CONSOLIDATION PROPERTIES OF HUKA FALLS FORMATION – LINKAGES TO SUBSIDENCE AT OHAAKI AND WAIRAKEI

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SUMMARY – Sandstones, siltstones and mudstones of the Huka Falls Formation have the properties of over-consolidated materials, but with high void ratios (e >1). Drillhole samples from Ohaaki geothermal field and surface samples from Te Totara Stream at Wairakei have been geotechnically tested in the laboratory and examined petrologically to better define their consolidation behaviour. The materials consistently show a sharp bi-linear loading behavior about their pre-consolidation pressures (0.5 - 5 MPa). Sediments with authigenic clay minerals that reflect higher hydrothermal temperatures (>120°C) show more plastic deformation than those with lower void ratios and lower temperature signatures.

1. INTRODUCTION

The Huka Falls Formation is the geological unit considered responsible for ground subsidence at the Wairakei and Ohaaki geothermal fields (Allis et al., 1998; Allis et *al.,* 1997; Allis and Zhan, 2000). At Wairakei, pumice breccias within the unit were initially identified as the likely cause (Allis and Barker, 1982), while later work at Ohaaki identified lower permeability mudstones as the prime cause (Allis et *al.,* 1997). The mudstone properties are now considered to provide more acceptable modelling of subsidence behaviour at both fields (eg. Allis and Zhan, 2000).

Our objective is to examine the consolidation properties of the Huka Falls Formation and its subsidence behaviour. This paper outlines initial laboratory testing of samples of the unit from both within and outside subsidence areas at the two geothermal fields. Specific testing aspects include the time to complete consolidation at each loading cycle, and the influence of slightly elevated test temperatures (<80°C). The testing is being complemented by petrological examination of test specimen fabrics, both before and after loading.

We have also examined the results of some of the previous testing (eg. Allis & Barker, 1982; Robertson, 1984, Allis et *al.,* 1997a;) used in numerical modelling of subsidence behaviour (eg. Allis and Zhan, 2000). In this paper we only comment on the properties determined and possible influences on subsidence mechanisms.

2. HUKA FALLS FORMATION

Huka Falls Formation is widespread between Taupo and Rotorua (Figure 1). It was deposited in a lake system from about 100,000 years ago until the Oruanui eruptions about 23,000 years ago.

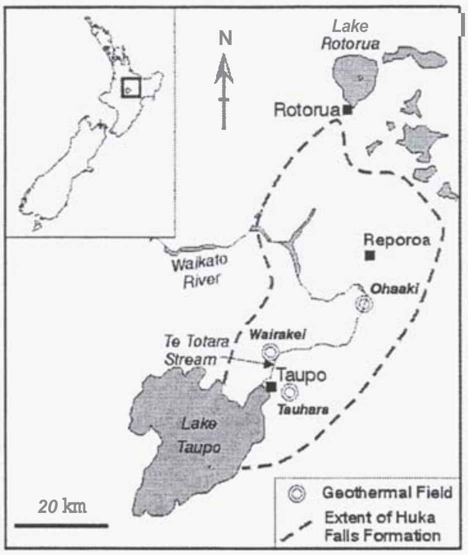


Figure 1: Location map.

The lake was influenced by active hydrothermal systems and nearby rhyolite domes. Younger mantling eruptive sequences are generally not very thick (<50m), but surface exposures are limited except where there has been significant erosion, such as close to the Waikato River.

2.1 Lithology

Grindley (1965) recognised four units within the Huka Falls Formation – three dominated by sediments and one by volcanics. The sediments typically range from very fine-grained, diatomaceous or carbonaceous mudstones, to siltstones and fine sandstones, although coarse sandstones and conglomerates are also locally present. The fine-grained sediments are commonly laminated or thinly bedded and include tuffaceous layers, while the volcanic unit is coarser-grained and dominated by vitric tuffs and tuffaceous sandstones.

The entire sequence may be up to 300 m thick, with sub-horizontal or shallow dipping bedding. Geothermal activity before, during and after deposition has resulted in varied mineral assemblages, such as discussed in Rosenberg and Hunt, 1999. Thin layers and some thicker horizons (eg. at the Huka Falls on the Waikato River) may be silicified.

2.2 Engineering Classification Properties

Huka Falls Formation materials typically have low density values (Table 1), with a greater volume for voids than for solids (ie. porosity n or void ratio e >0.5 or >1 respectively – NZS, 1986). In an engineering sense, rock lithology names (eg. mudstone) are appropriate as unconfined compressive strength (q_u) test values are greater than the traditional soil/rock boundary at q_u = 1 MPa. (q_u values from drillhole BRM-12 at Ohaaki - *Allis* et *al.*, 1997 - are 1.2 to 2.7 MPa).

Void ratios >1 are usually associated with softer, normally-consolidated soil materials (ie. those not subjected to stresses greater than the equivalent of their present overburden load). However, the weak rock strengths of Huka Falls Formation materials reflects significant over-consolidation (ie. apparent bonding greater than the effect of overburden pressure). In comparison, many New Zealand Tertiary-age sedimentary rocks with similar uniaxial strengths have void ratios between 0.6 and 0.4 (Read and Miller, 1991).

Table 1: Classification properties of Huka Falls Formation at Wairakei, Tauhara and Ohaaki.

Mean (std dev)	Density (t/m³) Bulk ρ	Dry ρ_d	Porosity n	Voidratio e
Wairakei, Tauhara (Robertson, 1984) – 15 samples [1]				
Sediments	1.57 (0.[illegible]8)	1.00 (0.24)	0.58 (0.08)	1.45 (0.47)
Breccia	1.55 (0.11)	0.97 (0.19)	0.59 (0.08)	1.50 (0.45)
Ohaaki (Allis *et al.*, 1997) – 23 samples [2]				
Sediments	1.69 (0.08)	1.13 (0.12)	0.57 (0.05)	1.37 (0.28)

Notes: [1] Volumes measured after drying and saturation
[2] Volumes measured at natural water content

3. CONSOLIDATION TESTING

The current, ongoing, testing programme is using samples from the 170m deep cored drillhole BRM-12 located within the subsidence area at Ohaaki and fiom surface exposures at Te Totara Stream (Figure 1), 1km downstream of Huka Falls, and outside the subsidence area at Wairakei.

3.1 Methodology

Testing used a conventional balance-arm oedometer loading frame, and the test procedure was based on NZS4402 (*NZS*, 1986). Test specimens were trimmed into a 50 mm diameter ring fiom either 60 mm diameter drill-cores (BRM-12) or block samples (Te Totara) preserved close to, or at, natural 'as received' water contents. After assembly of the test cell, the 20-25 mm thick specimens were covered by water.

Loading was applied approximately perpendicular to bedding in between 5 and 7 increasing increments. A 24 hour loading cycle was used for the lower load increments (eg. 0.13-0.26 MPa), while for higher loads (eg. 2.08–4.16 MPa) the cycle was extended until settlement in a 24 hour period was <<1% of total settlement for the increment (taking up to 4 weeks). Loads were applied for two or more increments beyond the apparent pre-consolidation pressure; the maximum being ≈8 MPa (ie. ≈500m of overburden).

For testing at slightly higher temperatures, the water around the specimen has been heated by connecting the test cell to a temperature-controlled water bath. Initial tests have been performed with the water at 50°C and 70°C, compared with room temperature (15° - 20" C) for normal testing.

Petrographic inspection of test specimens before and after loading has been carried out using a scanning electron microscope. An energy-dispersive X-ray (EDX) attached to the scanning electron microscope was used to estimate the gross chemical composition of clays and other minerals. Gross mineral composition of bulk samples was determined by X-ray diffractometry, and oriented glass smears of the <2µm clay fraction also used to establish clay composition and crystallinity.

3.2 Loading Results

The results in Figure 2 illustrate a consistent response to loading. All lithologies show little change in void ratio before reaching pre-consolidation pressure loads and considerable change after. Loading curves are therefore sharply bi-linear about their pre-consolidation pressures (0.5 – 5 MPa in Table 2). The greatest effect, about an overall 25% reduction in specimen height during testing, occurs for initial void ratios >1.4. The smallest effects are for lower void ratio samples from shallow depths in BRM-12 and at Te Totara.

The longer loading cycles used in the current testing (Figure 2a) have avoided 'continuing consolidation' effects apparent in previous testing (Figure 2b). All the lithologies tested have low permeabilities (10^{-8} to 10^{-11} m/sec) and therefore would be expected to be dominated by slow responses to loading. However, Figure 3 illustrates that sandy lithologies have an unexpectedly high immediate response (20-50 % of total) as well as continuing deformation. The mudstones do not show a significant immediate response (<20%) and an expected overall slower response.

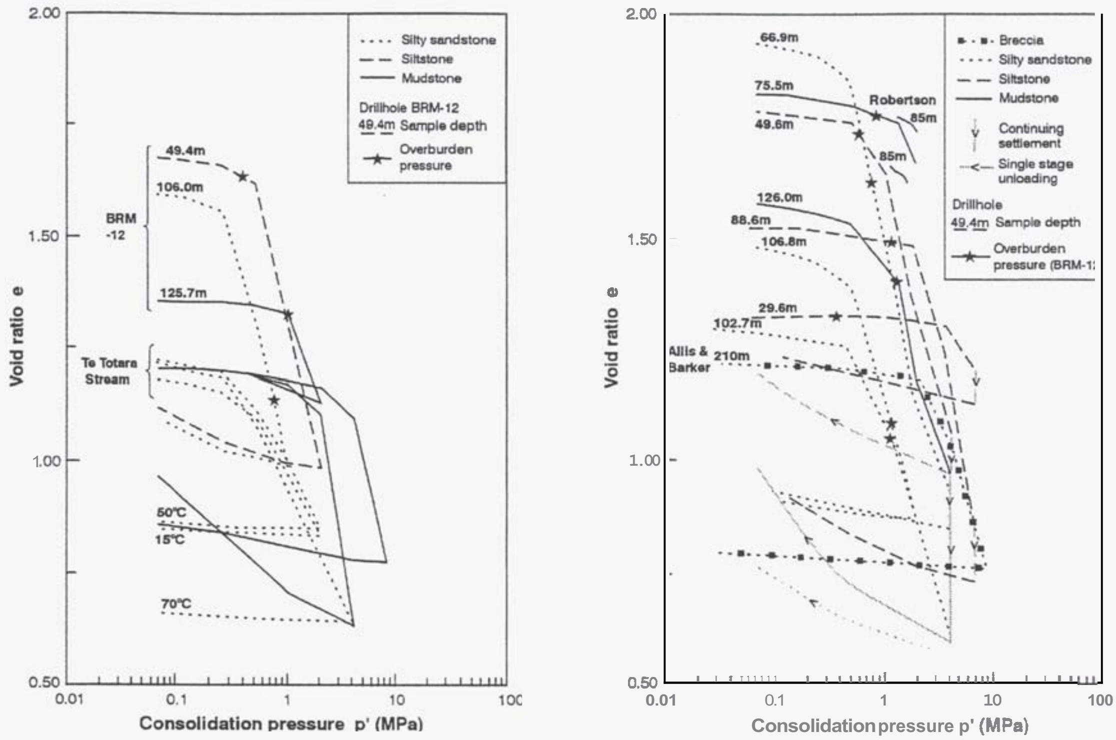


Figure 2a: Current results (this paper).

Figure 2b: Previous results.

Figure 2: Summary of laboratory consolidation test results. Current from Ohaaki and Te Totara Stream and previous from Wairakei (Allis & Barker, 1982; Robertson, 1984) and Ohaaki (Allis et *al.*, 1997).

The other noticeable feature in Figure 3 is the longer time needed for consolidation at loads close to pre-consolidation pressure (eg. 1.04 – 2.08 MPa for mudstone). Partially unloading the mudstone (125.7 m – Figure 2a) from just beyond its pre-consolidation pressure resulted in little recovery (ie. deformation was permanent). In contrast, there was a large rebound on final unloading. In the more preliminary previous testing (126.0 m – Figure 2b) this was thought to reflect the more rapid loading cycles used then.

Compressibility is a measure of the capability of a material to consolidate. Coefficient of compressibility values (eg. volume compressibility m_v – *NZS, 1986*) are calculated using ground pressure conditions known or inferred at the depth of sampling (values for samples from BRM-12 with water table at 70m depth in Figure 2). Figure 4 shows a wide range of compressiblity values for Huka Falls Formation materials. Lower values to the left of overseas data (eg. m_v = 0.01 MPa^{-1}) reflect over-consolidation (ie. ground pressures less than pre-consolidation values).

When ground pressures are closer to pre-consolidation values, compressibilities are greater (m_v >0.1MPa^{-1}), particularly for sandier materials. The values for sandier materials may, however, in part reflect some stress relief since sampling. This supposition is supported by the results for current testing of BRM-12 samples (Figure 2a) which show greater compressibilities than similar depth samples tested several years earlier (Figure 2b).

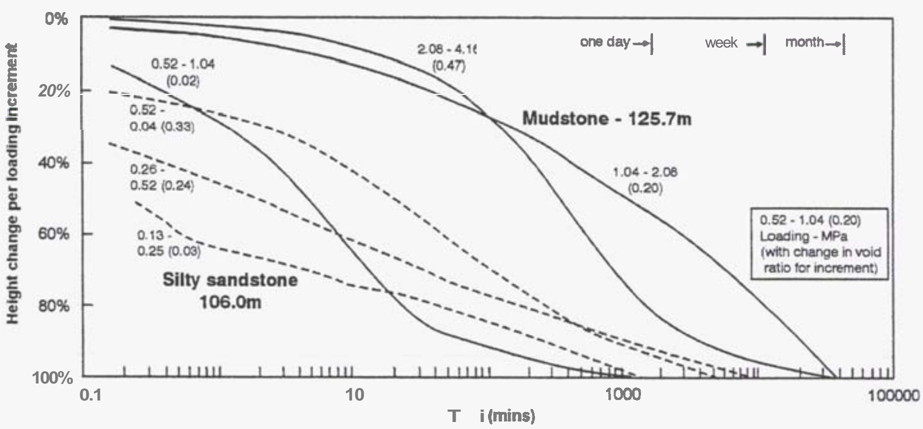


Figure 3: Time settlement curves for loading increments before, near, and past pre-consolidation pressure for silty sandstone and mudstone from BRM-12. Void ratio changes for comparison between increments.

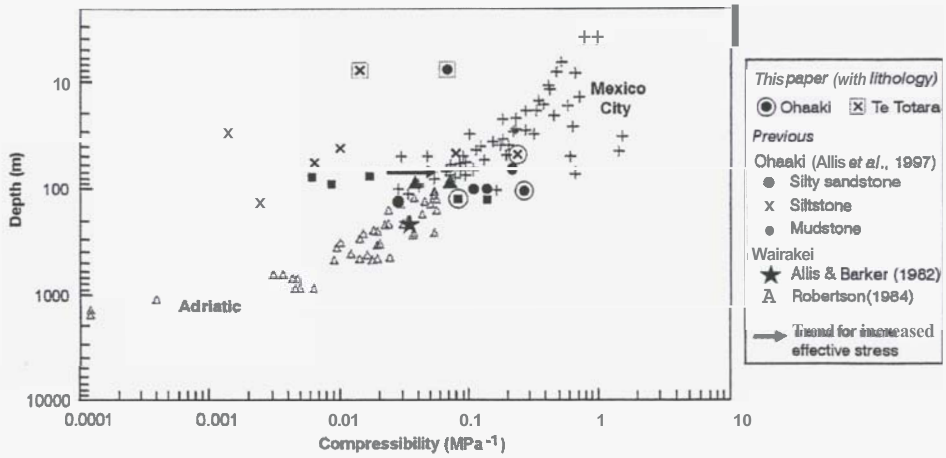


Figure 4: Compressibility chart. Hika Falls Formation values are coefficient of compressiblity (m_v) with water at 70m depth. Supporting data after Helm, 1984 (Mexico +) and from Bau et *al.*, 1997 (Adriatic A).

The sandier materials from Te Totara Stream were chosen for initial testing at slightly elevated (>50°C) temperatures. Of the two tests completed (Figure 2a), the result at 70°C has a slightly lower pre-consolidation pressure (Table 2). However, as these results are not demonstrably outside experimental errors no further comment is made before further testing is completed.

3.3 Mineralogy and Petrology

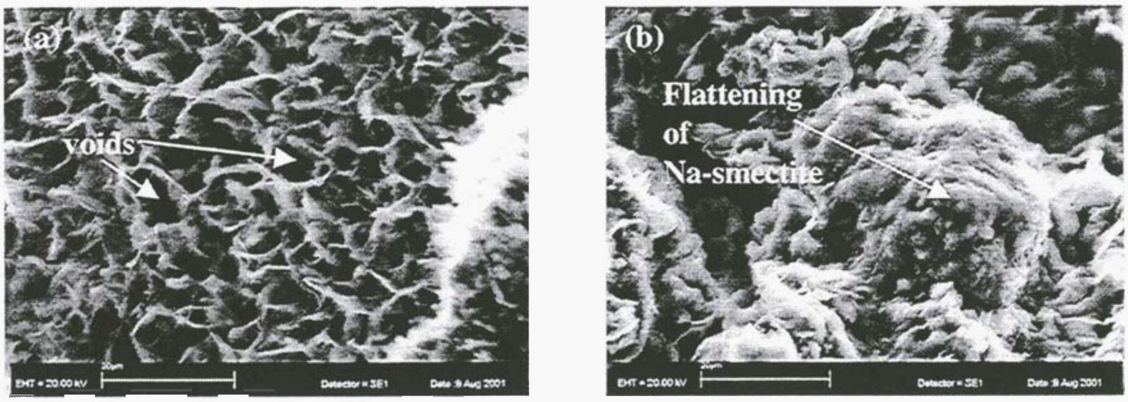
Detrital content is dominated by rhyolite-derived quartz and plagioclase, with lesser amounts of other minerals (Table 2). Most of the high temp-mature (180 - 220°C) hydrothermal minerals, such as quartz mosaic, chlorite and illite, were formed in the lithic and crystal fragments prior to incorporation into the sediments.

Authigenic minerals are dominated by clays. In BRM-12, swelling clays decrease with depth and increasing formation temperature, accompanied by minor amounts of pyrite, calcite and chalcedony. In general the major cation in the swelling clays changes with depth, from Na to Na + Ca to K, reflecting the increasing effects of >100°C hydrothermal solutions. Patchy occurrences of authigenic poorly crystalline chlorite at Te Totara *Stream* suggests past exposure to <100°C hydrothermal waters.

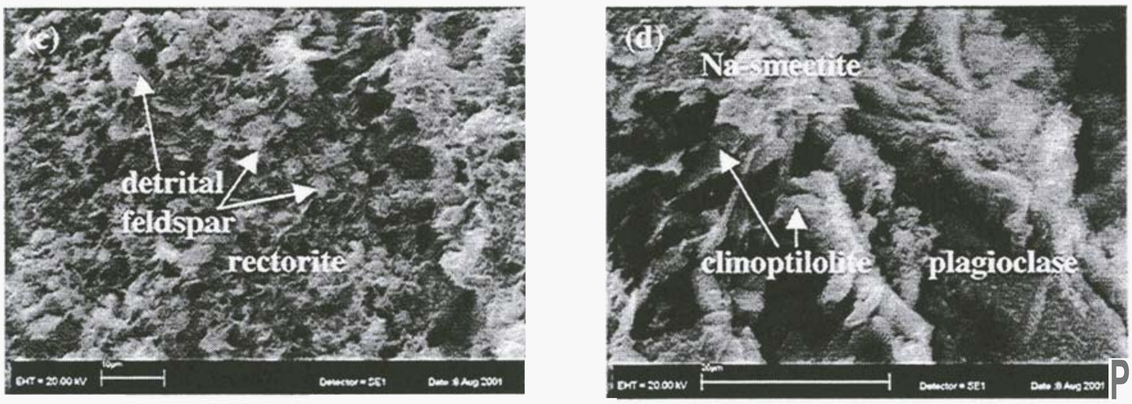
Table 2. Hika Falls Formation samples (this paper). Hand specimen lithologies used in text given as well as more specific determinations made petrologically (eg. clays from thin section point counting).

	Lithology Hand specimen / Petrology	Initial void ratio e	Pre-consol pressure p'_c (MPa)	Mineralogy Authigenic minerals in order of decreasing abundance	Clay content estimate
Ohaaki (BRM-12)					
49.6 m	Siltstone/ Rhyolitic crystal vitric tuff	1.68	0.5	Authigenic: Na-smectite > Ca-smectite, clinoptilolite, rare vermiculite Detrital: Volcanic plagioclase, quartz, K-feldspar, clinopyroxene, zircon, apatite, magnetite; hydrothermal chlorite, illite, zeolite, gypsum; others such as organic material, rare diatoms	*70%*
106.4m	Silty sandstone / Sandy claystone	1.60	0.4	Authiaenic: Ca-smectiie, chlorite, K-rectorite, pyrite Detriil: Volcanic plagioclase, quartz, clinopyroxene, magnetite, K-feldspar, apatite, zircon, hornblende; zeolite	55%
125.6 m	Mudstone/ Claystone	1.36	1.7	Authiaenic: K-rectorite with minor kaolinite, vermiculite, calcite, chalcedony, pyrite. Detrital: Volcanic plagioclase, K-feldspar, quartz, clinopyroxene, biotite, zircon, cristobalite, apatite; fresh glass; organic material, chlorite, illite	85%
Te Totara Stream					
Surface exposure	Silty sandstone / Clayey sandy Siltstone	1.20 1.28 1.23	15°C - 0.5 50°C - 0.5 70°C - 0.4	Authioenic: Chlorite, Ca smectite, kaolinite Detrital: Volcanic plagioclase, apatite, K-feldspar, pyroxene, hornblende, biotite, quartz, magnetite; fresh rhyolitic glass chlorite, goethite, gypsum, muscovite; quartz mosaic, pyrite, zeolite; rhyolite altered to illite, quartz and chlorite	*45%*
Surface exposure	Siltstone / Fine sandy claystone	1.22	5.0	Authiaenic: Ca smectite , kaolinite Detrital: Volcanic plagioclase, pyroxene, hornblende, biotite, quartz, magnetite; chlorite, goethite, chalcedony, pyrite, illite-smectite, clays, diatoms	55%

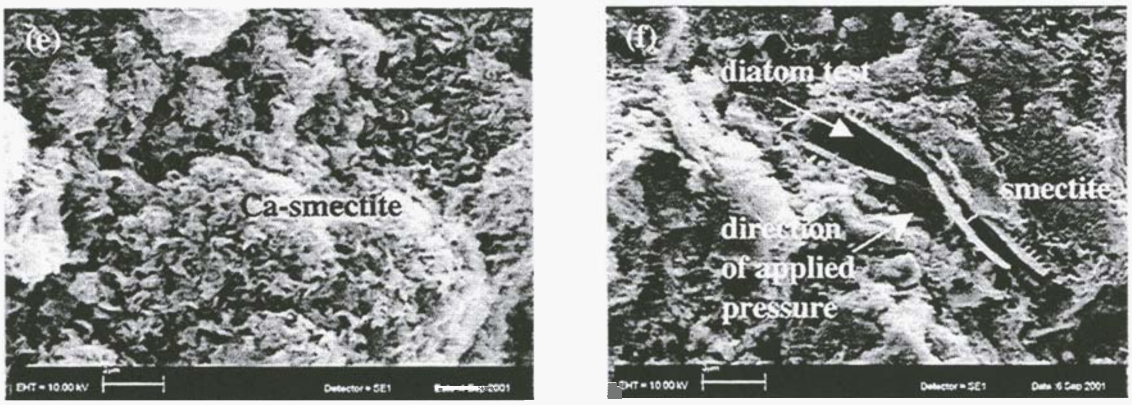
Before consolidation ⇓ (natural conditions) After consolidation ⇓ (reduced void ratio)



BRM-12 (106.0 m): Open structure of smectite (a) and reduction of void ratio after plastic deformation (b).



BRM-12 (125.6 m): Fibrous rectorite and detritals (c). BRM-12 **(49.6** m): Flattened Na-smectite fibres (d).



Te Totara sandstone: Smectite-coated detrital grains (e) and flattened clay fibres with fractured diatom *(f)*.

Figure. *5.* Scanning electron microscope images taken using secondary electrons before (a,c,e) and after (b,d,f) consolidation. Views are perpendicular to bedding (ie. in direction of loading) apart from image f.

Scanning electron microscope images of samples prior to loading (Figure 5 - a, c, e) show open clay structures associated with high void ratios. The reduction in void ratio during consolidation testing is shown in the samples from BRM-12 by the flattening of smectite sheets and plastic deformation of clay coatings around detrital minerals (b, d). There is little or no evidence of brittle fracture or total collapse of vugs surrounded by clinoptilolite aggregates (d), which is surprising given the strength of the materials. At Te Totara Stream there is more evidence of brittle fracture (f), possibly with less clay mineral slippage.

3.4 Discussion

Ground subsidence follows after changes in sub-surface conditions have resulted in higher ground pressure effective stresses (eg. from a drop in water table level). When these conditions equate near to andor just past the pre-consolidation pressure there is an effect of increasing compressibility (as shown by the horizontal arrow in Figure 4). Consequently the consolidation properties of the high void ratio, yet high strength and pre-consolidated, Huka Falls Formation materials provide a plausible mechanism for ground subsidence.

There are indications that materials with a lower void ratio (eg. from Te Totara Stream) are associated with authigenic clay minerals with structures that have lower hydrothermal temperature (<100°C) signatures and that these materials have less potential to consolidate. This conclusion was not readily apparent at Ohaaki geothermal field based on the work of Rosenberg and Hunt (1999), but shows the validity of testing a range of materials from both inside **and** outside of subsidence areas at geothermal fields, and even further away.

From a laboratory testing point-of-view, and for the provision of numerical modelling input parameters, better understanding of clay mineral influences, and the relative influences of immediate and continuing reaction to loading is required. Testing to higher loads (eg. 25 MPa) would define at what depth compressibilities and void ratios would return to those for normal consolidation. Further testing at elevated temperatures is also appropriate to better approach duplication of the effects in hydrothermal systems.

4. CONCLUSIONS

Consolidation testing of the high void ratio, yet high strength and low permeability, Huka Falls Formation silty sandstones, siltstones and mudstones has verified their sharp bi-linear loading behavior about the pre-consolidation pressure. The most marked reductions in void ratio are seen in materials with higher initial void ratios (>1.4), and which also appear to have higher temperature (>150°C) authigenic hydrothermal clay mineral assemblages and structures.

Responses to loading during testing appear to be a combination of both immediate and slower reactions in sandier lithologies, and predominately slower reactions in muddier lithologies. The greatest consolidation appears to be typified by plastic deformation with flattening of clay minerals and deformation of coatings around detrital grains. However, some brittle deformation may be seen in materials with lower initial void ratios and lower temperature hydrothermal signatures, such as at Te Totara Stream. Initial testing at slightly elevated temperatures (40°C) is insufficient to show effects outside experimental errors.

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