Three-Dimensional Seismic Study of Pluton Emplacement, Offshore Northwestern New Zealand

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Three-Dimensional Seismic Study of Pluton Emplacement,
Offshore Northwestern New Zealand

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A thesis submitted to the faculty of
Brigham Young University
in partial fulfillment of the requirements for the degree of

Master of Science

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ABSTRACT

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Detailed 3D seismic images of a volcano-plutonic complex offshore northwestern New Zealand indicate the intrusive complex lies in a relay zone between NE-trending en echelon normal faults. A series of high angle normal faults fan out from the margin of the Southern Intrusive Complex and cut the folded strata along the margin. These faults terminate against the margins of the intrusion, extend as much as 1 pluton diameter away from the margin, and then merge with regional faults that are part of the Northern Taranaki Graben. Offset along these faults is on the order of 10s to over 100 meters. Strata on top of the complex are thinned and deformed into a faulted dome with an amplitude of about 0.7 km. Steep dip-slip faults form a semi-radial pattern in the roof rocks, but are strongly controlled by the regional stress field as many of the faults are sub-parallel to those that form the Northern Taranaki Graben. The longest roof faults are about the same length as the diameter of the pluton and cut through approximately 0.7 km of overlying strata. Fault offset gradually diminishes vertically away from the top of the intrusion.

The Southern Intrusive Complex is a composite intrusion and formed from multiple steep-sided intrusions as evidenced by the complex margins and multiple apophyses. Small sills are apparent along the margins and near the roof of the Southern complex. Multiple episodes of deformation are also indicated by a series of unconformities in the sedimentary strata around the complex. Two large igneous bodies make up the composite intrusion as evidenced by the GeoAnomaly body detection tool.

The Southern Intrusive Complex has a resolvable volume of 277 km$^3$. Room for the complex was made by multiple space-making mechanisms. Roof uplift created ~3% of the space needed. Compaction/porosity loss is estimated to have contributed 20-40% of the space needed. Assimilation may have created ~0-30% space. Extension played a major role in creating the space needed and is estimated to have created a minimum of 33% of the space. Floor subsidence and stoping may have occurred, but are not resolvable in the seismic survey.

Keywords: Taranaki Basin, New Zealand, pluton emplacement, 3D seismic, igneous intrusion
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INTRODUCTION

Room Problem

One question regarding pluton emplacement is often summarized as the “room problem,” (e.g., Civarella and Wyld, 2008; Hutton, 1996). The essence of this research is to find how magmatic intrusions create the space they occupy in continental crust. Magma flows into the upper crust along zones of least resistance--faults, fractures, bedding planes--and then ultimately stops and solidifies. All along this path the magma must make room for itself while displacing the pre-existing layers of rock (Farris et al., 2006). The principal means of making this space include:

1. Doming of the roof rocks (Stevenson et al., 2007).
2. Thinning during stretching of roof strata (de Saint-Blanquat et al., 2006).
3. Shortening of side wall rocks (Morgan et al., 2008).
4. Regional extension (Morgan et al., 2008).
5. Pushing the floor of the pluton downward (e.g., Hutton et al., 2000).
6. Stoping, the process of roof and wall rocks sinking through the molten portion of the magma chamber and accumulating on the floor (Pignotta and Paterson, 2007).

Finding answers to the “room problem” is difficult due to incomplete, surficial views of plutons. A single, almost planar slice through the pluton (at Earth’s surface) is all that is typically available for study. Emplacement mechanisms rely on the limited data from geologic maps. Inferences from these limited two-dimensional studies are extrapolated into the subsurface to construct hypothetical cross sections through the outer few kilometers of the crust. The most deeply incised plutons offer vertical exposures typically less than a kilometer (e.g., Bachl et al.,
Deep mines and drill core provide some data on the deep structure related to pluton emplacement, but these studies are limited. Also, the roof rocks above plutons are rarely preserved. Best and Christiansen (2001) state that “perceived difficulties in accounting for the space occupied by a pluton...may be reduced if all three dimensions of it and the surrounding country rocks can be examined.”

3D seismic offers a powerful tool for investigating the “room problem”. The only intrusive bodies imaged by detailed 3D seismic are the mafic sills in the floor of the North Sea (e.g., Hansen and Cartwright, 2006). Spectacular images of the three-dimensional shapes of these sills have led to fundamental changes in our understanding of sill emplacement. However, most plutons intruding continental crust are not mafic sills like those in the North Sea. Instead, continents are mostly constructed at convergent plate margins where more viscous, silica-rich magma is generated. Petroleum exploration, which uses 3D seismic, rarely overlaps with settings where silica-rich igneous rocks are emplaced. The offshore region of northwestern New Zealand is one of these places.

In 2005, Pogo New Zealand/Plains Exploration acquired a 3D seismic survey northwest of the Taranaki Peninsula in the Taranaki Basin (Fig. 1). The seismic survey, conducted in 2005, covers 1520 km² and was processed with modern techniques used in hydrocarbon exploration. Several igneous intrusion complexes were imaged successfully in these data. These data provide new insight into the size, shape, and wall rock deformation associated with the emplacement of plutons.
GEOLOGICAL SETTING

The Taranaki Basin of northwestern New Zealand is approximately 100,000 km\(^2\) (Fig. 1) and is bounded to the east by the Taranaki Fault. The Taranaki Fault is a Miocene reverse fault with approximately 7000 m of vertical throw. To the west, the basin continues onto the Western Stable Platform. To the north, the basin continues into offshore western Northland, and to the south, it merges with the northwestern margin of the South Island (King and Thrasher, 1996). The basin is broadly subdivided by King and Thrasher (1996) into the Western Stable Platform and the Eastern Mobile Belt (Fig. 1). The Eastern Mobile Belt has undergone a multiply deformed tectonic evolution including folding and thrusting, extension, and multiple phases of erosion. The Western Stable Platform on the other hand has remained relatively stable and is structurally simple (Armstrong et al., 1997; Hansen and Kamp, 2004; King and Thrasher, 1996). Furthermore, the Eastern Mobile Belt is subdivided into a northern and southern region. The northern region includes the Northern and Central Taranaki Grabens, and the southern region includes the Tarata Thrust Zone and Southern Inversion Zone (Hansen and Kamp, 2004). The Northern Taranaki Graben is the area of interest for this study. It is bounded to the west by the Cape Egmont Fault Zone and to the east by the Turi Fault Zone (Fig. 1).

The Taranaki Basin has a complex tectonic history. The basin is floored entirely by continental crust (King and Thrasher, 1996). The floor of the basin is the Permian Brook Street terrane and Late Permian to Late Jurassic Murihiku terrane. These terranes are stretched by intrusion of the Median Batholith. The Median Batholith was formed from subduction-related magmatism at ca. 375-100 Ma (Mortimer, 2004). The oldest sedimentary strata are of mid-Cretaceous age and lie on an erosional contact with the basement. The development of the Taranaki Basin has been divided by King and Thrasher (1996) into three main phases. An
additional division of mid-Miocene to recent back-arc extension has been added as part of this study.

1. Late Cretaceous to Paleocene intra-continental rift.

2. Eocene to Early Oligocene passive margin.

3. Oligocene to Mid-Miocene active marginal basin.

4. Mid-Miocene to Recent back-arc extension.

1. Late Cretaceous to Paleocene

During the Late Cretaceous, sea-floor spreading in the Tasman Sea separated New Zealand from Gondwana, which was contiguous with Australia and Antarctica (Mortimer, 2004). Rifting in the New Caledonia Basin developed a series of NNE-SSW trending sub-basins and half-grabens in which Late Cretaceous sediments were deposited (Thrasher, 1989). Further spreading in the Tasman Sea helped to develop these basins around 80 Ma (Weissel and Hayes, 1977). Deposition in these Taranaki sub-basins was dominated by a variety of non-marine, fluviatile and fluviodeltaic facies. During the Late Paleocene, a major regional transgression occurred across the northern Taranaki Basin. Marginal marine facies of the Kapuni Group were deposited in the northwestern part of the basin. The Paleocene horizon interpreted in this study most likely corresponds to siltstones of the Kapuni Group (Figs. 2 and 3). At this time, the Taranaki Basin was part of the Pacific Plate.

2. Eocene to Early Oligocene
Extension and normal faulting in the Taranaki Basin ceased during the Late Paleocene. Subsidence, which had previously been localized within individual sub-basins, gradually became more regional. The Taranaki Basin evolved through the Eocene and Early Oligocene as a passive margin (King and Thrasher, 1992). Marine transgression continued until the Late Eocene. The Top Eocene horizon in this study most likely corresponds to the Turi Formation, which is part of the Moa Group. The tectonic style within the Taranaki Basin began to change in the Late Eocene as the Australian-Pacific plate boundary evolved. A predecessor of the modern Australian-Pacific plate boundary began to propagate through New Zealand around 45 Ma (Wood and Stagpoole, 2007). This is evidenced by several isolated sub-basins near the south and southeastern margin of the Taranaki Basin (King and Thrasher, 1992).

3. Oligocene to Mid-Miocene

Following the development of several small sub-basins in the Late Eocene, the Taranaki Basin experienced a hiatus in sedimentation. Sedimentation rate during this time was very low and strata from the Early Oligocene are either absent or very thin (King and Thrasher, 1996). This hiatus in sedimentation is represented by a widespread unconformity. This unconformity represents the base of the Oligocene to Early Miocene Ngatoro Group, which is dominated by carbonate and highly calcareous clastic sedimentation (Figs. 2 and 3).

A period of subsidence during the mid-Oligocene to Early Miocene was basin-wide but was most pronounced adjacent to the Taranaki thrust fault in the east (King and Thrasher, 1996). The Hikurangi subduction zone, which currently accommodates oblique subduction of the Pacific Plate underneath the Australian Plate in the North Island of New Zealand, began to form in the mid-Oligocene. Subduction along the Hikurangi margin is believed to have commenced
around 24-30 Ma (Kamp, 1999; Stern et al., 2006). The Taranaki Basin at this time began to resemble a foreland basin with lithospheric subsidence occurring in areas adjacent to an overriding thrust belt (e.g., DeCelles and Giles, 1996; King et al., 1992). This subsidence renewed marine transgression with greater water depths than the preceding Eocene transgression (King and Thrasher, 1996).

In the early Miocene, basement uplift by thrusting along the Taranaki Fault further enhanced foreland subsidence west of the Taranaki Fault and loaded the adjacent lithosphere (Holt and Stern, 1994; King and Thrasher, 1992). The onset of major horizontal shortening along the basin’s eastern flank began around 22-20 Ma (King and Thrasher, 1992). The Australian-Pacific rotation pole migrated southward and the subduction zone continued to propagate southward. This plate configuration preceded the formation of the modern Alpine Fault system, a strike slip fault system that traverses the south island of New Zealand (King and Thrasher, 1996). Active low-angle thrusting continued in the early Miocene west of the Taranaki Fault along the Tarata Thrust Zone (Fig. 1). The western limit of subduction-related, foreland fold thrust belt development is represented by this zone (King, 2000). Increased convergence also brought about a change in sediment deposition type from carbonate-dominated to terrigenous-dominated. This change also marks the onset of the regressive megacycle that continues today (King and Thrasher, 1992).

Near 14 Ma, the main zone of compression shifted to the south, and large amounts of sediment derived from areas to the south and southeast of the Taranaki Basin were shed northwestward into the basin (Giba et al., 2010; King, 2000; King and Thrasher, 1996). Sediment deposition throughout the Miocene was an entirely marine clastic-dominated succession known
as the Wai-iti group. Six formations make up the Wai-iti group, including the Manganui, Moki, Mohakatino, Mount Messenger, Urenui, and Ariki. The base of the Moki formation and the Ariki formation are mapped in this study (Figs. 2 and 3).

Arc volcanism began in the northern offshore Taranaki Basin around 15-14 Ma (Hansen and Kamp, 2004; King, 2000). Volcanic edifices that make up the Mohakatino Volcanic Arc form a NNE-SSW trend along the axis of the Northern Taranaki Graben (Fig. 1), which is subparallel to the modern Hikurangi subduction zone. This episode of subduction-related magmatism includes a submarine stratovolcano named Kora, located ~50 km north of the center of the Parihaka 3D survey, which was built from 16-12 Ma (Bergman et al., 1991). According to King and Thrasher (1996), the main period of submarine volcanism was between 14-11 Ma and consisted of mainly low- to medium-K, calc-alkaline andesite, basaltic andesite, and subordinate basalt.

4. Mid-Miocene to Recent

Volcanism continued into the Late Miocene, and magmatism in the back-arc seems to have continued to the present. The volcanic arc migrated onshore to the east during the Pliocene and was replaced by back arc extension and concurrent magmatism in the Taranaki Basin. The volcanic arc that migrated onshore is now known as the Taupo Volcanic Zone and is presently active (Hansen and Kamp, 2002). Near the end of active arc volcanism in the Taranaki Basin, N-NE trending extension and normal faulting began and the Northern Taranaki Graben began to develop (King, 2000). This marked the beginning of the back-arc phase in the Eastern Mobile Belt of the Taranaki Basin, which continues to the present. Volcanism there includes the Sugar
Loaf Islands; a Pliocene to Pleistocene intrusive center near New Plymouth (Leitner et al., 2000) aged 1.74-2.03 Ma (Hoke and Leitner, 2000); and the active Taranaki Volcano.

A thick accumulation of marine sediment was deposited contemporaneously with back-arc extension and buried the volcanic arc. Pliocene to Pleistocene deposition was dominated by the Giant Foresets Formation of the Rotokare Group, consisting of fine-grained mud to silt with interspersed sandstone, three horizons of which are mapped in this study (Figs 2 and 3).

Taranaki Basin is New Zealand’s only petroleum producing region and much of the basin lies offshore. It does come onshore, however, onto the Taranaki Peninsula and the northernmost South Island. There is still significant potential for hydrocarbon discoveries within the Taranaki Basin, and so it has been studied extensively. Numerous exploration seismic lines have been shot across the Taranaki Basin, including the 3D Parihaka seismic dataset that was used in this study (Fig. 4).

**METHODS**

To understand which processes are most important for solving the “room problem” and understanding pluton emplacement, a careful analysis of the Parihaka 3D seismic reflection data was done. The seismic survey was conducted by Pogo New Zealand from January 12 to February 24, 2004 and covers ~1520 km$^2$. It was acquired in 43 days by Veritas DGC’s vessel, *Viking II* which towed an array of cables with a 3.15 km$^2$ footprint in a NE-SW (57º/237º) direction (Fig. 5). The towed array included eight cables 4500 m long, imaging at a nominal 60-fold, with a spacing of 100 m at a depth of 9 m. Two pairs of air guns separated by 50 m were
towed at 7 m depth and fired flip-flop. Data were recorded to 6 seconds and sampled at 2 ms intervals (Cohen et al., 2005; Veritas/Pogo New Zealand, 2005)

Processing of the Parihaka 3D dataset by Veritas DGC Asia Pacific LTD included the application of a minimum phase source de-signature filter resampling from 2 to 4 ms with the application of a minimum phase anti-alias filter. A low cut filter of 5 HZ/18dB was also applied to the data. Other processing included a spherical divergence correction, automatic de-spiking, swell noise attenuation, and high resolution linear noise attenuation. A gain correction of 1.5 dB/sec was applied to further modulate the data. A spatial anti-alias K-filter, adjacent trace drop, and tidal statics correction were all applied. First pass velocity analyses were performed on a 1x1 km grid and normal moveout correction was applied using these first pass velocities. To obtain more uniform fold coverage, the Fourier Regularisation of Irregular Data (FROID™) option was used to fill up holes and bin-center the data. An attempt was made to remove the acquisition footprint of adjacent sail lines. The normal moveout correction applied prior to FROID™ and the spherical divergence correction were removed. A final, zero phase pre-stack time migration cube was completed and this is the version of the data used here. (Cohen et al., 2005; Veritas/Pogo New Zealand, 2005). All seismic images from the Parihaka 3D dataset used in this study have a vertical exaggeration of 2.2:1, assuming an average velocity of 3 km/s. The maximum vertical resolution is approximately 8-10 m, assuming a frequency of 60 Hz and an average interval velocity of 3 km/s.

GeoProbe© Volume Interpretation Software, a product of Halliburton, was used to visualize and interpret the seismic data. A number of seismic attributes (a measurable property of seismic data) were extracted from the data and placed into three-dimensional “volumes,” including amplitude and semblance. Seismic attribute analysis is based on using quantitatively
derived measures of the seismic waveform to enhance geologic features and to improve the visual ability of the interpreter. This basic concept is described by Taner and Sheriff (1977). The amplitude attribute uses the seismic signal amplitude. A red/blue color scheme was used for all images of the amplitude attribute in this study, with red representing maximum amplitude and blue representing minimum amplitude. The semblance attribute is Halliburton’s version of coherence or dissimilarity. Adjacent seismic waveforms that have high dissimilarity will be highlighted by the semblance attribute. This attribute is very useful for identifying faults and other contrasts in seismic character from geologic changes. It was very useful in this study in identifying igneous bodies as well as numerous faults caused by igneous intrusion. Other seismic attributes such as shaded relief and instantaneous “sweetness” were also created but were not useful for this study.

The Arawa-1 petroleum well is the only well within the Parihaka 3D survey. However, three other wells, Taimana-1, Witiora-1, and Okoki-1, located just outside the survey perimeter were tied into the survey by 2D lines during acquisition (Fig. 5). Of these wells, only Arawa-1 and Taimana-1 were used in this study. Pogo created a synthetic seismic tie to the Arawa-1 well, which allowed them to tie in several key seismic horizons (Cohen et al., 2005). Our selection of key seismic horizons and events to be interpreted was based on Pogo’s interpretation and included from youngest to oldest three horizons within the Giant Foresets Formation, a horizon within the Ariki Formation, the base of the Mangaa Formation, the base of the Moki Formation, the top of the Eocene, and the top of the Paleocene.

Faults were interpreted by using a tool within GeoProbe© entitled “ezFault™,” which uses a surface-fitting algorithm to generate smooth and geologically reasonable fault planes. This is a semi-automated process in which the interpreter picks the fault plane at user-defined
intervals and allows the algorithm to interpolate between interpreted picks. Faults were easiest to interpret by using a feature within GeoProbe© called volume co-rendering, in which an amplitude volume can be overlain with a semblance volume to highlight faults.

Stratigraphic horizons were created using manual, semi-automated, and automated horizon picking. A closely-spaced grid was first created by using manual horizon interpretation and waveform-based picking called “ManuTrack™” (Fig. 6). Next, the seismic trace tracking-based horizon generator, termed “ezTracker™,” was used to interpolate between the manually interpreted lines using specified settings to ensure the most accurate results. This included setting a score %, which is a measurement of how well the amplitude of the target trace matches the amplitude of the ManuTrack™ horizon trace. A maximum jump setting was also used to exclude Z values outside the maximum jump range of the input ManuTrack™ horizon. This was very effective in creating accurate horizons in places where the amplitude had a weak signal and to prevent jumping to a higher or lower seismic event. In an area such as the Northern Taranaki Graben where faults are numerous and fault throw varies considerably, much care must be taken to ensure that horizons do not bleed across faults and that the same seismic wavelet is picked on both sides of the fault. Therefore, faults were interpreted first and used as boundaries that the automated horizon picker could not pick through.

The shapes of the igneous bodies were mapped with “ezSurface™” which uses the same algorithm as “ezFault™” to create a three-dimensional body that resembles the shape of the intrusion. The shape of the igneous body is created using a semi-automated process, which involves interpreting the body at user-specified depths, typically every 100ms of two-way traveltime (TWT), and allowing the algorithm to interpolate the surface between user interpretations. Apophysis 2 and the main body of the Southern Intrusive Complex were
interpreted by digitizing its shape while moving the probe down in plan view. Apophysis 1 was interpreted by digitizing its shape while moving the probe in cross section view. The semblance volume was used in conjunction with the amplitude volume to better define the margins of the intrusion. Difficulties in defining the margins of the intrusion were caused by possible velocity pull-ups, over migration, and seismic attenuation.

GeoAnomalies were used to determine whether the intrusions are composite (formed from multiple episodes of magma injection) or if they were constructed by a single pulse of magma. GeoAnomalies is an automatic body detection tool that is able to extract features/bodies of interest from a volume of data using criteria such as similar amplitude, connectivity, and size.

The Parihaka 3D dataset is in two-way travel time (TWT). Depths were converted from a time-depth equation provided by New Zealand Oil & Gas that was created from time-depth tables from the Arawa-1 well, which is located in the center of the Parihaka 3D survey.

The volume of the Southern Intrusive Complex was calculated by measuring the area of the mapped surface of the Southern Intrusive Complex in plan view using the built in measuring tool in GeoProbe®. The area was then multiplied by a depth interval between each measurement to get a volume. This process was repeated at increments of 100 ms (115-175 m) from the top to the base of the Southern Intrusive Complex. The interval volumes were then summed over the 8.3 km height of the intrusive complex.

RESULTS

The uninterpreted Parihaka 3D dataset is presented in Movies 1-4. Movies 1-2 animate time slices through the dataset along the Z-axis from 0 ms (seafloor) to 4900 ms (~9 km depth) for the amplitude and semblance volumes, respectively. Movies 3-4 animate vertical slices at an
increment of 125 m along the X-axis (SW-NE) for the amplitude and semblance volumes, respectively.

**DISCUSSION**

Three intrusions are evident in the seismic data and form a north to south trend of older to younger intrusions. They have been termed the Northern Intrusion, Central Intrusion, and Southern Intrusive Complex (Fig. 7). The Southern Intrusive Complex is the focus of this study. We describe how the interpreted stratigraphic horizons were deformed and faulted by the emplacement of igneous intrusions and its apophyses (an apophysis is an offshoot from a larger igneous intrusive mass). We also discuss the regional fault patterns and intrusion-related faults. In order to answer questions relating to the “room problem,” igneous intrusion structures and pluton geometry are presented. Emplacement history of the Northern Intrusion, Central Intrusion, and Southern Intrusive Complex is discussed. Finally, multiple space making mechanisms that acted on the Southern Intrusive Complex are presented.

**Stratigraphic Interpretation**

A total of 8 stratigraphic horizons (Fig. 3) are mapped that correlate either to a specific horizon within a formation or to an interpreted age in the Northern Taranaki Graben (Fig. 2). These horizons are chosen because of their strong seismic reflection signals, large lateral extents, and ability to tie into well picks. They also have important implications for fault movement and timing of intrusion emplacement. The horizons and time periods that are mapped (from youngest to oldest) include:

- Giant Foresets Formation (~5 Ma to recent)
  - GFF Shelf 1
- GFF Shelf 2
- GFF Slope

- Ariki Formation or Ariki Formation Correlative (5-6 Ma)
- Base of the Mangaa Formation (~7 Ma)
- Base of the Moki Formation (14 Ma)
- Top of the Eocene Horizon (34 Ma)
- Paleocene Horizon (57 Ma)

**Giant Foresets Formation**

The Plio-Pleistocene Giant Foresets Formation is a shelf to slope to basin floor succession largely made up of fine-grained mud to silt and interspersed sandstone. It also contains localized volcaniclastic deposits (Hansen and Kamp, 2002). It is the youngest stratigraphic unit within the Northern Taranaki Graben. Thickness varies across the Taranaki Basin, but extension and opening of the Northern Taranaki Graben created a local depocenter visible in this dataset northeast of the Arawa-1 well where thickness is measured to be over 2 km (Fig. 8). The formation is easily identifiable in the Parihaka 3D seismic dataset as described by King and Thrasher (1996) as “stacked and progressively offlapping (basinward) sigmoidal wedges defined by clinoform-shaped reflectors.” The overall succession was separated into four divisions by Beggs (1990), which includes topset reflectors (shelf facies), progradational and degradational foreset reflectors (slope facies), and bottomset reflectors (basin floor facies). This division is also clearly seen in the seismic data (Fig. 9). Two of the horizons in this study (GFF Shelf 1 and GFF Shelf 2) were mapped within the shelf facies, and one other (GFF Slope) was
mapped within the progradational slope facies. All three horizons were deformed by the Southern Intrusive Complex to varying degrees.

GFF Shelf 1 (Fig. 10) is a topset reflector (shelf facies) and is the shallowest reflector within the Giant Foresets Formation that was mapped for this study. Its approximate age is 1.5 Ma. The Southern Intrusive Complex has clearly domed and faulted this horizon, but did not pierce it (Fig. 10A). The effects of the two apophyses of the Southern Intrusive Complex are evidenced by the domed and faulted horizon. A semi-radial pattern of normal faults is apparent above the Southern Intrusive Complex. Faults are most closely spaced above the crests of both apophyses with an approximate spacing of less than 200 m (Fig. 10B). Fault offset is on the order of 10s of meters. A second fault system is evident in this horizon east of the Southern Intrusive Complex and is caused by another intrusion in which the Parihaka 3D dataset shows only its western margin. Also visible in this horizon is the Cape Egmont Fault Zone to the west with its relay ramp character as well as the western margin of the Turi Fault Zone to the east. Fault throw along the Cape Egmont Fault Zone increases to the north.

GFF Shelf 2 (Fig. 11) is a topset reflector (shelf facies) which bounds the upper limit of progradational slope facies. It has also been domed and faulted considerably. The horizon has been deformed upwards and has a dip of about 12° that fans out radially from the center of the dome. A semi-radial fault pattern is especially apparent when the semblance attribute is used to color the mapped horizon (Fig. 11B). Also apparent when using the semblance attribute on this horizon are a number of canyon confined channels within the graben, and a large, faulted channel complex that began on the Western Stable Platform and flowed into the graben. A left stepping en-echelon normal fault pattern is apparent, as well as increasing throw with depth along the Cape Egmont Fault Zone.
GFF Slope represents the progadational slope facies of the Giant Foresets Formation (Fig. 12). This horizon is domed and pierced by two apophyses of the Southern Intrusive Complex that merge at depth into one large body. Apophysis 1 is 4 km in diameter and apophysis 2 is 2 km in diameter. Dip angles along the pierced sides of the horizon are approximately 18°. Numerous normal faults above the Southern Intrusive Complex and along the margins of the two apophyses are evident (Fig. 12B). Two sets of canyon-confined channels are also present on this horizon. One set formed just west of the Cape Egmont Fault Zone and flowed N-NE, while the other formed just west of the southernmost apophysis and flowed S-SE. The channel nearest the margin of the intrusion is cut by faults that are related to the intrusion, which provides more evidence that the channels were in place prior to the rising intrusion.

*Ariki Formation*

The Giant Foresets Formation is underlain here by either the Ariki Formation, a correlative of the Ariki Formation (Hansen and Kamp, 2008), or possibly the Urenui Formation. The Urenui Formation has been previously correlated with the Ariki Formation due to its stratigraphic position, lithologic similarity, and presumed age (King and Thrasher, 1996). West of the Cape Egmont Fault Zone and the Arawa-1 well, the Giant Foresets Formation appears to be underlain by an Ariki Formation correlative as evidenced by a bold and continuous single reflector that corresponds to a thin marl unit (Hansen and Kamp, 2008). East of the Cape Egmont Fault Zone and towards the Taranaki Peninsula, the correlative seismic event that was picked most likely corresponds to the Urenui Formation. This horizon marks the base of the Pliocene and represents condensed sedimentation deposited under deep water conditions and very low sedimentation rates (Hansen and Kamp, 2008). Whereas younger horizons in the Giant Foresets Formation are pierced and domed by the two apophyses of the Southern Intrusive Complex, the
Ariki horizon is pierced by the main body of the intrusion where the two apophyses merge into one large body (Fig. 13). The intrusion margins show evidence of the horizon being deformed upwards during magma emplacement. Numerous horsts and grabens trending NE-SW are evident on this horizon. The relay ramp character of the N-S trending Cape Egmont Fault Zone is especially apparent, as is an increase in the amount of throw to the north along the fault zone.

**Base of the Mangaa Formation**

The Mangaa Formation gets its name from sandstone beds found in the Mangaa-1 well in the Northern Taranaki Graben. It is of latest Miocene to Pliocene age and accumulated in the Northern Taranaki Graben as submarine fan deposits (Hansen and Kamp, 2004) with sediment transport from south to north (King and Thrasher, 1996). The formation was divided into younger (Mangaa A) and older (Mangaa B) units which are separated by a marly unit by Murray and de Bock (1996). The Mangaa B unit is the horizon mapped in this study. The horizon was mapped throughout the study area but may represent a time equivalent correlative of the Mangaa Formation. The Southern Intrusive Complex has pierced the Mangaa horizon (Fig. 14). A smaller offshoot near the northern margin of the Southern Intrusive Complex has also pierced this horizon. It is completely detached from the main body and domes the sedimentary layers above it (Fig. 15). What may be another small igneous diapir also pierces this horizon just west of the Cape Egmont Fault Zone. Fault throw along the Cape Egmont Fault Zone is very similar to the measured throw of 920 m on the Ariki horizon, which may help determine the timing of the syndepositional nature of the Cape Egmont Fault Zone and is discussed further under Fault Interpretation. The strike of the Cape Egmont Fault Zone along the southwestern margin of the survey becomes more N-NE, whereas in younger horizons, it was largely N-S. The Central Intrusion, which is a deeper intrusion 11 km north of the Southern Intrusive Complex, is
evidenced by some doming of the Mangaa horizon, as well as a concentrated, semi-radial pattern in the Mangaa horizon. These faults are especially evident when the semblance attribute is applied to the horizon (Fig. 14B).

**Base of the Moki Formation**

The Moki Formation consists of interbedded sandstone, siltstone, and mudstone, with occasional limestone stringers and concretion horizons (King and Thrasher, 1996). Its lithologic makeup causes a high amplitude seismic reflection signature, which is easy to identify throughout the study area. The Moki horizon is deformed upwards at the margins of the Southern Intrusive Complex, which is at its largest diameter at this location (Fig. 16A). The Northern and Central Intrusions have domed the Moki horizon (Fig. 16). The Central Intrusion exhibits a dominant radial fault pattern, and the Northern Intrusion was emplaced along the Cape Egmont Fault Zone, which is merged into one large fault at this depth. Fracture patterns are particularly evident when semblance is applied to this horizon (Fig. 16B). A dike-filled fault is interpreted to be present on the southeastern margin of the seismic survey, which pierced the Moki horizon. Magma emplacement of the Southern Intrusive Complex was strongly controlled by the NE-SW fracture trend as discussed below. Channeling on the Moki horizon is also evident on the Western Terrace of the study area.

**Top of the Eocene Horizon**

This horizon represents the end of the Eocene, and most likely corresponds to the Turi Formation, which was the most prominent formation being deposited in the Northern Taranaki Graben at this time. It is a carbonaceous, marine mudstone of significant lateral extent in the Taranaki Basin (King and Thrasher, 1996). The Eocene horizon is structurally very similar to the
Moki horizon, but notable differences are that the Northern Intrusion has domed the Eocene horizon significantly and the top of the Central Intrusion has pierced the Eocene (Fig. 17). A southward migration of older to younger intrusive events is evident in this horizon with the three intrusions. This matches the overall southward migration of volcanics of the Mohakatino Volcanic Centre (15 to 1.6 Ma) which intrudes and partially fills the Northern Taranaki Graben (King and Thrasher, 1996) and of which these intrusions are most likely related.

**Top of Paleocene Horizon**

The Paleocene horizon is interpreted to correlate with a sealing shale in the Maui and Tui areas to the south (Cohen et al., 2005). Due to the lack of a strong and coherent seismic reflector, the Paleocene horizon is mapped with less confidence than other horizons previously described, particularly in the southern half of the survey. A series of N-S trending tilt-fault blocks are visible in the northwestern extent of the survey (Fig. 18). The horizon is pierced by the Northern Intrusion, Central Intrusion, and Southern Intrusive Complex; however, the margins of the intrusions are difficult to define because of the lack of coherent seismic reflectors.

**Fault Interpretation**

Two normal fault patterns are present in the study area: the N-S trending Cape Egmont Fault Zone on the west and the NE-SW trending faults of the Turi Fault Zone on the east (Fig. 19). Together these fault zones define the Northern Taranaki Graben (Fig. 1). The Cape Egmont Fault Zone also separates the Western Stable Platform from the Eastern Mobile Belt. The two fault zones intersect to the southwest, marking the southern termination of the Northern Taranaki Graben. Both the Cape Egmont Fault Zone and Turi Fault Zone consist primarily of normal dip-slip faults. Pilaar and Wakefield (1978) have inferred that many faults in the basin
have a significant amount of right-lateral strike-slip. Recent studies, which include using a combination of contemporary strain data and slickenside striations from outcropping faults indicate regional extension in a NW-SE direction and provide no evidence to support significant strike-slip motion in the basin (Giba et al., 2010). The left-stepping, en echelon array of normal faults--particularly those that form the Cape Egmont Fault Zone--is interpreted to be a result of minor strike-slip motion. Minor amounts of strike-slip faulting have been reported in some N-S striking faults (King and Thrasher, 1996; Nodder, 1993), but no evidence for significant strike-slip motion was found in this study. For example, no lateral offset was found in the faulted submarine channel systems.

**Cape Egmont Fault Zone**

This fault zone has a left-stepping, en echelon fault pattern with a series of relay ramps and fault splays (Fig. 19). It has a dominant N-S strike. Renewed extension (post-Cretaceous) began along the Cape Egmont Fault Zone during the late Miocene (King and Thrasher, 1992). This renewed extension is evident in Figure 20, which indicates that fault movement must have started at ~8 Ma. Fault throw increases considerably with depth indicating syn-depositional movement. Fault throw also increases from south to north. Fault throw at 1 km southeast of the Arawa-1 well increases from 150 m as measured on the GFF Shelf 1 horizon to as much as 984 m as measured on the Eocene horizon (Fig. 20). The onset of offshore intrusion occurred while the Cape Egmont Fault Zone was active, which suggests magma may have migrated upwards along extensional faults associated with the Cape Egmont Fault Zone (King and Thrasher, 1992).
**Turi Fault Zone**

This fault zone consists of numerous Plio-Pleistocene normal faults and marks the eastern flank of the Northern Taranaki Graben. Most faults step strata down to the northwest; however, east-dipping faults are also present but typically have less cumulative throw (King and Thrasher, 1996). Only the western margin of the Turi Fault Zone is imaged in this study. Emplacement of the Southern Intrusive Complex was controlled by this fault zone as evidenced by the position and elongate shape of the complex in the direction of the regional fault pattern. A left stepping, en echelon array of normal faults is also present in the surveyed area, beginning west of the Southern Intrusive Complex and merging with faults that were caused during intrusion emplacement (Fig. 21).

**Faults Related to Igneous Intrusion**

Numerous extensional faults accommodated the emplacement of the Southern Intrusive Complex. Most faults extend from the top of the Southern Intrusive Complex to within ~200 m of the seafloor, indicating the young nature of the Southern Intrusive Complex. These steep, dip-slip faults form a semi-radial pattern in the roof rocks, but are strongly controlled by the regional stress field as many of the faults are sub-parallel to those of the Turi Fault Zone that form the graben (Fig. 21). Faults fan out across the top of the Southern Intrusive Complex and change dip direction from one side to the other. Most faults trend NE-SW and rotate from east-dipping on the northern side of the apophyses to west-dipping on the southern side of the apophyses (Fig. 22). These faults terminate against the margins of the intrusion and extend as much as 3 km away from the margin. The highest concentrations of faults are directly above the two apophyses of the Southern Intrusive Complex (Fig. 23), but deeper faults associated with the larger intrusive body are also present. Throw along the faults above the apophyses has a range of less than 10 m to
approximately 150 m. Throw is typically greatest over the crests of the two apophyses. However, the fault with the most throw as measured on the GFF Shelf 2 horizon, is located in the saddle between the two apophyses. It has an average throw of over 150 m and is greatest directly above the center of the main body of the Southern Intrusive Complex. Throw on faults that terminate against the margins of the intrusive complex is on the order of 10s of meters.

**Igneous Intrusion Structures**

Without knowledge of the geologic history of the Taranaki Basin, the intrusions as imaged in the Parihaka 3D seismic data may be interpreted as salt diapirs. However, no significant amount of salt was ever deposited throughout the geologic history of the Taranaki Basin. The intrusions are a continuation of the southern migration of the Mohakatino Volcanic Centre. Furthermore, gravity and magnetic studies are consistent with igneous vs. salt or shale “diapirs” (Fugro Robertson Incorporated, 2007). The two apophyses of the Southern Intrusive Complex have a strong magnetic signature as seen with a 4 to 2 km band pass filter of the reduced-to-pole magnetic data (Fig. 24). Approximately 5 km southeast of the Southern Intrusive Complex a dike-filled fault that trends NE-SW also has a strong magnetic signature. Where this dike pierced the base of the Moki horizon it is about 4 km wide (Figure 16). The Southern Intrusive Complex is ~5 km wider as seen in this seismic study than it has been modeled by magnetics. Neither this study nor the magnetic model shows a discernible pluton floor.

Most of the literature that discusses the geologic history of the Taranaki Basin refers to large offshore igneous features as buried submarine stratovolcanoes. Indeed, there are several documented volcano complexes in the northern Taranaki Basin, including the Kora stratovolcano. These complexes occupy over 25% of the area of the Northern Taranaki Graben based on aeromagnetic surveys (Bergman et al., 1991). However, the morphology of the bodies
imaged in the Parahaka 3D survey is not consistent with the submarine stratovolcanoes, as discussed below. In addition, intrusions may not be as uncommon as previously thought. In the Fugro Robertson Incorporated report (2007), difficulty was encountered in estimating magnetic basement depth due to “intrusives that may be present in the section at various levels as sills,” and “intrusive dykes or plugs that may be present in the section penetrating the overlying sediments above basement.” Also, intrusive rocks were encountered at a depth of 3.2 km in the Tua Tua-1 well. This well is 60 km north of the Kora stratovolcano. (Rankin et al., 1988). The Sugar Loaf Islands near New Plymouth expose igneous intrusions about 400 m across that may be part of an even larger igneous body at depth (Arnold, 1959; Leitner et al., 2000).

The seismic reflection response of submarine volcanoes, particularly those in the Northern Taranaki Graben and nearby Northland, differs significantly from the igneous intrusions imaged in the Parahaka 3D dataset. These submarine volcanoes as imaged by seismic methods typically have the following features:

- Circular shapes in plan view.
- Simple conical shapes in cross section (Figs. 25 and 26)
- Internal stratification with dips away from the center of the volcano (Figs. 25 and 26).
- Strong reflectors marking the base of the volcanoes (Fig. 26).
- Little or no faulting above the crests of the volcanoes (Figs. 25 and 26).
- Vertical extents of ~1-3 km (Figs. 25 and 26)
- Onlap of surrounding strata rather than doming and thinning (Figs. 25 and 26)

While the igneous intrusions in the Parahaka 3D dataset have circular shapes in plan view, they lack other features seen in buried volcanoes, such as an internal structure and distinct base. Seismic reflectors are dispersed and non-existent within the body of the intrusion, and there is no
discernible floor. The vertical extent of the Southern Intrusive Complex is approximately 5 to 7 km greater than the height of a typical stratovolcano (1-3 km). Numerous faults above the body of the intrusions are also present, which do not exist in the sedimentary layers above the volcanoes. The sedimentary layers onlap and bury the volcanoes, whereas the intrusions have domed and faulted the overlying layers. Other features within the Parihaka 3D dataset also provide evidence that the imaged “volcanic” features are in fact intrusions. These include timing relationships of the channel systems and intrusion-related faults. A prominent meandering channel system is present along the western flank of apophysis 1, and is cut by faults related to the emplacement of the intrusion (Fig. 27). This channel system is interpreted to have been deposited before the emplacement of the intrusion because of its cross-cutting relationship with the faults and its meandering nature along the flank of the intrusion, which would not be expected to occur along the flank of a pre-existing submarine volcano.

**Pluton Geometry**

Analysis of the seismic images show that the intrusions range from less than 3 to as much as 12 km across (Fig. 28). The intrusions are steep-sided and do not resemble sills, but their bases are not resolved. The top of the Southern Intrusive Complex is sharply delineated and marked by multiple apophyses as much as 4 km across and hundreds of meters high. Deformation along the sides of the Southern Intrusive Complex is dominated by highly attenuated, dipping strata with apparent dips of 45° or higher (Fig. 29). Dips decrease rapidly away from the intrusion, and doming extends several hundred meters from the margins. The interpreted body of the Southern Intrusive Complex and Apophysis 2 differ slightly than the interpreted body of Apophysis 1. This is due to the different views in which they were
interpreted, as described above. The ribbon-like features and their orientation are a result of the different methods in which the intrusive bodies were interpreted.

At its greatest extent, the Southern Intrusive Complex has a diameter of 12 km. The complex has two apophyses that merge at depth. Apophysis 1 has a diameter of 4 km, and apophysis 2 has a diameter of 2 km. Several small sills are located along the margins of the intrusive complex and are typically 200 m wide. There is no discernible floor to the pluton, making an estimation of pluton thickness difficult. This uncertainty is complicated by the possibility that the floor could be hidden by the inability of the seismic methods to return a coherent reflection below the main intrusive body. Nevertheless, the main body is interpreted to extend to a depth of at least 9 km giving a total vertical thickness of ~8.3 km (Fig. 29).

Both the Northern and Central Intrusion have much smaller diameters than the Southern Intrusive Complex. The Northern Intrusion is the second largest intrusion located in this study. It has a diameter of 3 km and appears to extend to a depth of at least 9 km. The Central Intrusion has a diameter of ~1.5 km and also extends to a depth of at least 9 km.

**Emplacement History**

The three intrusions within the Parihaka 3D dataset follow the trend of the Mohakatino Volcanic Centre with the Northern Intrusion being the oldest and the Southern Intrusive Complex being the youngest. The Northern Intrusion is emplaced in the footwall block of a fault splay from the Cape Egmont Fault Zone. It deforms the Eocene horizon into a faulted dome, and doming is also evident in the Moki horizon. Deformation is not evident above the Moki Horizon indicating that emplacement ceased at approximately 10 Ma.

The Central Intrusion is emplaced along the axis of the Northern Taranaki Graben. It pierces the Eocene horizon and deforms the Moki horizon into a dome with a radial fault pattern.
Deformation associated with emplacement of the Central Intrusion is not evident above the Ariki Formation, indicating the emplacement ceased about 5.3 Ma.

The Southern Intrusive Complex, which is the focus of this study, had a more complex emplacement history. The end of emplacement of the Southern Intrusive Complex is interpreted to be between 3-1 Ma based on cross-cutting relationships with the surfaces mapped in the Giant Foresets Formation. The Southern Intrusive Complex was emplaced along the southwestern margin of the Turi Fault Zone. This intrusive center is composite and formed from multiple, steep-sided intrusions as evidenced by its complex margins, roof domes, and multiple apophyses (Fig. 29). Multiple episodes of magma injection are indicated by angular unconformities in the sedimentary strata around the complex. Within the Southern Intrusive Complex, there are two distinct intrusions that correspond to the two main apophyses (Fig. 30). This is evidenced by the GeoAnomaly body detection tool, which is designed to distinguish three-dimensional bodies based on dissimilar seismic reflection characteristics. GeoAnomaly bodies are extracted either from the entire volume of data or from a selected probe that defines an area of interest in the seismic volume. A minimum and maximum anomaly size in voxels is specified so that the resulting GeoAnomaly bodies cannot be smaller or larger than the values you specify. An attribute search range is also used to determine what voxels will be used to create the GeoAnomaly bodies, and all extracted bodies will contain values within this range. For example, GeoAnomaly bodies of interest that have a high impedance contrast can be created by limiting the attribute search range to find only the brightest amplitude values from the amplitude attribute. However, to find the igneous bodies of interest, the GeoAnomaly body detection tool used the semblance attribute to find anomalous bodies within the discontinuous reflectors of the Southern Intrusive Complex. The GeoAnomaly tool provides evidence that two distinctive
igneous bodies comprise what appears to be one large intrusive body. The results indicate multiple episodes of magma injection and confirm that the two apophyses did not result from a single pulse of magma.

Numerous “bright spots” exist along the margins and near the roof of the Southern Intrusive Complex, which are interpreted as sills based on their geometry, position, and seismic response (Fig. 31). The character of the seismic reflection at their top boundaries mimics that of the seafloor, indicating an increase in seismic velocity created the bright spot. This is consistent with higher seismic velocity igneous rock below lower velocity sedimentary rock. The bright spots are typically 100-300 m in diameter and have circular to oval shapes in plan view. Many of the small sills also dome the sediment directly above them (Fig. 31), and magma migration paths are locally evident along faults with small offsets. In addition, small “off-shoots” of the Southern Intrusive Complex are visible at various depths along the margins of the intrusion, which are more evidence of its composite nature (Fig. 15), but because of their small sizes, they are not shown in the model of the intrusion’s shape.

**Space-Making Mechanisms**

As estimated by the method described above, the Southern Intrusive Complex has an approximate resolvable volume of 277 km$^3$ and extends to a depth of about 9 km. In order to accommodate this volume, multiple space-making mechanisms must have been involved during the emplacement of the intrusion (Fig. 32). The seismic data provide a unique opportunity to determine the amount of space made by mechanisms such as doming (roof uplift) and extension, whereas others that may have played a role are not seismically resolvable, such as stoping and floor subsidence.
**Doming**

Doming is an important space-making mechanism for many plutonic rock bodies. For example, the primary emplacement mechanism for many laccoliths, including those that make up the Henry Mountains in south-central Utah, is roof uplift (Horsman et al., 2010). To calculate the amount of space made by doming during pluton emplacement, a volume was calculated from the top of the first seismically resolvable horizon above the Southern Intrusive Complex to where the horizon is no longer affected by intrusion-related deformation. This volume represents a minimum amount of space created during pluton emplacement and is estimated to be 8.1 km$^3$, or 3% of the volume of the pluton. Line-length measurements were taken on sedimentary beds that were deformed and domed by the apophyses of the Southern Intrusive Complex. Sedimentary beds deformed over apophysis 1 were stretched 14% in a NE-SW direction and 17% in a NW-SE direction. Sedimentary beds deformed over apophysis 2 were stretched 19% in a NE-SW direction and 17% in a NW-SE direction. Sedimentary beds deformed along the margin of the Southern Intrusive Complex were also measured and found to have been stretched from 8.0% as measured near the Moki horizon to as much as 13.4% as measured near the Paleocene horizon. These measurements of margin deformation were not included in the total amount of space created by doming due to the unknown amount of velocity pull-up that may have occurred.

**Compression**

Compression of wallrocks can make significant space for pluton emplacement. Marko and Yoshinobu (2011) calculated as much as 54% shortening in the contact aureole of the White Horse Pluton in central Nevada, and Wang et al. (1999) estimated that about 20% of the space needed for a granitic pluton in southern China was the result of ductile shortening of its wall rocks. However, margins of the Southern Intrusive Complex were carefully studied and no
anticlines, synclines, or other complexities that would indicate significant compression of the sedimentary wall rocks were observed. No thickening or complex deformation is seen; only stretching and thinning are observed which is consistent with the doming described above.

Another type of compression could occur through compaction of the wet sediments around the intrusion as it grew, contributing to porosity loss (Morgan et al., 2008). The Southern Intrusive Complex intruded into wet sediments of the Giant Foresets Formation, which have an estimated minimum porosity of 23% at their maximum burial depth of 2000 m up to as much as 40% at shallower depths (King and Thrasher, 1996). Therefore, if the intrusion shouldered aside these sediments and caused their complete compaction, a minimum of 23% of the space at 2 km depth could have been formed. However, thicknesses of beds do not show any change within the aureole of the pluton. Thus, if this process occurred, then compaction must have been matched by compressive thickening, which is unlikely.

**Assimilation**

The process by which magma absorbs its host rock is known as assimilation and is important in many magmatic systems (e.g., Civarella and Wyld, 2008), but the amount of assimilated material in a specific pluton is difficult to estimate, even where it is well exposed at the surface.

Some assimilated materials are incompletely “digested” and are visible as xenoliths of the wall rock. Wang et al. (2000) estimated the areal percentage of these inclusions to conclude that about 1% of the volume of the Huichizi granite was made up of wall rock xenoliths. Most other studies of xenoliths find similar small proportions.

Radiogenic (e.g., Sr, Nd, Pb) and stable (e.g., O) isotopic studies can also be used to estimate the fraction of crustal materials assimilated by a magma that was initially derived from the mantle. For example, Perry et al. (1993) used Nd isotopic compositions to estimate that from 10
to almost 100% of some silicic magmas is of crustal origin. Wang et al. (2000) used Nd, and Sr isotopes to estimate a 64:36 ratio for mantle versus crustal proportions in the Huichizzi granite pluton. From this, they infer that 36% of the volume of the pluton consists of assimilated crustal materials, but they acknowledge that assimilation may not have occurred at the level of emplacement and probably occurred at a much deeper level. Host-rock ductile return flow (floor subsidence) may have transferred this “space” to the shallow level of emplacement.

Likewise, only very broad limits can be applied to the amount of assimilation in plutons by considering the thermal processes involved in digesting wall rock. Glazner (2007) has estimated that disaggregation of crustal material into hot basalt is limited to a few tens of percent. Careful consideration of thermal budgets show that assimilation to crystallization rates may exceed 1 for basaltic magmas deep in the crust and at high temperatures (Reiners et al., 1995). However, rates of assimilation in cooler andesitic magmas at the site of emplacement are thought to be much less than this. Graham et al. (1995) used a rate of assimilation to crystallization of only 0.2 in their models of the chemical and isotopic evolution of the andesite to rhyolite magmas from the nearby Taupo volcanic zone.

Moreover, assimilation at the site of emplacement may be limited by cooling at the contacts which builds an armor of solid rock that inhibits further assimilation of the wall rock (e.g., Best and Christiansen, 2001).

Not knowing the composition of the Southern Intrusive Complex, we have no way of estimating the amount of assimilation that may have occurred. However, assimilation is an important mechanism for explaining the space that a pluton occupies (e.g., Ciavarella and Wyld, 2008) and should be considered.
Extension

King and Thrasher (1996) measured 2 km of regional extension over a distance of 50 km across the Northern Taranaki Graben. This amount of extension was measured along the Top Eocene horizon from seismic reflection profiles. Locally, extension may have played a significant role in opening up space for the Southern Intrusive Complex during the time of emplacement. The amount of local extension was measured on a series of NW-SE transects across the Northern Taranaki Graben. Extension was estimated by using the Area/Distance tool within GeoProbe© to measure fault heave on a semblance time slice at two distinct depths within the Parihaka 3D dataset. A total of 2.2 km of extension over a distance of 30 km was measured near the crest of apophyses 1 and 2 at 600 ms (~0.5 km deep). It was also measured 10 km southwest of the Southern Intrusive Complex at 1820 ms (~2 km deep) to estimate the amount of extension near the initiation of emplacement. Extension was measured to be 2.3 km over a distance of 14 km. The diameter of the Southern Intrusive Complex at this depth is 7 km. Therefore, a minimum amount of the volume created by extension is estimated to be 33%. It is likely that numerous fractures and faults too small to be imaged by seismic methods exist in the section that was measured. For example, intense darkening above Apophyses 1 and 2 is evident in the GFF Shelf 2 horizon (Fig. 11B) that probably results from numerous small faults and fractures. Many “mode 1” fractures and multiple dikes or quartz veins are most likely present, but are below the resolution of the seismic data.

Other Mechanisms

Other mechanisms may have had a significant role in making space for the Southern Intrusive Complex, but are not seismically resolvable. Stoping may have occurred (e.g., Glazner and Bartley, 2006; Pignotta and Paterson, 2007), but stoped blocks are not imaged within the
intrusive complex. This is due to the inability of the seismic waves to return a coherent reflection from within the intrusive body. Stopped blocks may lack seismic contrast with the enclosing plutonic rock and they may also be too small to be seen. Floor subsidence is not seen due to the inability to seismically determine a base to the Southern Intrusive Complex.

CONCLUSIONS

We report for the first time the results of a detailed 3D seismic survey over large, steep-sided intrusive complexes in the shallow subsurface below the seafloor. Three large intrusive complexes are imaged off the western shore of New Zealand’s North Island. The Northern Intrusion with a diameter of about 3 km is the oldest of the three and emplacement ceased around 10 Ma. Emplacement of the Central Intrusion, also the smallest intrusion with a diameter of about 1.5 km, was completed by about 5.3 Ma. The Southern Intrusive Complex is the largest and youngest and was studied in the most detail.

The external shape of the Southern Intrusive Complex and several stratigraphic horizons were interpreted and reveal the adjacent strata are deformed and faulted by the intrusions. The Southern Intrusive Complex is 12 km across at its greatest diameter, extends to a depth of ~9 km, and has an estimated resolvable volume of about 280 km$^3$. The complex has 2 apophyses that rise 0.6 km before merging at depth, multiple sill-like off-shoots, steep walls, and domed and faulted roof rocks. The pluton was very shallowly emplaced, with the uppermost part of the intrusion reaching to about 1 km from the sea floor. Multiple episodes of magma injection were important during pluton growth as evidenced by multiple apophyses, sill-like off-shoots, and multiple stocks, as interpreted through the GeoAnomaly analysis.
The emplacement history of the Southern Intrusive Complex is complicated and may have lasted until 1 Ma based on the ages of its deformed and faulted wall rocks. The Southern Intrusive Complex was emplaced during back-arc extension and is located on a left-stepping relay ramp between two major normal faults. Intrusion-related normal faults were strongly controlled by the regional extensional stress field and mimic the trend of the regional fault patterns. The highest concentrations of normal faults related to emplacement of the Southern Intrusive Complex are located above the crests of its two apophyses.

Even though several potentially important space-making mechanisms--assimilation, stoping, and floor subsidence--are unconstrained by our data, several other important space-making mechanisms are likely for the Southern Intrusive Complex. Doming and roof uplift are most obvious in the 3D seismic data, but only create a small amount of the space required. Sidewall compression in the form of folding or stratal thickening has a minimal effect on creating space for the intrusion. However, lateral compression could have occurred if thickening of the beds was compensated by porosity loss in the wet sediments around the intrusion. Because the thickness of wall rock strata does not change away from the intrusion margin, porosity reduction must have been precisely matched by lateral compression. In this case, a significant fraction of the necessary space could have been made. Nonetheless, we consider this balancing of shortening and compaction to be speculative. Extension plays a major role in making space, with a minimum of 2.3 km of local extension measured over a distance of 14 km at the time of emplacement.
References Cited


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Figure 1. Index map of the Taranaki Basin and cross section of the Northern Taranaki Graben. (A) Simplified map illustrating the major geologic features of the Taranaki Basin and the location of the Parihaka 3D seismic survey. (B) Cross section through the southern margin of the Northern Taranaki Graben. The graben is bound to the west by the Cape Egmont Fault Zone and to the east by the Turi Fault Zone. (Modified from King & Thrasher, 1996)
Figure 2. Stratigraphic column of the Parihaka 3D seismic survey area in the Taranaki Basin. Thickness is measured in two-way traveltime (TWT) with approximate depths labeled. Interpreted seismic horizons of this study are indicated. Stratigraphic formations were based on King and Thrasher (1996) and Cohen et al. (2005).
Figure 3. Cross section through the Southern Intrusive Complex. All of the interpreted horizons are labeled and colored green. Cross section location seen in Figure 20.
Figure 4. Seismic coverage and well locations in the Taranaki Basin (modified from GNS Science, 2009).
Figure 5. Survey acquisition map showing Parihaka 3D survey, path of seismic vessel, and well ties (modified from Cohen et al., 2005).
Figure 6. Green lines show where the GFF Slope horizon was manually interpreted. Similar grids were created for all horizons. Lines were interpreted by using the “ManuTrack™” tool in the Geoprobe© Volume Interpretation Software.
Figure 7. Eocene horizon colored by elevation. Three intrusive centers are identified. The Eocene horizon is domed by the Northern Intrusion, is pierced by the top of the Central Intrusion, and is pierced by the Southern Intrusive Complex.

Figure 8. Isopach of the Giant Foresets Formation. The Giant Foresets Formation is thickest in the northeast corner of the survey, east of the Cape Egmont Fault Zone.
Figure 9. A) Division of the Giant Foresets Formation by Beggs (1990) as drawn by Hansen and Kamp (2002). B) Giant Foresets Formation divisions as imaged in the Parihaka 3D survey. (a) Topsets (b) Progradational Foresets (c) Degradational Foresets (d) Bottomsets
Figure 10. (A) GFF Shelf 1 horizon colored by elevation. (B) GFF Shelf 1 horizon overlain with the semblance attribute.
Figure 11. (A) GFF Shelf 2 horizon colored by elevation. (B) GFF Shelf 2 horizon overlain with the semblance attribute.
Figure 12. (A) GFF Slope horizon colored by elevation. (B) GFF Slope horizon overlain with the semblance attribute.
Figure 13. (A) Ariki horizon colored by elevation. (B) Ariki horizon overlain with the semblance attribute.
Figure 14. (A) Base of the Mangaa horizon colored by elevation. (B) Base of the Mangaa horizon overlain with the semblance attribute.
Figure 15. Offshoot near the northern margin of the Southern Intrusive Complex. This small intrusion has significantly domed the overlying sediment. A mapview of the amplitude volume with the interpreted body of the Southern Intrusive Complex is in upper-left. The cross section location is shown by the yellow line.
Figure 16. (A) Base of the Moki horizon colored by elevation. (B) Base of the Moki horizon overlain with the semblance attribute.
Figure 17. (A) Top of the Eocene horizon colored by elevation. (B) Top of the Eocene horizon overlain with the semblance attribute.
Figure 18. (A) Top of the Paleocene horizon colored by elevation. (B) Top of the Paleocene horizon overlain with the semblance attribute.
Figure 19. Oblique view of the GFF Shelf 2 horizon. This view shows the well-developed relay ramp style of the Cape Egmont Fault Zone and the western margin of the Turi Fault Zone.
Figure 20. A) Location on Cape Egmont Fault Zone where fault throw is measured and indicated by the white circle near the Arawa-1 well. Location of cross sections seen in Figure 3 and Figure 32 are also identified. B) Graph of measured fault throw on each interpreted horizon. The graph shows increasing fault throw with depth up until ~8 Ma, which is when back-arc extension likely commenced.
Figure 21. Time slice of the semblance volume at 660 ms. A left-stepping en echelon array of east-dipping normal faults is present to the west of the Southern Intrusive Complex and merge with faults caused during intrusion emplacement. Normal faults due to deformation caused by emplacement of the Southern Intrusive Complex were strongly controlled by the regional stress pattern and trend sub-parallel to regional faults of the Turi Fault Zone.
Figure 22. A) Cross section through Apophysis 2 of the amplitude volume. Numerous normal faults shown in yellow are imaged above the apophysis, and change dip direction from east-dipping on the northern side to west-dipping on the southern side. B) Semblance time slice at 600 ms (TWT). Location of cross section shown by yellow line.
Figure 23. Oblique view of the amplitude volume at 1692 ms (TWT) with the Southern Intrusive Complex mapped in red and faults in blue. Numerous normal faults are clustered above the two apophyses.
Figure 24. Reduced-to-pole magnetic anomaly map. Apophyses 1 and 2 are labeled. (Modified from Fugro Robertson Incorporated, 2007).
Figure 25. Cross section through the Kora Volcano. The internal stratification of the volcano is evident. Little to no faulting is present over the crest of the volcano. (constructed from the Kora 3D dataset, New Zealand Petroleum and Minerals)

Figure 26. Buried submarine volcano imaged by seismic data in the Northland Basin. In this cross section internal stratification and a discernible floor are evident in the seismic image. Little to no faulting is apparent over the crest of the volcano. Selected horizons are shown as black lines (Modified from Herzer, 1994).
Figure 27. An extensive submarine channel system is shown in this image of the GFF Shelf 2 horizon with the semblance attribute overlain. This horizon has been shifted down 116 ms to better image the submarine channel systems. The channels are offset by the intrusion related normal faults, and were formed prior to igneous intrusion. No strike-slip motion is apparent in offset channels.
Figure 28. Semblance time slice at 3060 ms (TWT) with measured diameters of the three intrusive centers.

Figure 29. Cross section of the amplitude volume with the interpreted body of the Southern Intrusive Complex. The complex was interpreted to 4.9 s (TWT) but there is no discernible floor.
Figure 30. Processing of the seismic data using the GeoAnomaly body detection tool suggest that multiple intrusions with distinct characteristics formed the composite Southern Intrusive Complex. Apophyses 1 and 2 are interpreted in blue. Apophysis 1 was fed by the GeoAnomaly that is represented in green. Apophysis 2 was fed by the GeoAnomaly that is represented in red.
Figure 31. A) Sill complex on western margin of the Southern Intrusive Complex as imaged in a cross section of the amplitude volume. The sill complex has domed the overlying sediment. B) Location of the cross section shown in yellow on a time slice at 1956 ms (TWT) of the amplitude volume.
Figure 32. Schematic cross section of the Southern Intrusive Complex summarizing the percentage of volume created by multiple space-making mechanisms. Also shown are the interpreted stratigraphic horizons and their ages. Cross section location seen in Figure 20.
MOVIES

Movies 1-4 can be downloaded at http://hdl.lib.byu.edu/1877/2833.

Movie 1. A series of time slices animated through the amplitude volume.

Movie 2. A series of time slices animated through the semblance volume.

Movie 3. Cross section animation from SW-NE through the amplitude volume.

Movie 4. Cross section animation from SW-NE through the semblance volume.