the three coarsest lithofacies (Figure 8).
2. Although the bases of depositional cycles may be erosional and marked by pebbles, the core suggests that they tend not to be mud-lined. In a 3D sense, these bounding surfaces should not significantly impair the lateral and vertical migration of hydrocarbons. Mud-lined bounding surfaces often significantly reduce reservoir communication and connectivity (Miall 1988). From the core data alone, we can not determine the scale of the ancient channels, and hence the lateral extent of these erosion surfaces.
3. The stacked nature of the conglomeratic and sandy lithofacies favours a thick total reservoir interval with high net:gross ratio of these lithofacies. Net sand in the cores is approximately 75%, and if this is representative of the reservoir interval as a whole, communication within the reservoir should be very good. The northwest-southeast faults in the field could compartmentalise the reservoir, though communication might be good within discrete fault blocks. Indeed, vertical communication and lateral connectivity may be enhanced between reservoir sands due to this faulting, especially if the faults are not smeared with gouge.
4. The fine-grained lithologies (mudstone lithofacies) at the top of depositional cycles, are probably geographically restricted lithologies related to the dimensions of the abandoned channel or flood plain. However, these mudstones may have been deposited more extensively over the field during periods of major channel avulsion, or braidplain subsidence. The brackish-marine transgressive surface recognised in Kupe South-4, for example, might extend over a wide area and act as an effective intra-reservoir seal. Transgressive muds of this type are likely to be more common to the north, based on the regional studies of King and Thrasher (1996). Similar

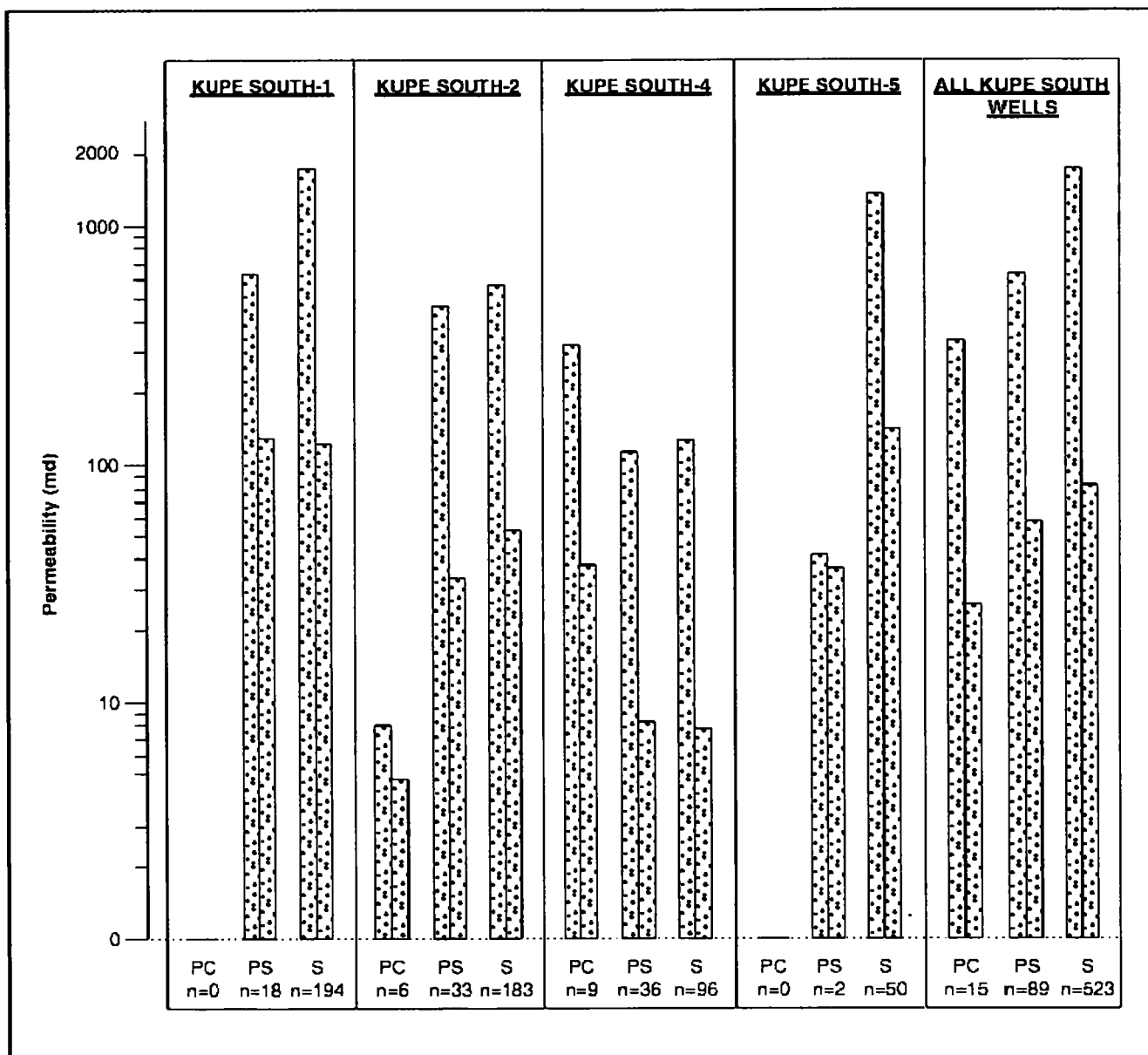


Figure 8. Summary of permeability for three conglomerate and sandstone lithofacies in the Kupe South Field. PC = pebbly conglomerate, PS = pebbly sandstone, and S = very fine to very coarse sandstone. Bar plots include data from Kupe South-1, -2, -4, and -5 wells. These data have been summed as "All Kupe South Wells." The bar on the left for each respective well is the highest recorded permeability; the bar on the right is the average permeability for this lithofacies in each respective well. Permeability measurements by Murray Helm, Core Laboratories.

marine transgressive units may exist in other (non-cored) parts of the reservoir and may offer scope for field-wide correlation.

Summary

Sandstones and conglomerates of the Paleocene Farewell Formation serve as major reservoirs for hydrocarbons in the Kupe South Field, Taranaki Basin. Cores through Farewell Formation in Kupe South-1, -2, -4, and -5 wells, indicate greater variability in depositional environment than previously recognised. Fine to very coarse sandstone and pebble conglomerate lithofacies display sedimentary structures consistent with deposition in braided streams. These coarser grained lithofacies are interbedded with

mudstone-dominated lithofacies consisting mostly of rooted, carbonaceous mudstone, and thinly interbedded sandstone and mudstone. These latter lithofacies formed in vegetated backswamp and/or lacustrine environments. Sedimentary structures and the presence of dinoflagellates in some of these beds also indicate paralic depositional settings.

The sandstone and conglomerate lithofacies form reservoirs that are internally heterogeneous, and contain, and are separated by, erosional bounding surfaces. Favourable permeabilities exist in coarse-grained lithologies, and average 800 mD in the very fine to very coarse sandstone lithofacies. Mudstone-dominated lithofacies are likely to form localised intra-reservoir seals.

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