SUBSIDENCE AT KAWERAU GEOTHERMAL FIELD, NEW ZEALAND

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ABSTRACT

Subsidence at Kawerau Geothermal Field (KGF) is closely monitored due to the presence of the Carter Holt Harvey (CHH) and Norske Skog Tasman (NST) pulp and paper mills which are located within the operating field and have the potential to be affected by subsidence. Spatial analysis of re-levelled benchmarks from 2007 – 2013 revealed two scales of subsidence: 1) Field wide subsidence currently covering ~17 km^2; and 2) Four localised subsidence anomalies covering 150 – 400 m^2 each. This paper focuses on two of the localised anomalies north of the CHH and NST mill site, and the mill site itself. Three dimensional modelling of KGF was completed to determine the stratigraphy below the localised subsidence anomalies and whether the same conditions exist beneath the pulp and paper mills. Samples of Recent alluvium were taken from three geotechnical boreholes drilled in the mill complex and analysed for materials such as smectite clay that could contribute to subsidence across the mill site. Samples of Tahuna and Caxton formations were also taken from boreholes KAM11 and KA37a to investigate the hypothesis that an anomalous thickness of Tahuna Formation could be responsible for the two localised subsidence features studied and that the Tahuna Formation is more compressible than the overlying Caxton Formation. To do this, the physical properties of both formations were compared and a new methodology utilising a soil shear box to measure compressibility was developed. Results show that the recent alluvium sampled from the mill site does not does not contain smectite clays and is unlikely to contribute to the formation of a subsidence anomaly. Compressibility measurements of Tahuna and Caxton Formations show that the Tahuna Formation is twice as compressible as the Caxton Formation when saturated. However further investigation would be necessary to confirm whether this contributes to the mechanism for the localised subsidence features.

1. INTRODUCTION

Subsidence at Kawerau Geothermal Field (KGF) is a concern because ground deformation associated with subsidence has the potential to misalign mill machinery beyond normal maintenance tolerances and the regular misalignment of machinery will cost time and money to remediate.

On-going analysis of subsidence at KGF is required so mill operators are aware of the potential for ground deformation to impact their operations and KGF tappers can mitigate the development of subsidence features. To do this, a spatial analysis of recent benchmark re-levelling surveys has been undertaken using ArcGIS to identify the areas affected by subsidence and the severity of that subsidence across KGF and, specifically, the Tasman Mill site. Following this, the shallow cover sequences of KGF are modelled using Leapfrog Geo (ARANZ Geo, 2014) and the KGF well logs (Milicich, 2013) to identify any anomalies in the geologic framework of the field and to compare the stratigraphy of the mill site with that of identified subsidence anomalies. The properties of the shallow cover sequences are examined for their potential to contribute to subsidence, utilising a new methodology developed to test the compressibility of samples taken from the Tasman Mill site and subsidence features within the field. Finally results are interpreted and recommendations made for future investigations regarding subsidence at KGF.

2. SPATIAL ANALYSIS OF SUBSIDENCE

Geothermal operations at KGF have been in place since 1957. Since 2008 Mighty River Power (MRP) has operated a 106 MW power station at KGF under resource consent conditions from Environment Bay of Plenty. One of the conditions of consent is that annual re-levelling surveys (completed by Energy Surveys Ltd.) of a subsidence benchmark network are completed (BOPRC, 2013). Ngati Tuwaretoa Geothermal Assets Limited (NTGA) and Geothermal Developments Limited (GDL) also have operations at KGF and are also required to undertake annual re-levelling under their resource consent conditions.

Since 2007, the benchmark network has been significantly expanded which has resulted in higher resolution surveys and a greater understanding of the ground deformation occurring; the most recent survey analysed here, completed in 2013, consisted of 577 benchmarks and covered an area of 75 km^2.

Spatial analysis of these benchmarks reveals two scales of subsidence within KGF; 1) Field wide subsidence currently covering ~17 km^2; and 2) Four localised subsidence anomalies covering 150 – 400 m^2 each. It should also be noted that the field is likely impacted by regional subsidence driven by the spreading of the Whakatane Graben but this is not quantifiable from the benchmark levelling surveys, because all of the levelled benchmarks lie within the graben. Figure 1 shows the cumulative subsidence from 2010 to 2013 which was found using the benchmarks consistently re-levelled across those years. The two largest anomalies north of the mill site (labelled Bowls B and D) are the subject of this investigation along with the mill site itself.

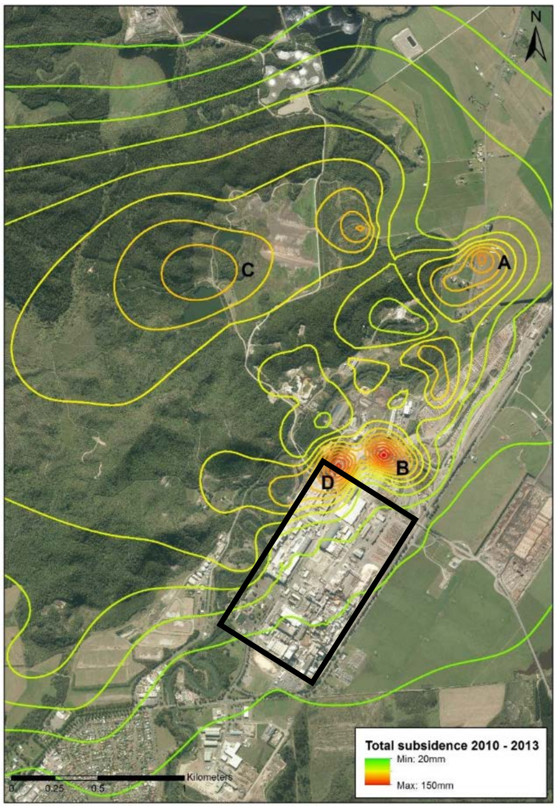

Figure 1: Cumulative subsidence across KGF from 2010 - 2013 with the Tasman Mill site approximately contained in the black box. Contour spacing is 10 mm.

2.1 Spatial analysis of Bowls B and D

The subsidence occurring at the sites termed Bowls B and D has most likely been occurring for more than 20 years (GeoMechanics Technologies, 2013), but it is only due to the increase in benchmark density that they are now clearly observed. The bowls are superimposed on field wide subsidence which occurs at a lower rate across a much larger area. Given their proximity to each other there is a possibility that the two bowls are driven by the same or similar mechanisms, and may represent one single subsidence feature with a sinuous shape. Reasons for subsidence anomalies in geothermal fields include, but are not limited to; anomalously soft zones altered by fluids (Powell, 2011), steam zones, voids created by hydrothermal eruptions, cooling because of an invasion of meteoric waters, and the settling of shallow river sediments (Bromley et al., 2015).

2.2 Mill site subsidence

The mill site is defined by industrial infrastructure of three operating companies; Carter Holt Harvey Tasman (CHH), Norske Skog Tasman (NSK), and SCA Hygiene Australasia (SCA) and is located south of Bowls B and D. The site is bounded by State Highway 34 (SH34) in the east and south, and the Tarawera River in the west.

From the 2010 – 2013 cumulative subsidence map (Fig. 1) it is clear that the mill site is largely unaffected by the two subsidence features on its northern boundary. Furthermore the sensitive machinery is located at the southern end of the highlighted mill site. An analysis of the ground deformation occurring across vital mill machinery such as the NST paper machines and CHH recovery boiler, digesters and lime kilns shows that the ground tilt occurring across this machinery is within the NST tilt rate limit of circa 3 mm/100 m/year and CHH tilt rate limit of 2 mm/100 m/year (Derrick Hope, pers. comm.). The mill site is therefore only subject to the broad field wide subsidence feature.

3. MODELLING OF COVER SEQUENCES

The ability to visualise the subsurface of a geothermal field is vital to comprehensively understanding the stratigraphic relationships of the area. Using the well logs from Milicich (2013) and drilling data (dip and azimuth) from MRP datasets, a three-dimensional model of the shallow cover sequences is developed here. The aim of the model is to identify whether the presence of the subsidence anomalies (Bowls B and D) can be accounted for within well logs and if the geologic conditions below the mill site have the potential to cause a subsidence anomaly.

For the purpose of analysing the cover sequences and their contribution to subsidence at KGF the model is limited to -750 mRL. This removes the need to model the more complicated lithologies at depth which have been offset by faulting; Milicich et al. (2014) includes a complete Leapfrog Geothermal model of KGF and shows the complexity of faulting at depth.

The model presented here includes four units present in the KGF boreholes (Recent Alluvium, Matahina Ignimbrite, Tahuna Formation, and the extrusive Caxton Formation) and three units drawn into the model from the surface geology QMAP (Onepu Formation, Rotoiti Formation, and Industrial fill). Descriptions of the seven units present are summarised in Table 1.

Formation	Description
Recent Alluvium	Pumiceous silts, sands and gravels interspersed with clay lenses and peat deposits.
Matahina Ignimbrite	Partly welded grey-brown ignimbrite and vitric tuff (pl, qz, px).
Tahuna Formation	Crystal rich, fine sandstone, siltstone, muddy lithic breccia, and unwelded pumice-rhyolite lapilli tuff.
Caxton Formation	Buried domes of spherulitic and banded rhyolite (corroded and fractured qz and pl).
Onepu Formation	Two surficial domes of rhyodacite (pl, qz, px, hbl, bt)
Rotoiti Formation	Non-welded rhyolite ignimbrite usually with moderate to high crystal content.
Industrial Fill	Anthropogenic mill waste.

Table 1: Summary of the stratigraphic units modelled at KGF. Descriptions from Milicich et al. (2014) and Leonard et al. (2010). pl – Plagioclase, qz – Quartz, px – Pyroxene, hbl – Hornblende, bt – Biotite.

To investigate potential geological anomalies four cross sections; three W – E and one S – N were placed through the model (Fig. 2): 1) through subsidence bowls B and D (Fig. 3); 2) through the north area of the mill site ~500 m south of the bowls B and D (Fig. 4); 3) through the south area of the mill site ~1 km south of bowls B and D (Fig. 5); and 4) parallel with SH34 through the mill site and bowl C (Fig. 6).

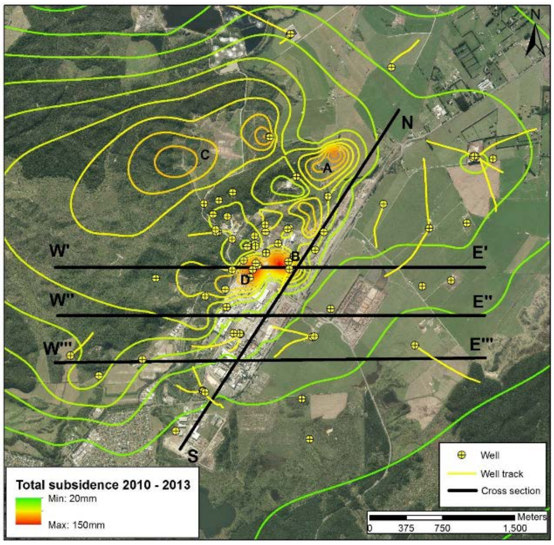

Figure 2: Map showing location of cross sections, wells used to complete cover sequences model and total subsidence from 2010-2013 (10 mm contour spacing) showing the location of subsidence anomalies.

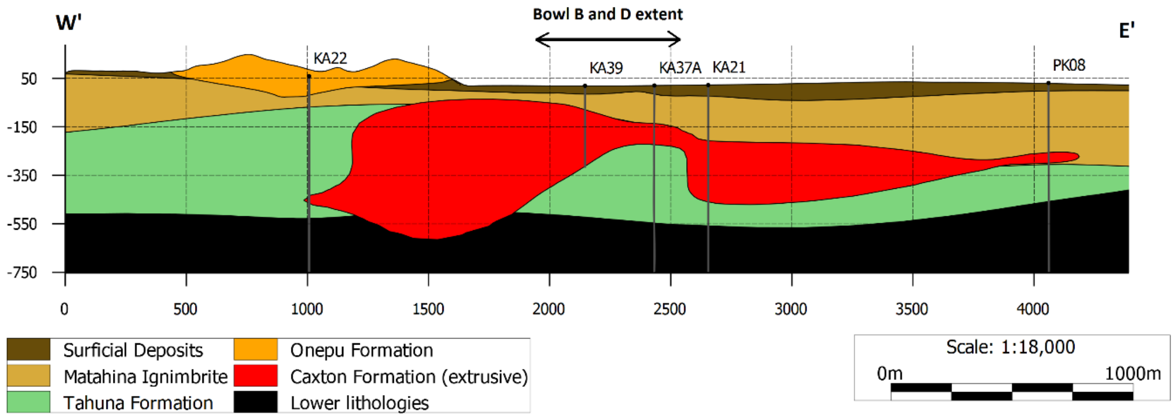

Figure 3: West to East cross section through subsidence Bowls B and D.

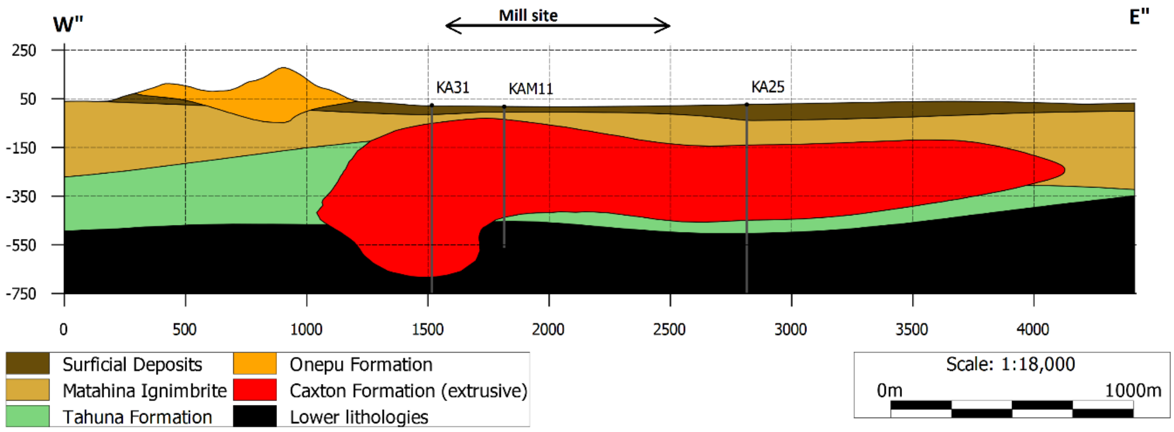

Figure 4: West to East cross section through northern area of the Tasman Mill site ~500 m south of Fig. 3.

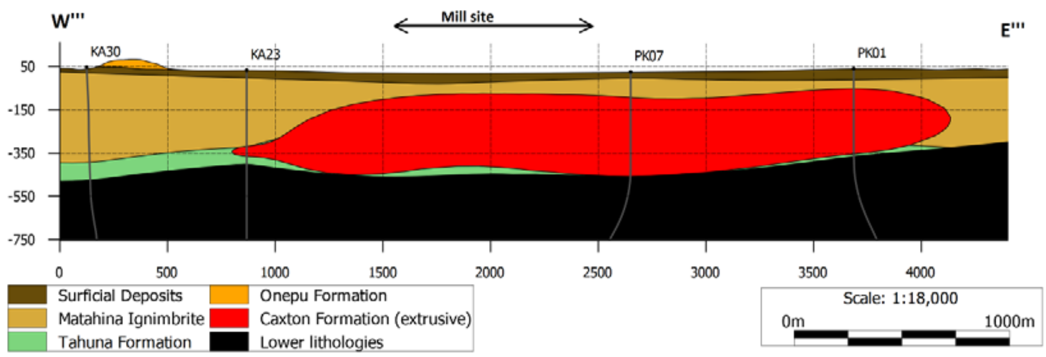

Figure 5: West to East cross section through southern area of the Tasman Mill site ~1000m south of Fig. 3.

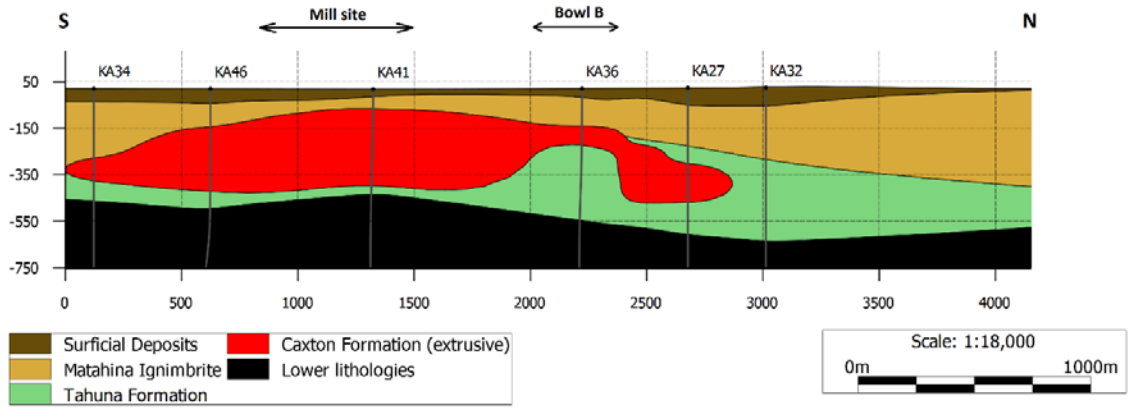

Figure 6: South to North cross section through the Tasman Mill site and subsidence Bowl B.

The cross section through Bowls B and D (Fig. 3) shows that below the bowls is an anomalous thickness of Tahuna Formation, (interpreted to be a softer and more compressible formation), and presence of a thinner Caxton Formation (less compressible than Tahuna), in comparison with the mill site (Fig. 4). Physical properties of the two formations are discussed in Section 4. The four wells superimposed on Figure 3 are KA39, KA37A, KA21, and PK08 and are located 125 m, 0 m, 156 m, and 113 m from the cross section respectively, the relatively close spacing of the wells in the cross section provides confidence in the cross section.

The cross sections through the mill site (Fig 4, 5 & 6) and isopach map (Fig. 8) shows that the Caxton Formation is of a relatively uniform thickness beneath the mill site with the exception of a potential source area near KA31 where it is thicker. Below the mill site the Tahuna Formation is thin compared to below Bowls B and D (Fig 4, 5 & 6). The S-N cross section (Fig. 6) through the mill site and Bowl B shows the difference in thicknesses of Caxton and Tahuna Formation between the mill site and subsidence anomalies and a slice through the three-dimensional model shows the thickness of Tahuna Formation beneath Bowls B and D (Fig. 7).

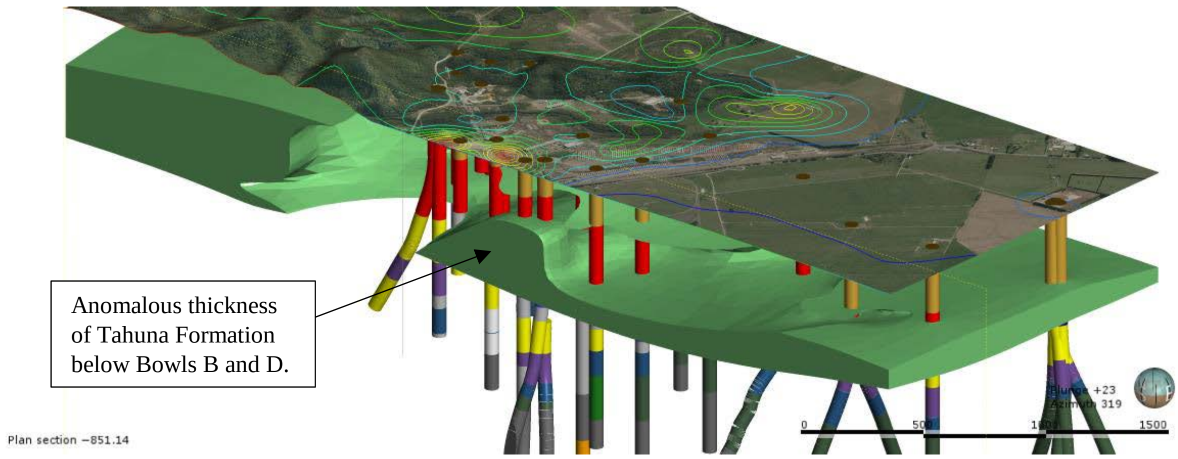

Figure 7: West to East slice through the Tahuna Formation showing the anomalous thickness of the formation below Bowls B and D.

Another method utilised to investigate potential mechanisms for the subsidence anomalies was the development of isopach and relative level maps of formations across the field. Paleo-channels in units can result in the deposition of softer materials within these channels which react differently to anthropogenic changes than the surrounding geology. The relative level of the Matahina Ignimbrite and thickness of the Caxton Formation have been mapped in ArcGIS using well data from Milicich (2013).

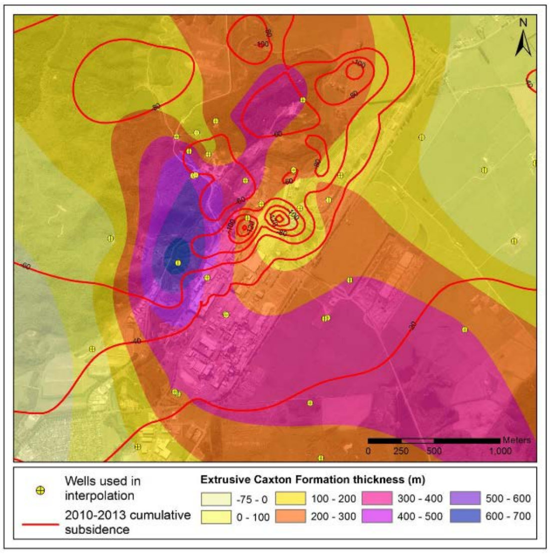

Figure 8: Isopach map showing the thickness of the extrusive Caxton Formation across KGF. Created in ArcMap using Milicich (2013) well logs.

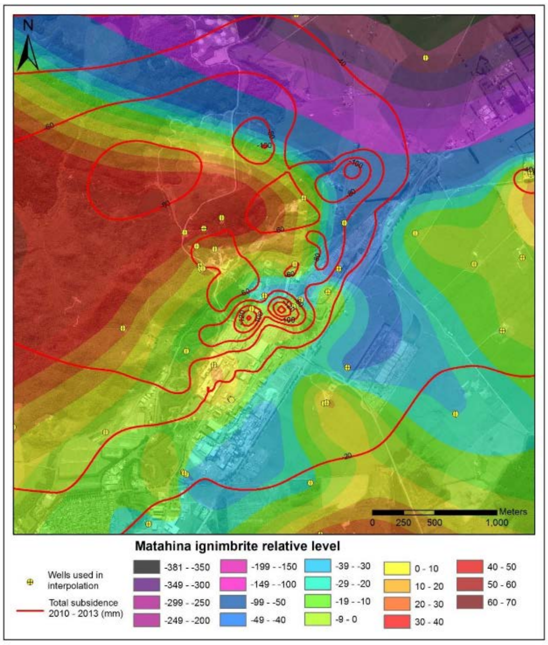

Figure 9: Relative level of Matahina Ignimbrite across KGF with 2010-2013 cumulative subsidence to show location of subsidence features (relative level structural shapefile from John Clark, pers. comm., 2014).

The isopach maps produced for the Caxton Formation (Fig. 8) and relative level map for the Matahina Ignimbrite (Fig. 9) shows a thinning of the Caxton Formation near Bowl B and a paleo channel near Bowls B and D in the Matahina Ignimbrite in which a larger amount of Recent alluvium would have been deposited in comparison to the mill site.

The isopach map for the Caxton Formation (Fig. 8) shows that the formation is thinner beneath Bowls B and D and thicker across the mill site. This leads to the hypothesis that the Caxton Formation is acting as a supporting formation, preventing a large amount of differential subsidence from occurring across the mill site. The thinner thickness of the formation beneath Bowl B also supports this hypothesis. The Matahina Ignimbrite relative level map shows the presence of a paleo channel in the formation where there is a relatively greater thickness of Recent alluvium due to the paleo channel. The extra thickness of Recent alluvium has the potential to be the source mechanism for the subsidence occurring north of the Tasman Mill site.

3.1 Geological Interpretation

Following the deposition of the Tahuna Formation (0.44 Ma) the Caxton Formation (0.36 Ma) was extruded from around the location of KA31 (Fig. 4). The Caxton Formation was extruded across the Tahuna Formation and filled channels where the Tahuna Formation had been eroded, probably by the Tarawera River; the western end of Figure 4 and northern end of Figure 6 show how thick the Tahuna Formation may have been before erosion occurred. In some wells on the spatial edge of the Caxton Formation the Tahuna and Caxton Formations are interlayered, where the Tahuna Formation is present above and below the Caxton Formation e.g. KA27, (Fig. 6).

This indicates that there has been some Tahuna Formation deposition following the extrusion of Caxton Formation, where processes from a paleo-channel of the Tarawera River in combination with faulting have created a large (>200 m deep) valley into which the Caxton Formation has flowed. Dating of a tuff near the base of the Tahuna Formation (Milicich et al., 2013), indicates deposition of the Tahuna Formation occurred after the 0.44 Ma age provided by the tuff.

Cross sections of the model through the mill site (Figs. 4, 5 and 6) show that the stratigraphy beneath the mill site is relatively consistent the across the site. The lack of a subsidence anomaly can be explained by the uniform geology, it also shows that the geological conditions for an anomaly to form under the Tasman Mill site in the future is unlikely. The model is well constrained across the mill site with the presence of KA46, KA47 and KA52 at the south end of the mill, and KA41 and KA42 in the north.

3.2 Proposed Mechanisms for the Anomalies

The mechanism proposed and tested here for Bowls B and D is that anomalous thickness of Tahuna Formation below the bowls is more compressible than the overlying Caxton Formation which is also thinner in the area of the subsidence bowls in comparison to the mill site. The lack of a subsidence anomaly across the mill site, where the Caxton Formation is three times thicker than below Bowl B (KA41 vs. KA36), provides further support to this mechanism.

4. PROPERTIES OF THE SHALLOW COVER SEQUENCES

To test the hypothesis of compressibility as a factor in subsidence, samples of the Tahuna and Caxton formations were selected from KGF and their compressibility compared. From this an interpretation is made on whether the anomalous thickness of Tahuna Formation present below Bowls B and D is the primary mechanism for their presence.

The samples used in this study are sourced from Kawerau production and monitoring wells (Table 2). Samples obtained vary in diameter and length due to drill bit sizes, well purpose and conditions encountered. KA37 was cored at ~50 mm diameter and KAM11 cored to ~80 mm diameter with sample lengths between 140 and 250 mm.

The samples have been described by GNS Science (KAM11) and Milicich (2013) (KA37). GNS Science logged KAM11 during drilling and produced engineering geological logs for the well (Kilgour, 2008; Read & Kilgour, 2009), and Milicich (2013) re-logged all KGF wells. All samples were stored in the Kawerau core shed where they have dried out over time, the youngest of the samples (KAM11) has been in storage since late 2008.

Well	Depth of sample (m BGL)	Well Type	Formation	Drilled
KAM11	203.5 – 203.8	Shallow monitoring	Caxton	June-July, 2008
KAM11	424.4	Shallow monitoring	Tahuna	June-July, 2008
KA37	474.2	Production	Tahuna	November, 1999

Table 2: Summary of wells and depth of samples used for this study.

The physical properties of the samples are the controlling factors on their behaviour at depth and whether they contribute to subsidence at Kawerau; it is therefore vital to record the properties of each sample before testing. This includes density and effective porosity was measured using saturation and calliper techniques, as well as saturation and buoyancy techniques. Key results showed that the Caxton Formation is ~1.5 times denser when dry than the Tahuna Formation, and the Tahuna Formation has 3 times more effective porosity than the Caxton Formation.

Due to the age, condition and amount of suitable material available from KGF, over-coring the samples to complete triaxial testing risked destroying the samples. The failed recovery of over-cored samples would result in no data collection with no additional samples available. The decision was made to develop a testing procedure that could compare the compressibility of Caxton and Tahuna formations whilst reducing the likelihood of destroying the samples during preparation. A soil shear box at the University of Canterbury was used, which has a loading lever with a known ratio of 1:10 that could place load on a sample. To control the load on the samples a platen of known area and mass is placed on top of the sample onto which load is applied in 50 kg (on sample) increments, up to a total of 500 kg, and the strain calculated at each effective stress. Because of the dimensions of the samples chosen from KGF, the cores were cut into 30 mm thick sections ensuring they are of approximately the same dimensions. A resin was used to provide confinement to the sample as it would experience at depth. This has compressive and tensile strengths greater than that of the sample, preventing the sample from failing. To measure the amount strain occurring along the sample length during loading a Silvat gauge is used. This records the change in height of the sample at two second intervals from which strains are calculated.

4.1 Saturated Tahuna Formation versus Saturated Caxton Formation

Comparing the saturated Tahuna and Caxton samples (Fig. 10); shows that the Caxton Formation deforms less than the Tahuna Formation but is less elastic. The deformation occurring in both samples is mostly elastic, exhibited by the small hystereses in both plots. A comparison of both plots shows that the Tahuna Formation is approximately twice as compressible as the Caxton Formation The greater amount of deformation initially exhibited by the Tahuna Formation is likely due to the higher effective porosity.

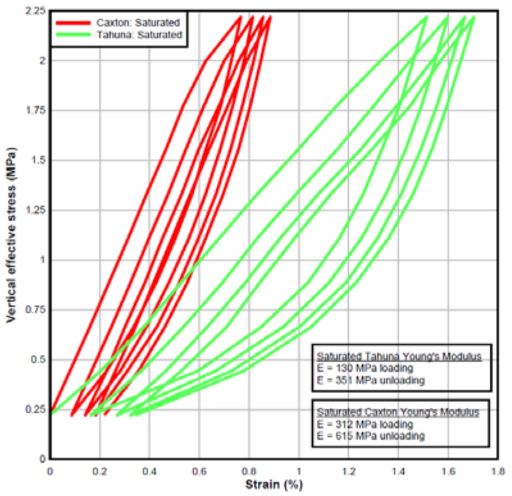

Figure 10: Stress-strain graph showing the deformation of the saturated Caxton sample vs. the saturated Tahuna Formation sample.

5. CONCLUSIONS

- The relatively high thickness of the Caxton Formation compared with the Tahuna Formation combined with the consistent strength of Caxton Formation suggests that the formation acts as a supporting formation for the Tasman Mill site, preventing anomalous subsidence.
- The Tahuna Formation underlies the Matahina Ignimbrite and Caxton Formation, and is variable in its depth, thickness, and lithology. Where the extrusive Caxton Formation overlies it the Tahuna Formation is relatively much thinner, except beneath Bowls B and D. This led to the hypothesis that the Tahuna Formation is anomalously compressible and the cause of Bowls B and D.
- Compressibility testing completed on Tahuna and Caxton samples concluded that the Tahuna Formation is approximately twice as compressible as the Caxton Formation and could be contributing to the presence of Bowls B and D but is not compressible enough to be the sole cause of Bowls B and D.
- Subsidence across the Tasman Mill site is part of the field wide subsidence with low differential tilt values and is unlikely to disrupt mill operations.

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