

# Diagenesis of the late Cretaceous Kawau sandstone, Great South Basin, New Zealand: Implications for reservoir potential

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## Abstract

The distribution of the Late Cretaceous Kawau Sandstone is known from well penetrations and seismic correlation. The unit is 15-40 m thick and generally consists of kaolinitic, quartzose sand.

The composition of the Kawau Sandstone is variable. In the Hoiho-1C well the unit ranges from a moderately to well sorted, subangular, medium, subfeldsarenite to lithic feldsarenite. In Kawau-1A the unit ranges from a well to a moderately to poorly sorted, subangular, medium to coarse, sublitharenite to litharenite. This variation in composition may largely reflect differences in diagenetic histories rather than the original composition at the time of deposition.

The diagenetic sequence observed in Hoiho-1C is inferred to be: framboidal pyrite development, partial feldspar dissolution, partial alteration of muscovite to illite/kaolinite intergrowths, kaolinite precipitation. This diagenetic sequence is consistent with the estimated present day formation temperature of 70°C.

The diagenetic sequence observed in Kawau-1A is inferred to be: framboidal pyrite development, siderite precipitation, feldspar and siderite dissolution, partial alteration of muscovite to illite/kaolinite intergrowths, kaolinite precipitation, hydrocarbon emplacement, kaolinite precipitation, authigenic quartz precipitation, illitization of kaolinite, euhedral pyrite precipitation. This diagenetic sequence is consistent with the estimated present day formation temperature of 120°C.

Porosity in the Kawau Sandstone is inversely related to clay percentage. Clay percentage may be influenced by both depth and hydrocarbon emplacement. The presence of quartz overgrowths in Kawau-1A probably also reduces porosity although this effect has not been quantified.

Despite these observations flow was achieved from the Kawau Sandstone in Kawau-1A and log derived porosities from Kawau-1A sit on the high side of the regionally determined depth-porosity trend.

## Introduction

The Great South Basin lies off southeastern New Zealand (see Figure 1) with water depths generally in excess of 500 m. The bathymetry of the basin is subdued and the presence of a thick sedimentary sequence was not discovered until geophysical research cruises in the late 1960s. The basin is now known to contain mid- to Late Cretaceous and Tertiary sediments exceeding 7500 m in thickness within a series of northeast-southwest trending grabens and half grabens associated with mid-Cretaceous rifting between New Zealand and Antarctica (Cook & Beggs, 1990) (see Figure 2).

The first exploration licence covering the Great South Basin was granted in 1969. The seventies and early eighties saw a

series of seismic lines acquired and a total of eight exploration wells drilled in the basin. These wells were Takapu-1A, Toroa-1, Pakaha-1, Kawau-1A, Hoiho-1C, Tara-1, Rakiura-1 and Pukaki-1. Since 1983 the Great South Basin has received little industry attention.

The Late Cretaceous Kawau Sandstone that is the focus of this study is the reservoir in the Kawau-1A gas discovery well and has potential as a reservoir unit in the wider Great South Basin area. The Kawau Sandstone was named by Beggs (1993) who described it as "...a shallow marine sandstone..." that succeeds the unconformity separating the lower Hoiho Sequence from the upper Pakaha Sequence. Cook et al. (1999) further defined the Kawau Sandstone as a transgressive

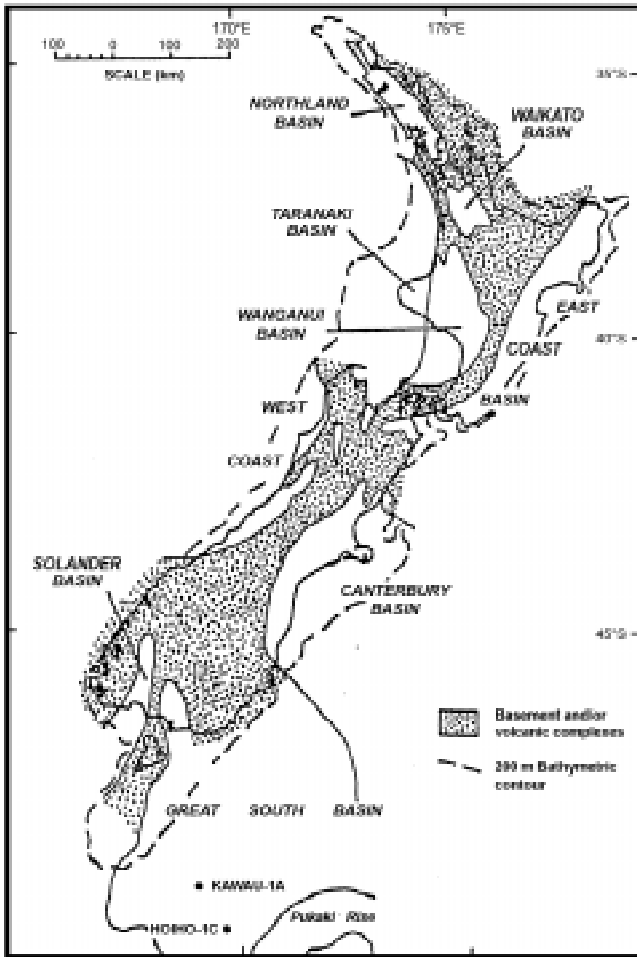


Figure 1: Map showing the position of the Great South Basin relative to other major New Zealand sedimentary basins. The Hoiho-1C and Kawau-1A wells are also shown (after Palmer & Carter, 1983).

sandstone and use the Hoiho-1C occurrence as a type section (see Figures 3 & 4).

This study uses sidewall core material from the Kawau-1A and the Hoiho-1C wells. These samples come from a wider depth range than the depth range of the Kawau Sandstone as described by Cook et al. (1999) (see Table 1). However, as the compositions, pressure and temperature conditions are very similar within the individual wells all sandy samples have been considered to be Kawau Sandstone samples for

Well	Sample Range	Unit Range
Hoiho-1C	1894 – 1949 mKB	1897-1938 mKB
Kawau-1A	3225.5 – 3396 mKB	3224-3258 mKB
Pukaki-1	NA	2980 – 2995 mKB
Rakiura-1	NA	2158 – 2176 mKB

Table 1: The depth range of samples used from the Hoiho-1C and Kawau-1A well compared to the depth ranges of the Kawau Sandstone as described by Cook et al. (1999).

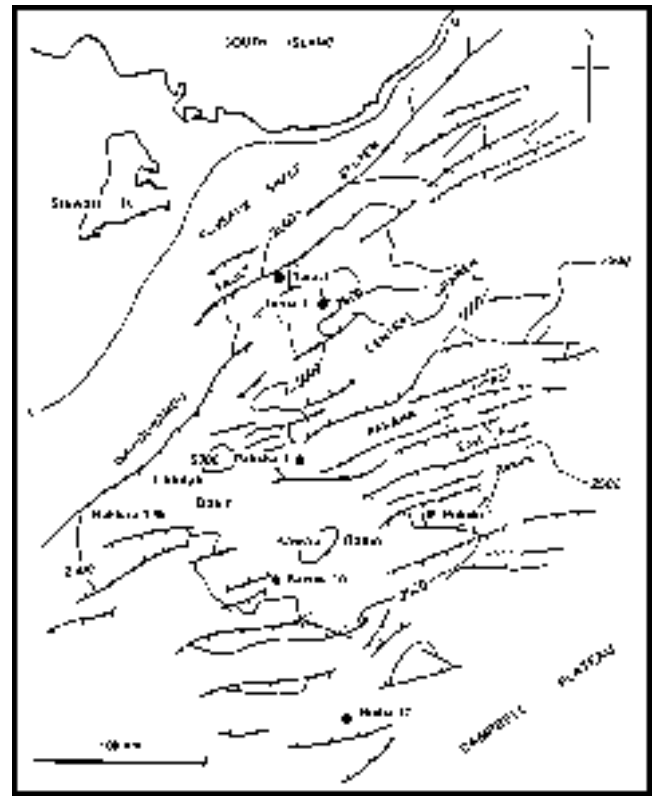


Figure 2: Structural and total sediment thickness map of the Great South. Contours are in metres (after Cook & Beggs, 1993).

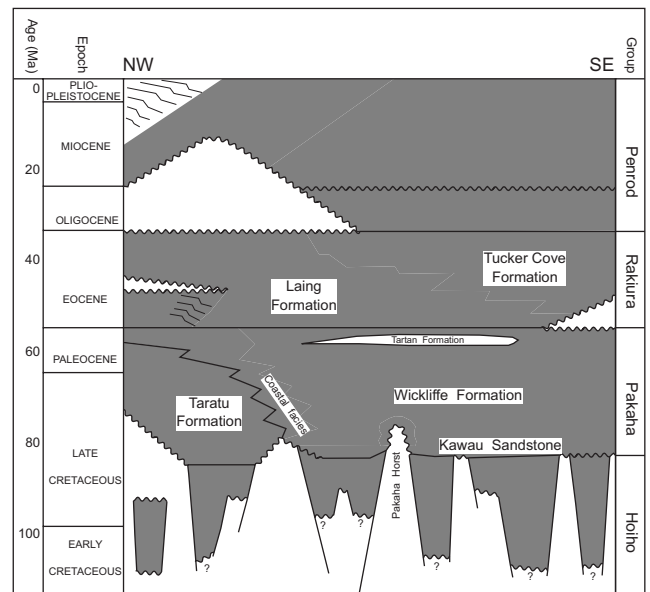


Figure 3: Schematic diagram showing the stratigraphic and tectonic relationships of the Kawau Sandstone (after Cook et al., 1999).

the purposes of this study. The samples themselves are small (0.50 to 1.89 g) and fractured by the down hole sampling process.

This paper aims to describe the composition, diagenetic sequence and influence of hydrocarbon generation on the diagenesis of the Kawau Sandstone and the implications of this on the exploration potential of the Great South Basin.

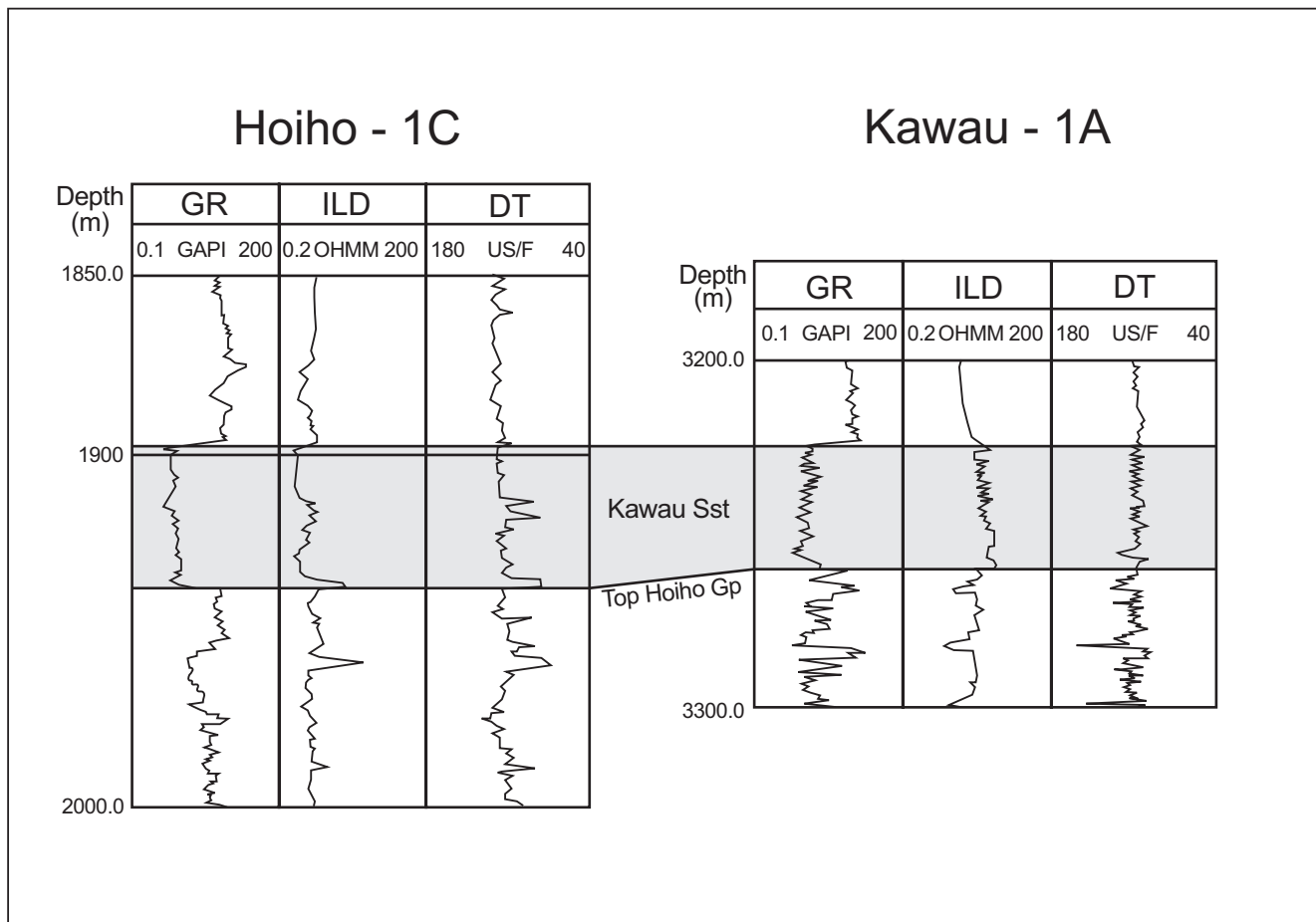


Figure 4: Log curves from the Hoiho-1C and Kawau-1A wells showing the Kawau Sandstone and the top of the Hoiho Group (after Cook et al., 1999)

## Composition

The composition of the Kawau Sandstone is relatively consistent within each of the two well sections studied although compositional variation between wells is significant. This variation in composition is discussed in **Diagenesis** section below.

### Hoiho-1C

The Hoiho-1C occurrence of the Kawau Sandstone is a moderately to well sorted, subangular, medium sand, subfeldsarenite to lithic feldsarenite according the Folk et al. (1970) classification (see Figure 5 & 6).

Approximately 70% of the detrital grains consist of subangular quartz. Monocrystalline quartz is volumetrically dominant. Polycrystalline quartz is less common, amounting to about 10% of the total quartz. Quartz containing inclusions of muscovite and tourmaline amount to about 10% and 2% of the total quartz respectively.

Detrital subangular potassium feldspar forms 10–15% of the rock volume. This consists of orthoclase and microcline in approximately equal proportions. Plagioclase displaying lamellar albite twins present in quantities very much less than 1% of the rock volume. Occasional clasts of coarse grained sericite containing fine grained quartz are also present. These are interpreted to be hydrothermally altered feldspar grains.

Muscovite is also a minor rock constituent, less than 1%.

Lithics are present in variable amounts, 4–15% of the rock volume, and are generally deformed aggregates of quartz, muscovite and clay. However, a single sample also contained granitoid lithics containing quartz and potassium feldspar

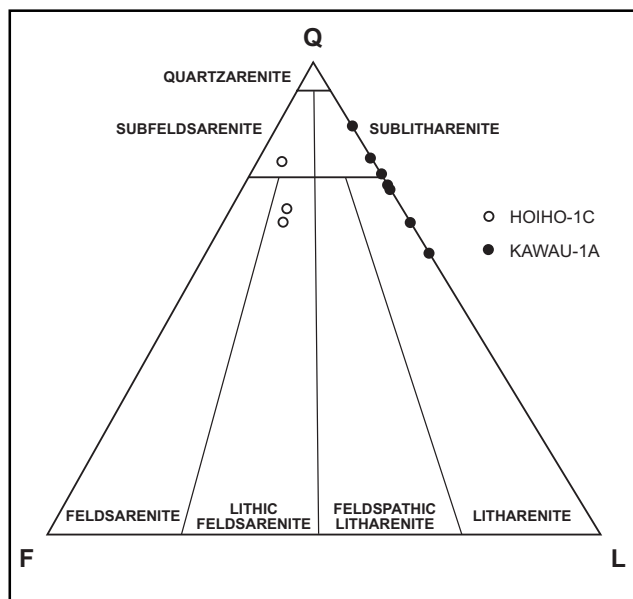


Figure 5: Composition of the Kawau Sandstone. Sandstone classification diagram from Folk et al. (1970).

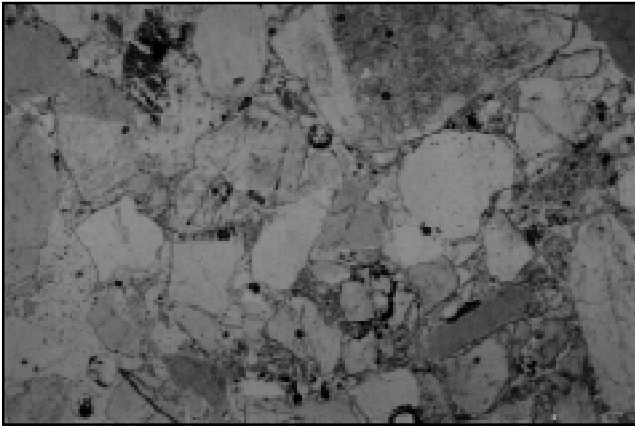


Figure 6: Typical view of the Kawau Sandstone from the Hoiho-1C well. Note the dissolving feldspar grain top right and the large pore space bottom left (plane polarized light, x70 magnification (at A4 portrait width)).

contributing to 7% of the rock volume and giving the sample an anomalously high lithic proportion of 15%.

Authigenic kaolinite cement is ubiquitous and forms 14–24% of the total rock volume. Opaques mostly framboidal pyrite form less than 2% of the rock volume. An organic stain also occurs as a band across one of the samples.

Porosity has been estimated at 6–10% under the microscope.

### Kawau-1A

The Kawau-1A occurrence of the Kawau Sandstone is a moderately to poorly sorted, subangular, medium to coarse sand, sublitharenite to litharenite as per the Folk et al. (1970) classification (see Figure 5 & 7).

Approximately 72% of the detrital grains consist of subangular quartz. Monocrystalline quartz is volumetrically dominant. Polycrystalline quartz is ubiquitous but of variable abundance, 15–50%, of the total quartz. Quartz containing inclusions of muscovite amount to between 4 and 8% of the total quartz.

Detrital muscovite are present in minor quantities, less than 5% of the total rock volume. Rare clasts of coarse grained sericite containing fine grained quartz are also present. These are interpreted to be hydrothermally altered feldspar grains as above.

The lithic component of the rock constitutes 9–21% of the total rock volume and are persevered as deformed aggregates of quartz, muscovite and clay.

Authigenic clay is pervasive forming a volumetrically important constituent of the rock, 19–30%. The clay dominantly kaolinite, however, in the pore filling clay occurrences kaolinite is associated with illite.

Authigenic magnesium-rich siderite is also present forming up to 3% of the rock volume. Opaques, dominated by framboidal pyrite, constitute up to 4% of the volume of the

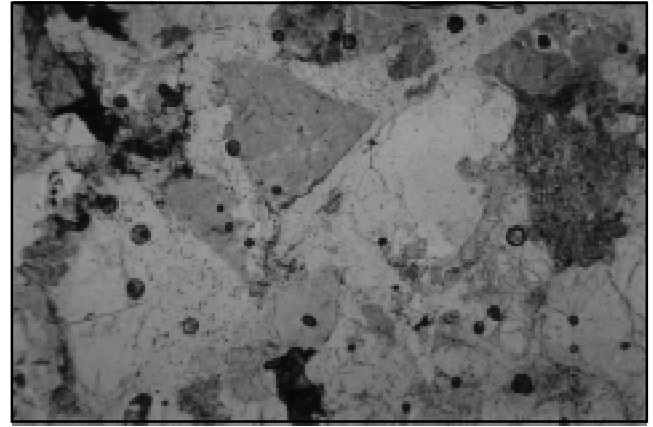


Figure 7: Typical view of the Kawau Sandstone from the Kawau-1A well. Note the absence of feldspar and the dominance of microcrystalline pore filling kaolinite left (plane polarized light, x70 magnification (at A4 portrait width)).

rock. An organic stain occurs as a band across a single sample from the Kawau-1A well.

Observed porosity varies between 1.5 and 4%.

## Diagenesis

The diagenesis of the Kawau Sandstone is a continuum that starts with diagenesis in the sulphate reduction zone and continues through to high temperature quartz overgrowth development. The most complete sequence of this sequence is recorded in the Kawau-1A occurrence of the Kawau Sandstone due to the higher present day formation temperature (see Figure 18). However, the partial sequence in the Hoiho-1C well offers valuable information on the dissolution of feldspar and a point for comparison with the Kawau-1A derived diagenetic sequence.

### Early diagenesis

#### Framboidal pyrite

Framboidal pyrite is present in all the samples from both wells and constitutes about 1% of the rock volume. The individual framboids of pyrite are 20 to 50  $\mu\text{m}$  across and occur in pore spaces that have been infilled by authigenic kaolinite. This is taken as indicating the framboids pre-date the kaolinite, however, this does not tightly constrain the timing of framboidal pyrite precipitation.

Framboidal pyrite is common in sediments of marine origin (Gautier et al., 1985) and forms by inversion of the first products of sulphate reduction, metastable acid-soluble iron sulphides (Sweeny & Kaplan, 1973). As such, framboidal pyrite is inferred to be the earliest authigenic mineral in the Kawau Sandstone samples.

#### Siderite

Authigenic siderite occurs in the Kawau Sandstone samples from the Kawau-1A well as rhombs, commonly displaying features of dissolution in areas between and sometimes containing framework grains. Framboids of pyrite are sometimes contained within the siderite rhombs. Quartz

overgrowths enclosing remnants of partially dissolved siderite have also been observed (see Figure 8).

Elsewhere siderite has been identified as both an early and a late diagenetic feature (Warren, 1987; Surdam et al., 1989). Three lines of evidence from the Kawau-1A samples suggest that the siderite in the Kawau Sandstone is an early diagenetic feature. Mudrocks have in some cases been deformed around siderite rhombs during compaction suggesting that siderite precipitation preceded significant compaction. Gautier et al. (1985) and Mozley (1989) have used this as evidence of early diagenesis in the past. Siderite has been precipitated directly on to framework grains without an intervening claycoat. Hansley & Whitney (1990) used this as evidence of diagenetic siderite being an early feature. The enclosing of remnants of siderite by quartz overgrowths suggest that both siderite dissolution and quartz overgrowth development post-date siderite development and as such siderite precipitation is likely to be an early phase of diagenesis.

The siderite in the Kawau Sandstone has been analysed using an electron microprobe and found to be a magnesium rich form of siderite. This is rare in fresh-water early diagenetic siderite but common in early marine diagenetic siderite (Mozley, 1989). The distinction between fresh-water and marine origin is possible because the early diagenetic siderite effectively records the early pore-water chemistry (Matsumoto & Iijima, 1981). The interpretation that the siderite is marine in origin is consistent with other evidence suggesting that the Kawau Sandstone is a marine transgressive sand.

The precipitation of siderite is commonly associated with early biogenic methane in the methanic zone (Gautier et al., 1985; Hansley & Whitney, 1990; Mozley & Carothers, 1992). Methanic zone biogenic methane occurs under specific conditions at temperatures below 50°C (Claypool & Kvenvolden, 1983). In marine sediments methane production does not occur at maximum rates until more than 80% of the  $\text{SO}_4^{2-}$  is depleted (Nikaido, 1977). Depletion of  $\text{SO}_4^{2-}$  may be achieved through reduction and pyrite precipitation

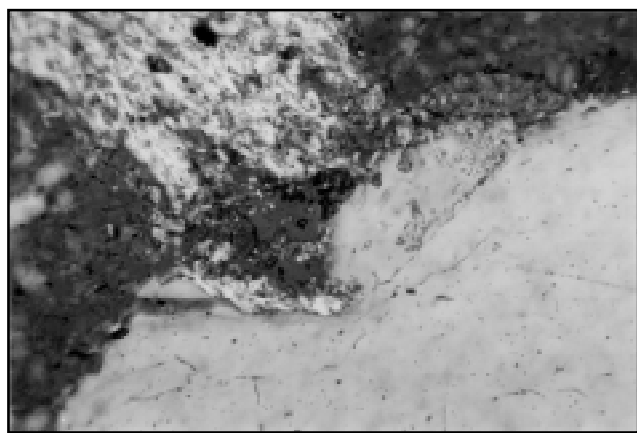


Figure 8: Partially dissolved siderite rhomb surrounded by later authigenic quartz. Note the siderite remnants share a common optical orientation (cross polarised light, x400 magnification (at A4 portrait width)).

(Gautier, et al. 1985), thus the association of early diagenetic siderite and early authigenic pyrite should be expected. This association of siderite with pyrite is often reported in the literature (Hansley & Whitney, 1990; Mozley & Carothers, 1992) and is observed in the samples from Kawau-1A.

The source of iron for the precipitation of iron rich minerals, pyrite and siderite, in the early diagenesis of the Kawau Sandstone remains uncertain.

The siderite dissolution noted above is addressed below.

## Hydrocarbon-related diagenesis

The key features of hydrocarbon-related diagenesis observed in the Kawau Sandstone are the dissolution of aluminosilicates and siderite, and the precipitation of kaolinite and illite.

### Aluminium silicates

Detrital muscovite and feldspar are present in the Kawau Sandstone, although feldspar is present only in the Hoiho-1C samples.

Muscovite is variably altered in all samples, ranging from largely unaltered to entirely replaced by intergrowths of illite and kaolinite. The kaolinite appears to have grown as optically continuous crystals paralleling the muscovite cleavage. This growth has apparently displaced the mica parallel to cleavage as seen in back-scattered electron images (see Figure 9a). Hugget (1984) and Warren (1987) have previously described this process during sandstone diagenesis. The distribution of potassium observed using x-ray detection element mapping (see Figure 9b) shows that the distribution of potassium drops slightly from the unaltered parts of the muscovite grain to the areas of illite development. However, the drop in potassium concentration from the areas of illite development to the kaolinite intergrowths is sharp.

As noted above, feldspar is present in the samples of the Kawau Sandstone from Hoiho-1C. The feldspar is dominantly potassium feldspar, contributing to up to 16% of the rock volume. Fined grained plagioclase is also present in small amounts (less than 1% of the rock volume). All feldspar grains are partially dissolved with the degree of dissolution ranging from light etching to dissolution of all but a skeletal frame of the original grain. Plagioclase, orthoclase and microcline appear to have undergone similar amounts of dissolution, although, the small sample size of the plagioclase population makes this inconclusive.

Kaolinite is ubiquitous in the Kawau Sandstone samples from both wells. It occurs as both a microcrystalline pore-filling phase (see Figure 10) and, as noted above, as intergrowths with illite replacing muscovite (see Figure 9a).

The microcrystalline pore-filling kaolinite occurs as “books” with individual crystals approximately 20  $\mu\text{m}$  across. In general porosity is inversely proportional to the kaolinite

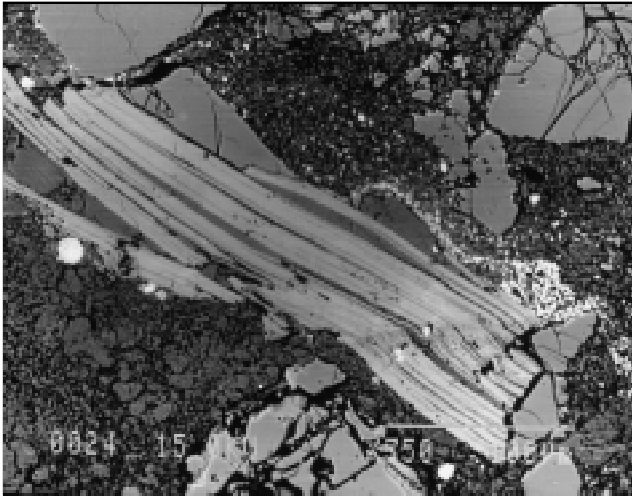


Figure 9a: Back-scattered electron image of muscovite partially altered to illite and kaolinite. The illite occurs as a compositional change within the muscovite. The kaolinite can be seen as a grey mass between the splayed muscovite cleavages. Pore filling microcrystalline kaolinite surrounds the altered muscovite.

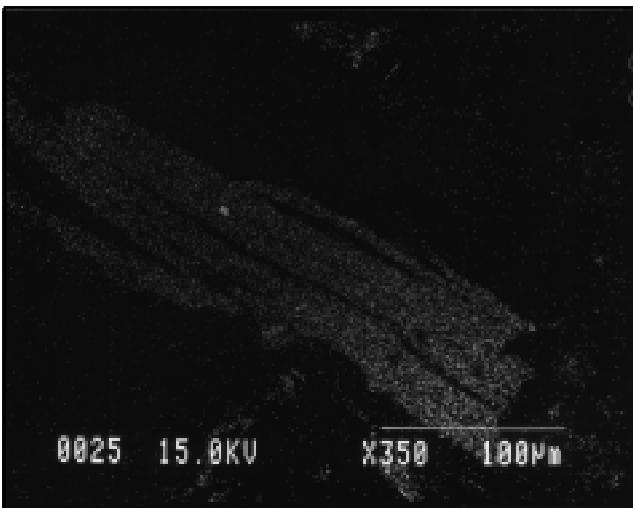


Figure 9b: X-ray detection element mapping micrograph showing the distribution of potassium.

percentage (see Figure 11) and the Kawau-1A samples contain higher proportions of kaolinite and lower porosity than the Hoiho-1C samples. Under the scanning electron microscope it is clear the pore throats in the Hoiho-1C samples are much more open than the pore throats in the Kawau-1A samples that are clogged with kaolinite (see Figures 12a & b).

In Kawau-1A there appears to be two phases of kaolinite precipitation as there are organically stained and unstained kaolinite filled zones that lie immediately adjacent to each other. This suggests that the stained kaolinite formed at a time when organic rich fluids were present in the system trapping the organics in the microporosity between kaolinite “books”. Authigenic quartz has also been observed in intimate association with kaolinite and apparently replacing it in samples from the Kawau-1A well. Illite is present within some clusters of pore filling kaolinite in Kawau-1A, apparently replacing it.

The timing of kaolinite development in the Kawau Sandstone is poorly constrained by textural relationships. However, there

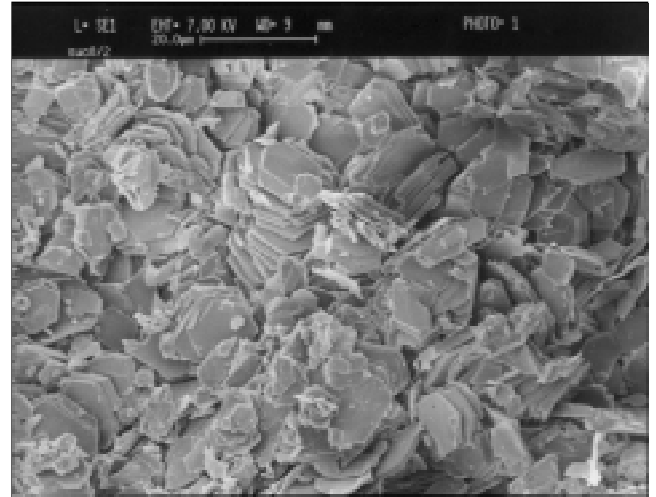


Figure 10: SEM of books of pore filling kaolinite.

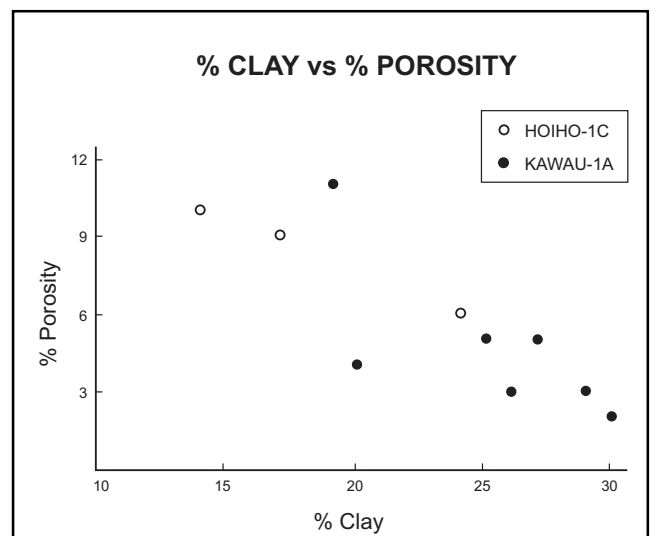


Figure 11: Clay content versus porosity for the Kawau Sandstone (from point counts of individual samples).

are at least two phases of kaolinite development which are clearly either contemporaneous with or immediately succeed feldspar and siderite (see below) dissolution; they also precede authigenic quartz development. Illitization of kaolinite appears to be a late feature (see below).

The mechanisms for the diagenesis of aluminium silicates in the Kawau Sandstone proposed here are hydrocarbon maturation-related. The need to invoke hydrocarbon maturation-related diagenesis is due to some features of the diagenesis that would otherwise be difficult to explain with conventional burial diagenesis. These features are:

- Kaolinite precipitation in the absence of meteoric water. The only other environment this commonly kaolinite precipitation occurs is related to hydrocarbon maturation (Weaver, 1989).
- Potassium feldspar dissolution without forming a claycoat. This suggests that aluminium is transported in solution away from the grain surface and is effectively mobile. The mechanism regarded as being responsible



Figure 12a: Typical SEM view of the Kawau Sandstone from Hoiho-1C.

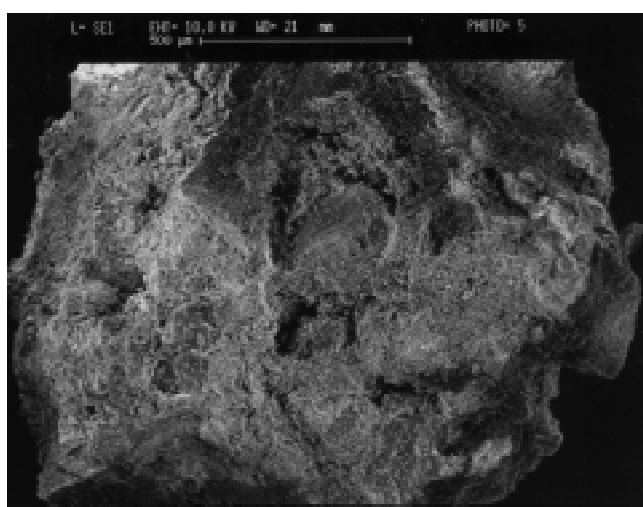


Figure 12b: Typical SEM view of the Kawau Sandstone from Kawau-1A.

for this mobility is the complexing of aluminium by carboxylic acids released during hydrocarbon maturation (e.g. Surdam et al., 1984; Surdam et al., 1989; Kharaha et al., 1985).

- Muscovite alteration to kaolinite and illite is unlikely under normal organic free diagenesis. Muscovite would be expected to alter directly to illite or to kaolinite and then possibly to illite (Weaver, 1989). The muscovite/illite/kaolinite series, described above, has however been reported to occur under some organic-related diagenetic conditions (Warren, 1987).

The presence of organic staining in samples from both wells and a known gas column at Kawau-1A also shows that hydrocarbon maturation-related compounds are likely to be available in the diagenesis of the Kawau Sandstone at the Hoiho-1C and Kawau-1A locations.

Aluminium silicate dissolution is a problem of aluminium solubility and mobility (Surdam et al., 1982). Surdam et al. (1984) found that organic acids present in oil field water increase the solubility of aluminium significantly. At the same

concentration and temperature the monofunctional carboxylic acids (a hydrocarbon chain with a single organic acid functional group attached) raise the solubility of aluminium by an order of magnitude while difunctional carboxylic acids (a hydrocarbon chain with two organic acid functional groups attached) raise the solubility of aluminium by three orders of magnitude. The increase in solubility is because the carboxylic acids can form an organic complex with aluminium that is stable in solution (see Figure 13).

The source of these carboxylic acids is the thermal maturation of kerogen (Surdam et al., 1984). The generation of carboxylic acids has been studied by Carothers and Kharaka (1978, 1980), Boudou et al. (1984), and Surdam et al. (1989). A summary of the current knowledge of the production, destruction and concentration of carboxylic acid in oil-field waters against temperature is given in Figure 14. The region of high carboxylic acid concentrations between 80 to 120°C coincides with zone of most active aluminium silicate and carbonate dissolution recognised in reservoirs worldwide (Surdam et al., 1989).

The onset of feldspar dissolution in the Hoiho-1C occurrence of the Kawau Sandstone is consistent with the estimated formation temperature of approximately 70°C (calculated using a geothermal gradient of 36°C/km (Cook & Beggs, 1990). The absence of feldspar in the Kawau Sandstone of

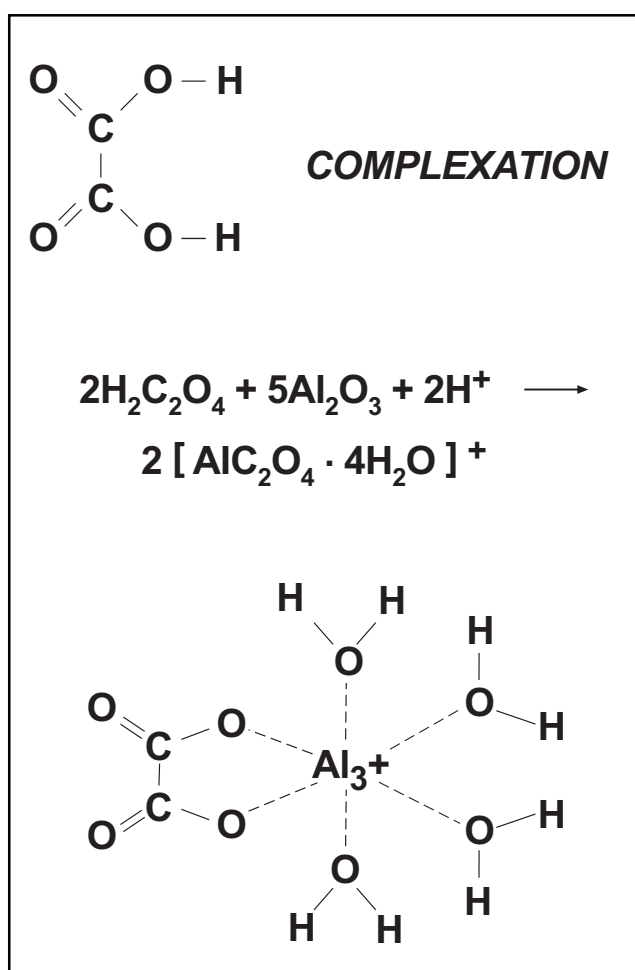


Figure 13: Diagrammatic view of the formation of an aluminium complex (from Surdam et al., 1989).

Kawau-1A is also consistent with the estimated formation temperature of approximately 120°C. It should be noted that because feldspar is entirely absent in the Kawau-1A occurrence it is not possible to definitively state that the absence is due to dissolution rather than a lack of feldspar in the original sediment. However, the higher proportion of kaolinite in Kawau-1A relative to Hoiho-1C, presence of feldspar in Hoiho-1C, and the evidence of siderite dissolution in Kawau-1A all suggest that feldspar is likely to have been present in the original sediment and subsequently dissolved and reprecipitated as kaolinite and quartz. (see below).

The question raised by the presence of aluminium in solution is “What is the ultimate destination of the mobilized material?” (Surdam & Crossey, 1985). In some cases aluminium silicate dissolution has led to porosity enhancement in these cases mass transfer must have occurred and the material has been transported away and probably ultimately forms kaolinite (Surdam & Crossey, 1985). Observations have shown that aluminium can be conserved on a thin section scale (Boles, 1984 & 1987) while in other cases aluminium has not been conserved on the centimetre scale (Moncure et al., 1984). The distance of aluminium mass transfer is probably dependent on the stability of aluminium complexes and the fluid flow through the rock. The stability of aluminium complexes is pH dependent (Small, 1993; Surdam et al., 1989). If the pH of the fluids changes significantly (e.g. if the fluid encounters carbonate rich rocks, degasses, changes temperature, or mixes with other subsurface waters) the complexes may be destabilised and precipitate kaolinite. Thus, mass transfer is dependent on fluid pH and the migration pathway including any impermeable barriers.

In the occurrences of the Kawau Sandstone in Hoiho-1C and Kawau-1A, the kaolinite precipitation appears to be dependent on several factors but mainly temperature (controlling pH) and the lack of a fluid migration pathway

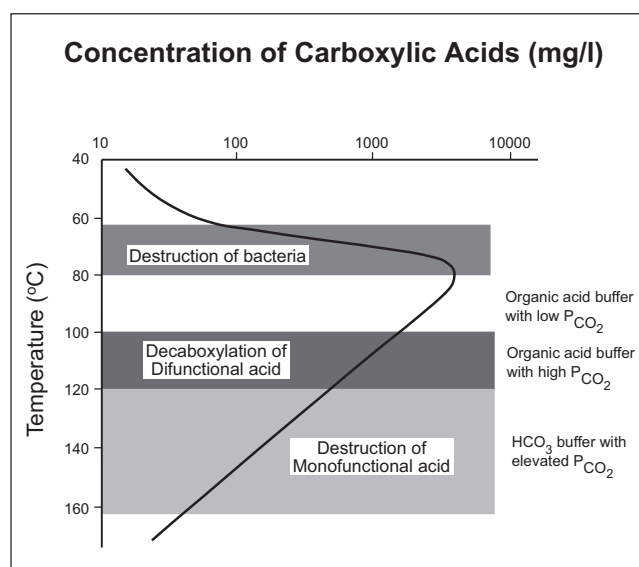


Figure 14: Maximum concentration of carboxylic acids against temperature, with the zones of carboxylic acid production and destruction shown (modified from Surdam et al., 1989).

from the well occurrences. Hoiho-1C has kaolinite in intimate association with feldspar dissolution. This may be an example of where formation fluids contain some carboxylic acids, aiding feldspar dissolution but insufficient to lower the pH sufficiently for the aluminium complexes to remain stable in solution. In Kawau-1A there are two phases of kaolinite precipitation; one organically stained, the other unstained. The unstained kaolinite may be equivalent to the early kaolinite in Hoiho-1C above; at this time any feldspar in Kawau-1A would be dissolving and precipitating kaolinite locally. The other organically stained generation of kaolinite may be a later phase that is related to an increase in temperature, lowering the concentration of carboxylic acid, and destabilising aluminium complexes in solution. As a trap is present at Kawau-1A, the aluminium complexes may have existed in solution without migrating away while the formation temperature increased from in the order of 80°C to 110°C and the aluminium complexes destabilised with decarboxylation (see Figure 14). The organic stain may be due to hydrocarbons being present in the formation fluids during the precipitation of kaolinite. These hydrocarbons would have had to have been emplaced between the two phases of kaolinite precipitation, this is consistent with the temperature range for non-precipitation of kaolinite suggested above.

#### Siderite dissolution

In some samples from the Kawau Sandstone in the Kawau-1A well, siderite is partially dissolved and encapsulated in quartz overgrowths. The siderite remnants are clearly optically single grains (see Figure 8). The timing of this dissolution is poorly constrained but predates quartz overgrowth development.

The stability of carbonate minerals is normally dependent on the pH and  $\Sigma\text{CO}_2$  (the sum of aqueous carbonates species in solution) (Surdam et al., 1989). However, between 80°C and 120°C in sediments were organic acids related to hydrocarbon carbon maturation are present the buffer effect of the acid and the  $P_{\text{CO}_2}$  (partial pressure of  $\text{CO}_2$ ) are the dominant factors (Carothers & Kharaka, 1978; Surdam et al., 1989). Near the 80°C isotherm, where the carboxylic acid anions are at a maximum, the carbonate system is buffered by the organic acid system. At this point carbonate dissolution may occur due to the pH and low partial pressure of  $\text{CO}_2$ . Above 100°C the carboxylic acids begin to decarboxylate, increasing the partial pressure of  $\text{CO}_2$ , but the pH is still constant due to the buffering effect of the carboxylic acids. Carbonates become increasingly stable and may even be precipitated. At some point between 120°C and 160°C the carboxylic acid diminishes to a level where the alkalinity of the fluid is again dominated by the carbonate system (Surdam et al., 1989). The specific path taken by the carbonate system will depend on the availability of  $\text{Ca}^{2+}$ ,  $\text{Fe}^{2+}$ ,  $\text{Mn}^{2+}$  and  $\text{Mg}^{2+}$  as well as the initial pH of the fluids.

The presence of only partially dissolved siderite being present in the Kawau-1A occurrence of the Kawau Sandstone may be explained by the partial dissolution occurring between 80°C and 100°C while the pH of the carboxylic acids

dominated the carbonate system. As the temperature increased the decarboxylation of the organic acids would increase the partial pressure of CO<sub>2</sub> halting siderite dissolution.

## Late diagenesis

### Illitization of kaolinite

Partial alteration of kaolinite to illite is common to all samples of the Kawau Sandstone from Kawau-1A. Illitization of kaolinite does not occur in the samples from Hoiho-1C. Illitization of kaolinite is common in reservoir rocks of the North Sea (Bjørlykke & Aagaard, 1992; Burley & MacQuaker, 1992). In the North Sea the illitization process is reported to occur at depths between approximately 3 and 4 km (Burley & MacQuaker, 1992) (see Figure 15), succeed hydrocarbon emplacement (Bjørlykke & Aagaard, 1992) and require temperatures of 130°C to 140°C (Bjørlykke & Brendsdal, 1986; Ehrenberg & Nadeau, 1989).

In the case of the Kawau-1A occurrence of the Kawau Sandstone the depth and timing relative to hydrocarbon emplacement are similar to North Sea occurrences, however, the temperature of illitization is slightly lower. This temperature discrepancy is not considered significant.

In order to alter kaolinite to illite a source of K<sup>+</sup> is required. In the Kawau Sandstone this would require K<sup>+</sup> to stay in solution from the initial dissolution of feldspar and muscovite at approximately 80°C to the alteration of kaolinite to illite at approximately 120°C. This seems unlikely, however, the absence of K-bearing minerals being precipitated prior to illitization and the presence of a fluid impermeable trap suggest that K<sup>+</sup> has been present in solution for this period.

### Authigenic quartz

The quartz from the Hoiho-1C samples of the Kawau Sandstone has sharp grain boundaries and is considered to be unmodified detrital quartz. In contrast the quartz grains from the Kawau-1A samples display what are interpreted to be diagenetic morphologies and associations.

The quartz grains from the Kawau-1A occurrence of the Kawau Sandstone have ragged edges and occur in intimate association with kaolinite. These ragged edges are interpreted to be due to overgrowths of quartz growing away from the original grain and possibly replacing kaolinite as it grows (see Figure 16). Further evidence of authigenic quartz growth is the enclosing of siderite remnants by quartz (see Figure 8). As such, authigenic quartz is believed to be a late diagenetic feature that is likely to be continuing to form at the present.

In the North Sea quartz overgrowths generally post-date carbonate and feldspar dissolution, and pre-date or are contemporaneous with the latest phase of illitization (Burley & MacQuaker, 1992). These overgrowths are commonly found, by cathodoluminescence, to represent multiple

generations of quartz precipitation (Burley et al., 1989; Burley & MacQuaker, 1992).

In the Kawau Sandstone cathodoluminescence has not been undertaken but it is likely that there are multiple generations of quartz overgrowths present.

### Euhedral pyrite

Euhedral pyrite is present in late, clay free, fractures and concentrated along the edges of quartz overgrowths in the Kawau-1A samples of the Kawau Sandstone. No euhedral pyrite has been observed enclosed in quartz overgrowths. The

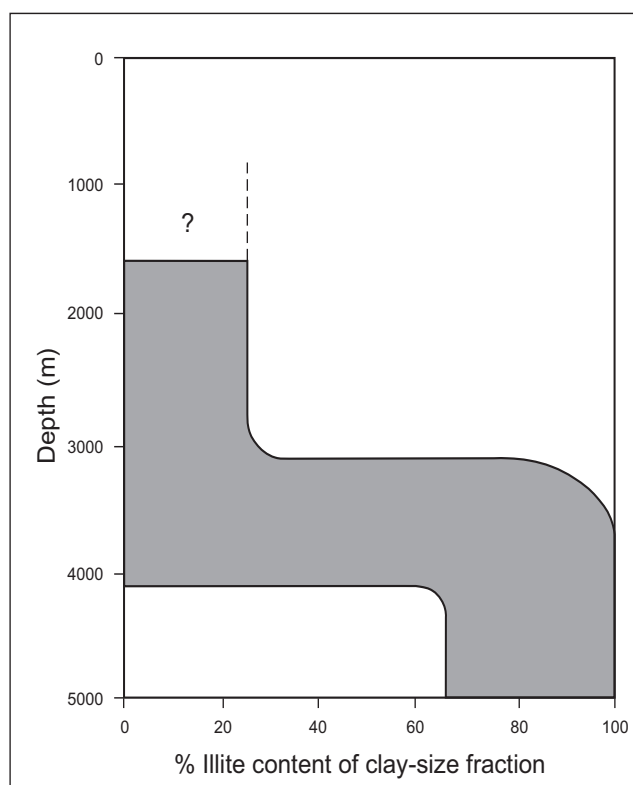


Figure 15: Proportion of illite in the clay fraction of various North Sea Jurassic sandstones versus depth (from Burley & MacQuaker, 1992).

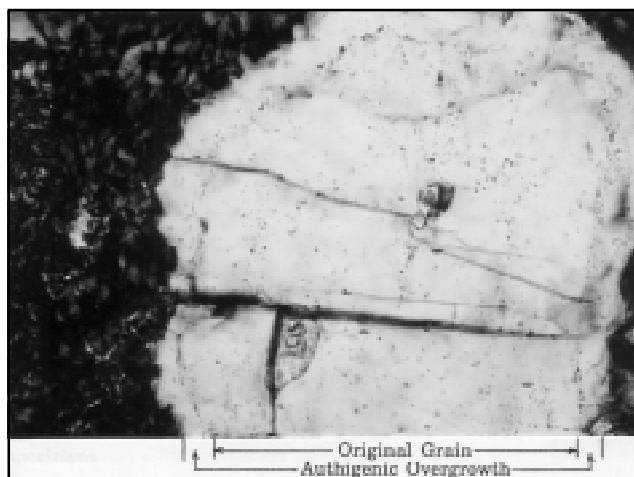


Figure 16: Authigenic quartz overgrowths on original detrital grain (cross polarised light, x400 magnification (at A4 portrait width)).

crystals are octahedral, non-magnetic with the distinctive colour of pyrite under a microscope (see Figure 17). Based on the textural relationships described above euhedral pyrite is the latest phase of diagenesis recognised in the Kawau Sandstone. It has also been described as a late diagenetic feature elsewhere by Boles (1987), Hansley and Whitney (1990), Mozley and Carothers (1992) and McMahon et al. (1992).

## Diagenetic sequence

The full diagenetic sequence for the Hoiho-1C and Kawau-1A occurrences of the Kawau Sandstone is shown in figure 18. The two occurrences are consistent with each other within range of their common temperature histories except for minor variations such as the presence or absence of siderite.

The diagenetic sequence is typical of diagenetic successions elsewhere, for example the Taranaki Basin (Cook et al., 1999) and the North Sea (Burley & MacQuaker, 1992).

## Implications for exploration

The implications of this study for the exploration potential of the Kawau Sandstone are two fold: the prediction of reservoir quality and the reservoir floor for both gas and oil. To understand these issues other facts must be considered.

- The log derived porosities for the Kawau Sandstone in both Hoiho-1C and Kawau-1A (Anderton et al., 1982; Cook et al., 1999) are much higher than estimated from thin section in this study.
- The DST of Kawau-1A well flowed gas and condensate from the Kawau Sandstone (Anderton et al., 1982). Figure 19 shows a section through Kawau Structure at Kawau-1A.

The difference between thin-section estimates of porosity and log derived porosity could be due to a combination of reasons. It is common that, even in the cleanest of samples, porosities derived from point counting are significantly lower than the log derived porosities. This may in part be due to geometrical

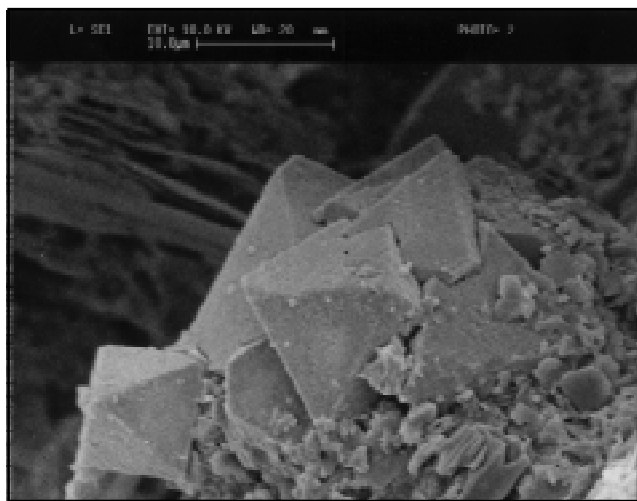


Figure 17: SEM of octahedral pyrite from the Kawau Sandstone.

sampling basis in point counting a planar surface, however, this can not be the factor here. The thin-section derived porosities for the Kawau-1A samples are generally 2-5% (one occurrence of 11%) whereas the log derived porosities are as high as 16-21% for the same well section (Anderton et al., 1982). Similarly the thin section derived porosities from the Hoiho-1C samples are 6-10% compared to the 29-34% log derived porosities well (Anderton et al., 1982). Additionally the discrepancy between thin-section and log derived porosities may be due to a thin section porosity being at most an effective porosity measurement whereas log derived porosity is a total porosity measurement. The difference between total and effective porosities in cases where pore filling clays are present can be significant and are considered important in this case.

True effective porosities for the well penetrations of the Kawau Sandstone are unknown. However, the fact that

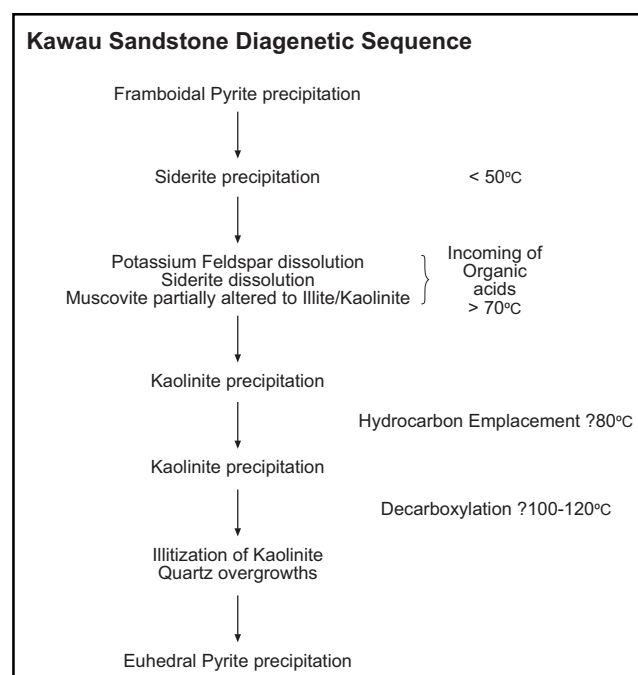


Figure 18: The diagenetic sequence observed in Kawau Sandstone

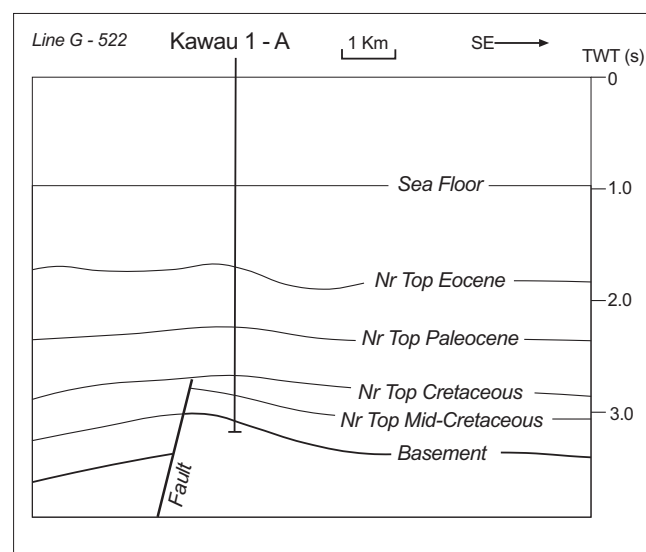


Figure 19: NW – SE section through the Kawau-1A well.

Kawau-1A flowed gas from the Kawau Sandstone suggests that Kawau-1A is above the reservoir floor for gas and probably has porosities above the 2-6% estimated from thin section. If Kawau-1A effective porosities lie above the thin section-derived value and lower than the log-derived porosities, then the same is probably true for Hoiho-1C. The Kawau Sandstone in Hoiho-1C is therefore believed to lie above the reservoir floor for oil. Therefore the reservoir floor for oil in the Kawau-1A is at least 1200 mSSF and the reservoir floor for gas is at least 2500 mSSF. Much of the Kawau Sandstone in the Great South Basin sits above the reservoir floor for gas and around structural highs (see Figure 2) above the reservoir floor for oil.

The Great South Basin has been under explored to date. The Basin has proven charge, seal and reservoir at the Kawau Sandstone stratigraphic level. As Figure 2 shows the Basin has much structural potential that warrants further investigation. Cook et al. (1999) reviewed the potential for reservoirs at other stratigraphic levels and have suggested that reservoir potential exists at several horizons from mid-Cretaceous to Eocene. Therefore given the proven presence of charge within the basin, there is significant scope for play potential within these horizons.

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