Mechanisms and Timing of Pluton Emplacement in Taranaki Basin, New Zealand Using Three-Dimensional Seismic Analysis

Phillip C. Cammans
Brigham Young University - Provo

Follow this and additional works at: https://scholarsarchive.byu.edu/etd

Part of the Geology Commons

BYU ScholarsArchive Citation

This Thesis is brought to you for free and open access by BYU ScholarsArchive. It has been accepted for inclusion in Theses and Dissertations by an authorized administrator of BYU ScholarsArchive. For more information, please contact scholarsarchive@byu.edu, ellen amatangelo@byu.edu.
Mechanisms and Timing of Pluton Emplacement in Taranaki Basin, New Zealand
Using Three-Dimensional Seismic Analysis

Phillip C. Cammans

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

Eric H. Christiansen, Chair
Ron A. Harris
John H. McBride
R. William Keach II

Department of Geological Sciences
Brigham Young University
October 2015

Copyright © 2015 Phillip C. Cammans
All Rights Reserved
ABSTRACT

Mechanisms and Timing of Pluton Emplacement in Taranaki Basin, New Zealand
Using Three-Dimensional Seismic Analysis

Phillip C. Cammans
Department of Geological Sciences, BYU
Master of Science

Several off-shore volcano-plutonic complexes are imaged in detail in the Parihaka 3D seismic survey in the Taranaki Basin of New Zealand. Three intrusions were analyzed for this study. Part of the Mohakatino Volcanic Centre (15 to 1.6 Ma), these intrusions have steep sides, no resolvable base reflectors, no internal stratification or structure, and they exhibit doming and faulting in the sedimentary strata above the intrusions. Deformation along the sides is dominated by highly attenuated, dipping strata with dips of 45° or higher that decrease rapidly away from the intrusions. Doming extends several hundred meters from the margins and produced many high-angle normal faults and thinned strata.

The intrusions lie near normal faults with the Northern Intrusion lying directly adjacent to a segment of the Parihaka Fault. The Central Intrusion has localized normal faults cutting a graben in the area directly above the intrusion and extending in a NE-SW direction away from it. The Western Intrusion is near the western edge of the Parihaka 3D dataset and is not situated directly adjacent to extensional faults.

Two distinct zones of intrusion-related faults developed around both the Northern and Central Intrusions representing two different stress regimes present during emplacement, a local stress field created by the intrusions during emplacement and the regional stress field. The deeper zones contain short radial faults that extend away from the intrusion in all directions, representing a local stress field. The shallower faults have a radial pattern above the apex of each intrusion, but farther from it, they follow the regional stress field and trend NE. Using our techniques to interpret radial faulting above both intrusions and the principal of cross-cutting relations, timing of emplacement for these intrusions are 3.5 Ma for the Northern Intrusion and between 5 and 4 Ma for the Central and Western Intrusions.

Observed space-making mechanisms for the Northern and Central Intrusions include doming (~16% and 11%, respectively), thinning and extension of roof strata (~4% for both), and extension within the basin itself (29% and 12%). Stopping and floor subsidence may have occurred, but are not visible in the seismic images. Magmatic extension may have played a significant role in emplacement.

Several gas-rich zones are also imaged within the seismic data near the sea-floor. They appear as areas of acoustic impedance reversal compared to surrounding sedimentary strata and have a reversal of amplitude when compared to the sea floor. The gas in these zones is either biogenic or sourced from deeper reservoirs cut by normal faults.

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

I would like to thank Gerald Morton and Plains Exploration and Production Company (formerly Pogo Producing Company) for providing Brigham Young University with a license to use the Parihaka 3D seismic dataset. Also, thanks to Halliburton (Landmark) for the generous grant of their software (GeoProbe©) to BYU’s Department of Geological Sciences.

A special thanks goes to my committee, Drs. Eric H. Christiansen, Ron A. Harris, and John H. McBride, and R. William Keach II for their invaluable support, mentoring, and guidance through not only my time here at BYU during graduate school, but also during my time as an undergraduate.

Most of all, I would like to thank my dear wife and children. Their patience, love, and unconditional support have been key to my progress as a student, father, and husband. Half of this degree belongs to my wife.
# TABLE OF CONTENTS

**TITLE PAGE** ........................................................................................................................................... i  
**ABSTRACT** ............................................................................................................................................ ii  
**ACKNOWLEDGEMENTS** .................................................................................................................. iii  
**TABLE OF CONTENTS** ................................................................................................................ iv  
**LIST OF FIGURES** ........................................................................................................................ vi  
**INTRODUCTION** .......................................................................................................................... 1  
**GEOLOGICAL SETTING** ................................................................................................................. 3  
  - Late Cretaceous to Paleocene – Intra-continental rift ................................................................. 5  
  - Eocene to Early Oligocene – Passive margin .............................................................................. 6  
  - Oligocene to Mid-Miocene – Foreland basin ............................................................................ 6  
  - Mid-Miocene to Recent – Intra-arc extension and magmatism ................................................ 8  
**METHODS** ....................................................................................................................................... 8  
**RESULTS** ......................................................................................................................................... 12  
**DISCUSSION** .................................................................................................................................... 12  
  - Interpreted Stratigraphic Horizons ......................................................................................... 12  
    - Top of Cretaceous fill .......................................................................................................... 12  
    - Top of Paleocene ............................................................................................................. 13  
    - Top of Eocene .................................................................................................................. 13
LIST OF FIGURES

Figure 1. The “room problem” diagram

Figure 2. Seismic coverage in the Taranaki Basin

Figure 3. Map of survey area within the Taranaki Basin

Figure 4. Stratigraphic Column

Figure 5. Parihaka 3D survey acquisition map

Figure 6. Fault heave cross-sections

Figure 7. Interpreted Top of Cretaceous fill horizon

Figure 8. Interpreted Top of Paleocene horizon

Figure 9. Interpreted Top of Eocene horizon

Figure 10. Interpreted Base of Moki Formation horizon

Figure 11. Interpreted Base of Mangaa Formation – Mangaa B Unit horizon

Figure 12. Interpreted Base of Giant Foresets Formation horizon

Figure 13. Location of igneous intrusions
Figure 14. Cross-section of Northern Intrusion in amplitude volume

Figure 15. Cross-section of Central Intrusion in amplitude volume

Figure 16. Cross-section of Hot Poker Intrusion in amplitude volume

Figure 17. Regional stress regimes

Figure 18. Schematic map of regional and intrusion-related fault

Figure 19. En-echelon faulting and horsetail splays

Figure 20. Rose diagrams of Central Intrusion radial faults

Figure 21. Rose diagrams of Northern Intrusion radial faults

Figure 22. Schematic cross-section of the Northern Intrusion summarizing space-making mechanisms

Figure 23. Schematic cross-section of the Central Intrusion summarizing space-making mechanisms

Figure 24. Magnetic anomaly map

Figure 25. Location of gas reservoirs with possible gas chimneys
INTRODUCTION

The “room problem”, understanding how igneous intrusions make room for themselves in the crust, is one of the least understood questions regarding pluton emplacement. Research on this topic has focused on if zones of least resistance such as faults, fractures and bedding planes are utilized by intruding magma to displace layers of rock. The primary means of host-rock displacement are doming of roof rocks (Stevenson et al., 2007), thinning of roof strata through stretching (de Saint-Blanquat et al., 2006), normal faulting and extension (Morgan et al., 2008), horizontal compression of side wall rocks (Morgan et al., 2008), pushing the floor of the pluton downward (e.g., Hutton et al., 2000), and stoping, the process of roof rocks falling through the molten portion of the magma chamber and accumulating on the floor (e.g., Pignotta et al., 2007) (Fig. 1).

A geologist’s attempt to answer questions about the “room problem” usually involve limited access to an intrusion with a surficial, planar view, and eroded roof-rocks (removing critical interactions with the host rock) to create hypothetical, subsurface cross-sections (e.g., Johnson et al., 1999). Occasionally, plutons may experience tilting, uplift, and erosion to expose a partial cross-section although these generally only have less than a kilometer of the intrusion exposed.

Many critical interactions between host rock and an igneous pluton may be observed and interpreted in order to account for space problems when the entire pluton is considered three-dimensionally (Best, 2003). Some ways to observe and interpret igneous bodies from a three-dimensional viewpoint are through deep mines or drill core (e.g. Kloppenburg et al., 2010), but these are generally expensive and proprietary.
Another way to image a pluton in the subsurface is through high-resolution seismic surveys, such as those done for petroleum exploration. Few of these have been performed in igneous provinces due to a general lack of economically recoverable oil and gas in these regions. Those that have been done are generally in the North Sea area and have increased our understanding of mafic sill emplacement (e.g., Hansen and Cartwright, 2006) and have not involved more silicic magmas that generally form continental crust.

Most silicic continental crust is generated at convergent plate margins such as the subduction zone between the Pacific plate and Australian plate east of the north island of New Zealand. Here, andesitic volcanism and magmatic intrusion has been occurring since the middle Miocene in the Taranaki Basin (King and Thrasher, 1996; Luke, 2012; Giba et al., 2013). This basin is, currently, the only hydrocarbon producing basin in New Zealand and because of this many 2D and 3D seismic surveys have been obtained to understand the geologic structure and hydrocarbon potential there (Fig. 2).

A 3D seismic survey was obtained in 2005 by Pogo New Zealand/Plains Exploration. Located just northwest of the Taranaki Peninsula in the Taranaki Basin (Figs. 2 and 3), this survey covers an area of 1520 km² and was performed and processed using modern geophysical techniques. Within this survey several igneous bodies are imaged in detail providing information about their shapes, sizes, relative timing of intrusion, location relative to geologically important structural features, and deformation of the host rocks: all of these giving insight into important emplacement mechanisms.

Luke (2012) studied the larger, southern-most intrusion in this data-set and created a 3D interpretation, discussed evidence for multiple pulses of magma into it, interpreted stratigraphic
horizons, and looked at the intrusion’s relationship to the Turi Fault Zone. Luke (2012) was partially successful in understanding part of the “room problem” through doming of overlying rock, but was unable to gain a full understanding of how the pluton was emplaced. He also suggests that extension within the basin may have played a role in their emplacement. Extension and faulting of rocks above the intrusions can also aid in constraining the timing of emplacement of intrusions by using cross-cutting relations.

For the purpose of this study, we focused on the intrusions named by Luke (2012) as the Central Intrusion and the Northern Intrusion by interpreting pluton shape, important geologic horizons, and faults (both regionally important fault zones and those related to emplacement). Also interpreted are two smaller intrusions, the Western Intrusion and a smaller intrusion located just southwest of the Northern Intrusion.

GEOLOGICAL SETTING

Northwestern New Zealand’s Taranaki Basin has a complex geologic and tectonic history. The basin has an area of about 100,000 km² (Fig. 3) and is constrained to the east by the Miocene-age, east-dipping Taranaki Fault. This fault is the back-arc thrust associated with subduction of the Pacific Plate at the Hikurangi Trench to the east of New Zealand’s North Island. The fault shows approximately 6 km of vertical throw exposing basement rock.

The Taranaki Basin has been subdivided by King and Thrasher (1996) into the Western Stable Platform and Eastern Mobile Belt. The Western Stable Platform is a continuation of the basin to the west and includes the Deepwater Taranaki Basin. The north end of the basin continues into offshore western Northland, the northernmost part of the north island of New
Zealand. Finally, to the south the basin lies on the northwestern margin of the southern island of New Zealand (King and Thrasher, 1996).

The Western Stable Platform has remained relatively quiet since the Eocene, tectonically, and retains a simple geologic structure. To the east, however, the Eastern Mobile Belt has experienced normal faulting and extension, multiple phases of deposition and erosion, and folding and thrusting creating a complex structural history (Armstrong et al., 1997; Hansen and Kamp, 2004; King and Thrasher, 1996).

Hansen and Kemp (2004) subdivided the Eastern Mobile Belt into a northern and southern region according to different geologic structures. The southern region contains the compressional Tarata Thrust Zone and Southern Inversion Zone, whereas the northern region includes extensional structures – the Northern and Central Taranaki Grabens. The Northern Taranaki Graben is bound to the west by the NNE-SSW trending Cape Egmont Fault Zone (the main fault in the Parihaka 3D seismic survey is the Parihaka Fault (Giba et al., 2010)) and to the east and south by the NE-SW trending Turi Fault Zone. These two fault zones meet at the southwest corner of the Parihaka 3D seismic survey (Fig. 3).

Rocks deposited in the basin overlie a basement of Permian to Late Jurassic age composed of the Brook Street (Permian age) and Murihiku (late Permian to late Jurassic age) terranes. These terranes represent fault-bound regions with distinctive structures and geologic histories. Between 375 and 100 Ma these terranes were intruded by the subduction-related Median Batholith while the area was part of Gondwana (Mortimer et al., 1997). Late Jurassic to mid-Cretaceous sedimentary rocks overlie this basement unconformably and are the oldest sedimentary strata in the basin (Luke, 2012).
The Taranaki Basin’s geologic history began in the late Cretaceous after deposition of these older sedimentary strata and continues to the present (Fig. 4). This history has been broken into four main time-frames by King and Thrasher (1996) as follows:

- Late Cretaceous to Paleocene – Intra-continental rift
- Eocene to Early Oligocene – Passive margin
- Oligocene to Mid-Miocene – Foreland basin
- Mid-Miocene to Recent – Intra-arc extension and magmatism

**Late Cretaceous to Paleocene – Intra-continental rift**

Beginning around 85 Ma, following cessation of subduction around Gondwana and the peneplanation of the Permian-Early Cretaceous age Rangitata Orogenic belt, formed from subduction of the Pacific plate beneath Gondwana (Knox, 1982), the Taranaki Basin was created. A series of NNE-trending sub-basins and half-grabens formed (Thrasher, 1989) as rifting opened up the Tasman Sea between Australia and New Zealand (Weissel and Hayes, 1977). Fault systems developed at this time, such as the Turi and Cape Egmont Fault Zones, follow structural trends from the Rangitata Orogeny. The Turi Fault Zone connects to a larger zone called the Cook-Turi Lineament (Fig. 3). This lineament provides a rough boundary between the Gondwanan metamorphic basement and rocks related to the Rangitata Orogeny (Knox, 1982).

Fault movement diminished toward the end of the Paleocene and sediment filled in the sub-basins and half grabens. Sediments deposited during this time included non-marine and fluviodeltaic sediments. The Paleocene horizon interpreted by Luke (2012) most likely correlates to the top of the Kaimiro Formation of the Kapuni Group, a package of siltstones deposited in the northwestern portion during a regional marine transgression of the basin (Fig. 4).
The Kaimiro Formation has been correlated with the end of the Paleocene by Palmer (1985) using data from wells throughout the Taranki Basin.

**Eocene to Early Oligocene – Passive margin**

As extension ceased, the main cause of accommodation was regional basin subsidence caused by sediment loading, as opposed to the more localized sub-basin subsidence of the Paleocene (Wood and Stagpoole, 2007). As New Zealand moved further from the Tasman Sea rift a passive margin developed and a marine transgression occurred on New Zealand. This continued into the early Oligocene. The Top Eocene horizon interpreted for this paper likely corresponds to base of the Turi Formation, which is part of the Moa Group (Fig. 4; Luke, 2012).

**Oligocene to Mid-Miocene – Foreland basin**

At the end of the Eocene and beginning of the Oligocene, sedimentation rates dropped resulting in strata from the Oligocene either being absent or very thin in this part of the basin (King and Thrasher, 1996). The lack of strata from this time is denoted by an unconformity corresponding to a local sea-level regression (King and Thrasher, 1996). Above this unconformity is the base of the Oligocene to Early Miocene Ngatoro Group. This group represents a basin-wide subsidence from the mid-Oligocene to Early Miocene (King and Thrasher, 1996). This subsidence was a response to folding and thrusting just to the east due to the initiation of subduction along the Hikurangi Trench. The Ngatoro group is dominated by carbonate and carbonate rich clastic sediments (Palmer, 1985).

This initiation of subduction and formation of a fold and thrust belt between 24 and 30 Ma (Kamp, 1999; Stern et al., 2006) represents a fundamental shift in the tectonic evolution of the region with the Taranaki Basin becoming a foreland basin. Early Miocene, west-directed
thrusting along the Taranaki Fault enhanced this subsidence by loading the lithosphere and causing a renewed marine transgression (Holt and Stern, 1994; King and Thrasher, 1992).

Horizontal shortening of up to 3 km occurred in the Taranaki Basin between 22 and 20 Ma in the Early Miocene as the Australian-Pacific rotation pole and Hikurangi subduction migrated southward and active, low-angle thrusting continued along the Tarata Thrust Zone just to the west of the Taranaki Fault. The Tarata Thrust Zone represents the western limit to subduction-related fold-and-thrust belt (King, 2000).

The onset of convergence changed sediment deposition from marine carbonate-dominated to terrigenous clastic-dominated. As subduction progressed southward the main zone of shortening moved with it, which shed large amounts of sediment from the south and southeast north toward the basin (Giba et al., 2010; King, 2000; King and Thrasher, 1996). These marine clastic deposits are known as the Wai-iti group made up of six formations including the Manganui, Moki, Mohakatino, Mangaa, Urenui, and Ariki (Fig. 4) (King and Thrasher, 1996).

Subduction also initiated arc volcanism around 15-14 Ma (King, 2000; Hansen and Kamp, 2004; Giba et al., 2013), which produced NNE-SSW trending magmatic and volcanic edifices known as the Mohakatino Volcanic Arc. The arc is subparallel to the Hikurangi Trench and follows the axis of the Northern Taranaki Graben (Fig. 3). Plutons and submarine volcanoes associated with the arc mark the progression of subduction from north to south with the ages of these plutons becoming younger to the south. Petrologically, the magmas are comprised of low-to medium-K, calc-alkaline andesite, basaltic andesite, and subordinate basalt (King and Thrasher, 1996; Seebeck et al., 2014). The modern-day Taranaki Volcano (Mt. Egmont) exhibits
island-arc chemistry with low Ce/Pb ratios and high Ba/Nb ratios relative to normal mid-ocean ridge basalts and is considered part of Mohakatino arc (Giba et al., 2013; Seebeck et al., 2014).

**Mid-Miocene to Recent – Intra-arc extension and magmatism**

Arc magmatism continued into the Late Miocene and migrated southeastward in the early Pliocene with a succession of magmatic episodes that young to the south (Fig. 3) (Seebeck et al., 2014). This pattern of arc migration is coincident with intra-arc extension and was accommodated by reactivation of preexistent NNE-trending normal faults in the Cape Egmont Fault Zone (Giba et al., 2010; Seebeck et al., 2014). At this same time normal faulting occurred along the Cook-Turi lineament to the southeast of the Cape Egmont Fault Zone forming the Turi Fault Zone (Fig. 3; King, 2000). Intra-arc extension continues to the present with the geologically recent (1.74-2.03 Ma) Sugar Loaf intrusion (Hoke and Leitner, 2000) and active Taranaki Volcano on the Taranaki Peninsula (Fig. 3) as well as in the Taupo Volcanic Center located on the North Island of New Zealand (Seebeck et al., 2014).

Beginning in the Pliocene and through the Pleistocene, thick units of marine sediment were deposited in the basin. These units consist of fine-grained mud and siltstones, with interlayered sandstones, and mostly lie within the Giant Foresets Formation (King and Thrasher, 1996).

**METHODS**

In order to better understand New Zealand’s only hydrocarbon producing basin, the Taranaki Basin has been imaged with numerous 2D and 3D seismic surveys (Fig. 2). Included in these surveys is the Parihaka 3D seismic survey (Fig. 5). Analysis of the Parihaka 3D survey data is important for understanding pluton emplacement mechanisms. This survey was
completed by Pogo New Zealand between January 12 and February 24, 2004 by the Veritas DGC’s vessel Viking II. The vessel towed and array of eight, 4500-m long hydrophone cables with a 3.15 km² footprint. Imaging was at a nominal 60-fold with a cable spacing of 100 m and a depth of 9 m. Two air gun pairs, separated by 50 m and towed at 7 m depth, were fired flip-flop. Data was recorded to a depth of 6 seconds and sampled in 2 ms intervals (Veritas/Pogo New Zealand, 2005).

Airborne magnetic anomaly data obtained in 1990 by Austirex International Pty Ltd was combined with additional magnetic anomaly data from 2000, obtained by Tesla Airborne Geoscience Pty Ltd. Flight line spacing for both data sets was 400 m. The data it was then reduced-to-pole. Reduced-to-pole is a processing technique that recalculates total magnetic intensity as if the inducing magnetic field has a 90° inclination. This simplifies the interpretation by making the data to the causative geology.

Seismic attributes, such as amplitude and semblance, were extracted and placed into 3D volumes. Analysis of seismic attributes, as described by Taner and Sheriff (1997), is done by quantitatively deriving seismic waveform measures to enhance geologic features and provides improved images for the interpreter.

Amplitude attributes use the seismic signals amplitude and reflection strength to color the data. In this study, red represents maximum amplitude and blue represents minimum. This attribute is useful for visualizing reflectors, some bedforms such as angle, faulting, contacts between strata and intrusions, and relationships between geologic structures and intrusions (such as doming of roof rock).
In the software used for this study, the “semblance” attribute was also used. Neighboring waveforms with high coherence or dissimilarity are brightened by the semblance attribute and look blue while those with low coherence are black. This tool is useful for visualizing faults and fractures and for identifying the contacts of igneous bodies with their sedimentary hosts.

Interpreting key horizons was based on Pogo’s (Cohen et al, 2005) and Luke’s (2012) horizon picks and interpretations. Seismic horizons were interpreted using the amplitude volume by manual and semi-automated processes. Semi-automated processes involve creating a grid on the surface of the chosen horizon then allowing the interpretation software to interpolate between the grids. Settings for the horizon interpretation include a score %, to measure how well an amplitude trace matches the original grid trace, as well as a maximum jump range to exclude Z values outside the grid traces. Using these tools enabled accurate horizons to be created even where the seismic signal was too weak to accurately trace manually and to prevent the software from jumping to a higher or lower reflection.

The shapes of igneous bodies were interpreted using software as well. A three-dimensional surface approximating the shape of the intrusion was used by picking points on the edge of the intrusions. The software interpolated the surface between the points. Points were moved or added to achieve an accurate intrusion shape. These surfaces were created vertically in a SW-direction. Both amplitude and semblance volumes were used to interpret intrusive margins. Seismic attenuation and possible velocity pull-ups caused some difficulties in defining these margins.

The volumes of the Northern and Central Intrusions were calculated by measuring the area of the mapped surface of the intrusions in plan-view at specific intervals using the built in
measuring tool in the software. The area was then multiplied by the time interval between each measurement to get a volume. This process was repeated at increments of 100 ms TWT (179-297 m) from the top to the base of each intrusion. The interval volumes were then summed over the height of the intrusions (4.16 km for the Northern and 4.59 km for the Central).

Two-way travel time (TWT) is the vertical reference measurement in the Parihaka 3D seismic survey. A depth-to-time conversion used by Luke (2012) (Fig. 4) were employed in this study because they correlate with wells tied into this dataset such as the Arawa-1, Witiora-1, and Taimana-1 (Fig. 4).

For this study, faults were interpreted first by using the semblance volume in order to constrain interpretations of key horizons and intrusions later. The Taranaki Basin is highly faulted and fractured and caution must be used in correlating horizons offset by faults. Interpreting faults involves picking points on a fault plane that are then used by an algorithm in the software to interpret the surface between the points. This process generates smooth, geologically reasonable surfaces. These faults were then used as boundaries that the software could not interpret across when creating horizons.

Fault heave was measured across NW-SW seismic cross-section and calculated using a distance measuring tool in the interpretation software. Two seismic cross-sections were used for both the Northern and Central Intrusions. Faulting near both intrusions was measured twice. The first was across the shallowest (highest-reaching) part of each intrusion and the second along a cross-section to the SW away from the intrusions completely in order to estimate differences (Fig. 6).
RESULTS

Multiple horizons were interpreted including, from oldest to youngest, the top of Cretaceous fill, top of Paleocene, top of Eocene, base of the Moki Formation, base of the Mangaa Formation’s B Unit, and base of the Giant Foresets Formation (GFF). Images of these are seen in Figures 7-12. Numerous faults, including regional and intrusion-related faults, were interpreted. Four intrusions were interpreted including the Northern Intrusion, Central Intrusion, Western Intrusion, and a small intrusion located just southwest of the Northern Intrusion (Figs. 13-16).

DISCUSSION

The focus of this study is the Northern and Central Intrusions with a limited study of the Western Intrusion. I discuss possible relationships between igneous intrusions, fault patterns, stratigraphic horizons deformed by the intrusions, and possible hydrocarbon accumulations or gas chimneys. With the aim of understanding emplacement mechanisms, interpreted faults and horizons are given with interpreted intrusions’ geometries.

Interpreted Stratigraphic Horizons

Six stratigraphic horizons were investigated in order to obtain an understanding of pluton geometry, emplacement timing, and mechanism. These will be discussed in detail from oldest to youngest.

Top of Cretaceous fill

At the end of the Cretaceous, as Gondwana rifted apart, the Taranaki Basin extended eastward. This horizon shows the resulting highs and lows related to horsts and grabens (Figs. 7 and 17). Zones of offset associated with these highs coincide with the major faults along the
NNE-trending Cape Egmont Fault Zone and, more specifically, the Parihaka Fault (Figs. 3 and 17).

This horizon is not laterally extensive throughout the seismic survey area. Areas where this horizon is not present have an unconformity between older late Jurassic-early Cretaceous basement and the younger Paleocene and Eocene formations (Fig. 7). The horizon is cut by the Northern Intrusion, but the Central Intrusion formed in an area where the top of the Cretaceous is missing. Another small intrusion south of the Northern Intrusion has uplifted this horizon as well (Fig. 7).

Top of Paleocene

The top of the Paleocene is interpreted to correlate with a shale found to the south (Cohen et al., 2005). A series of N-trending, tilted fault blocks are visible in the northwestern portion of the survey (Fig. 8). All three intrusions, including the Northern, Central, and Western, pierce the top of the Paleocene (Fig. 8).

Top of Eocene

The top of the Eocene is laterally extensive throughout the Parihaka dataset, represents the top of the Turi Formation, and is probably an erosional unconformity (Luke, 2012). This horizon is broken by all three interpreted intrusions (Fig. 9). The small igneous body between the Northern and Central Intrusions also domes this horizon, but does not break it. Normal fault offsets are evident in this horizon, but the older Cretaceous horsts and grabens have been completely covered by Paleocene and Eocene formations (Fig. 9).

Bottom of Mid-Miocene Moki Formation

The base of the Moki Formation represents a change in tectonic setting from a shallow marine depositional environment to a deep marine basin. Deposits in this formation consist of
submarine fan systems made up of interbedded sandstones, siltstones, and mudstones. Limestone stringers are also seen to a lesser extent (King and Thrasher, 1996). Doming from the Northern and Central Intrusion is evident in this horizon along with intrusion-related faults (Fig. 10).

*Late Miocene-Pliocene Mangaa Formation – Mangaa B Unit*

The Mangaa Formation derives its name from beds found in the Mangaa-1 well and consists of sandstone. This formation was deposited at the end of the Miocene and possibly the beginning of the Pliocene in the Northern Taranaki Graben as submarine fan deposits (Hansen and Kemp, 2004) with sediment transported from the south (King and Thrasher, 1996). Luke (2012) described this formation as having two units, Mangaa A and Mangaa B. His interpretation of the Mangaa B unit was modified for this study (Fig. 11).

The Mangaa B horizon shows only slight doming above the Northern and Central Intrusions (Fig. 11). The doming in this horizon is the youngest in any interpreted horizon, although radial faults are still evident through the Mangaa strata and into the younger Ariki Formation deposited immediately following the Mangaa. The semblance attribute allows for these radial faults to be clearly seen (Fig. 11).

Regional faults that cut this horizon show a change in strike from the Cretaceous-Eocene trend of nearly N-S to a more NE-SW orientation (Fig. 17) (Luke, 2012; Giba et al, 2013). This change in faulting direction represents the change in the tectonic stress field due to propagation of the Hikurangi subduction zone southward. The Taranaki Basin began experiencing intra-arc spreading as a result (Seebeck et al., 2014).
Bottom of Giant Foresets Formation

The Giant Foresets Formation is a thick package of strata representing the filling of the basin by continentally derived sediments. Deposition of this formation began about 3.5 Ma and continues today (Beggs, 1990). Some members of this formation exhibit large clinoforms and others show large turbidite channels carved into the formation (Fig. 12) (Hansen and Kemp, 2002). Hansen and Kemp (2002) and Luke (2012) include in-depth descriptions of the different packages of strata within the Giant Foresets Formation.

The Giant Foresets Formation was only used to constrain the timing of emplacement. Luke’s horizon was used (Fig. 12) to show that intrusion-related faults generally do not break the bottom of this formation, but some faulting above the Northern Intrusion breaks the base of the Giant Foresets Formation.

Interpreted Faults

Cape Egmont Fault Zone (CEFZ) – Parihaka Fault

The Turi and Cape Egmont Fault Zones, with top down to the southeast, define the northern graben of the Taranaki Basin. For the purposes of this study, only faults in the Cape Egmont Fault Zone are interpreted as segments of the Parihaka Fault (Figs. 3 and 18). The Cape Egmont Fault Zone is a NE-trending set of faults with a left-stepping, en-echelon pattern within the Parihaka 3D survey (Figs. 18 and 19). The key fault within this dataset, the Parihaka Fault, is a continuous, NNE-trending fault from the Cretaceous to Eocene and a left-stepping, en-echelon, NE-trending series of faults in post-Eocene rocks (Fig. 19) (Giba et al., 2010). Faults within the zone show normal offset in the seismic data (King and Thrasher, 1996). Between 420-2020 ms TWT, the fault segments terminate in horsetail splays (Fig. 18) indicating movement between about 8 and 1 Ma based on the ages of formations broken by these faults. No lateral offset has
been found along any structures, such as submarine channels visible in the seismic data, across any of the fault strands.

Most previous studies that used slickenside striations and strain data from outcropping faults (e.g. Giba et al., 2010) have not shown any significant evidence to support a strike-slip component. Giba et al. (2010) discuss oblique reactivation of normal faults in the Parihaka 3D survey and imply small amounts of oblique-slip movement may have occurred along the main Parihaka Fault. This inference is based on a relative change in direction of the Cretaceous-age faults and more recent Miocene faults, although no lateral offset can be seen along any of the faults. In the seismic data, the faults trend NNE in one continuous fault from the end of the Cretaceous horizon into the beginning of Eocene strata and have only normal offset. Later, during the late Miocene and early Pliocene, the regional stress regime changed (Fig. 17). This new stress regime created new faults with a NE-trend that, at depth, connect and reactivate older faults (Giba et al., 2010). Due to this change in regional stress regime there should be strike-slip movement along relay faults that trend NNE and are aligned with the older, pre-existing NNE-trending Cretaceous faults. This movement would accommodate normal movement along faults with a NE-trend.

Focal measurements of recent earthquakes suggest a right-lateral, strike-slip component possibly due to magmatic movement beneath the Taranaki Peninsula (Sherburn and White, 2006). Sherburn and White (2006) recognized that the onshore Inglewood Fault, on the Taranaki Peninsula northeast of Mt. Taranaki, shows oblique normal slip along a 3 m scarp formed over the last 13 ka. There have been no recent earthquakes along the Cape Egmont Fault Zone within the Parihaka survey’s boundaries with fault plane solutions.
Movement along the Parihaka Fault, and along the entire Cape Egmont Fault Zone, occurred in two time intervals. The first was late Cretaceous to early Eocene as the rifting of Gondwana split New Zealand from Australia and has vertical throw of 1400-1800 m (Nicol et al., 2005; Giba et al., 2010). The second interval was from the end of the Miocene (12 Ma) to Recent, with most of this movement occurring since ca. 3.7 Ma (Nicol et al., 2005), showing a 900-1450 m vertical throw down to the southeast on the Parihaka Fault (Giba et al., 2010). This can be seen in the data by the variation in the thickness of growth strata along the Parihaka Fault (Fig. 6). Cretaceous to Eocene strata exhibit growth on the hanging wall. This relative thickening on the hanging wall occurs again, up-section in the data, at the end of the Miocene through the Plio-Pleistocene to recent Giant Foresets Formation (Giba et al., 2010). Plio-Pleistocene displacement is minimum along individual faults in the relay zones between fault sections (Giba et al., 2010). Vertical offset of the top of the Moki horizon used in this study is about 1 km near the Northern Intrusion.

Intrusion-Related Faults

Intrusion-related faults are visible above all intrusions discussed for this study, but were only interpreted for the Central and Northern Intrusions. Faults related to the Central Intrusion are most evident and have been separated into shallow and deep zones to show their differences (Figs. 18 and 20). Faults exhibit a radial pattern that is best developed at depth (greater than 2900 ms) in strata pierced by the pluton (Fig. 20 d-f). These radial faults do not break the bottom of the Moki Formation, which is about 10 Ma.

At depths less than 2900 ms TWT above the Central Intrusion, intrusion-related faults located directly above and in the dome created by the intrusion are radial near the center of the intrusion (Fig. 20 a), but with increasing distance switch to a NE-trend (Fig. 20 b and c), the
same orientation as faults formed in the regional stress system (Figs. 18 and 20). These upper radial faults break the Ariki (7-3.5 Ma), but do not break through into the Giant Foresets Formation (3.5 Ma to recent).

This fault pattern is similar to the radiating dikes found in Spanish Peaks, Colorado (Billings, 1972; Muller, 1986). There, these dikes fill pre-existing tensional fractures formed from pressure to due magmatic intrusion (Acocella and Neri, 2009). The Spanish Peaks dikes begin with a typical radial pattern nearest the intrusion, but reorient to follow the regional stress field and extend up to 16 km away from the intrusion. Dikes typically develop parallel to the maximum horizontal principal stress. Although these faults are similar to those found around the intrusions in Taranaki Basin, there is no evidence from the seismic data that the intrusion-related faults in the Taranaki Basin are filled by dikes.

Local faults above and around the Northern Intrusion are much like those found above the Central Intrusion (Figs. 18, 20-21). Pluton-associated faults are absent in the southeast quadrant where the apparently contemporaneous Parihaka Fault accommodated pluton emplacement. This quadrant is highlighted by the pink-highlighted zone in Figure 21 a-c. There are fewer radial faults near this intrusion than by the Central Intrusion, but there are still two distinct orientations of pluton-associated faults. The deeper level of faults exhibits a more normal radial pattern (Fig. 21 d-f) whereas the shallower level shows a normal radial pattern near the intrusion, but with distance the faults reorient and are more consistent with the regional fault pattern of NE-SW normal faults (Figs. 21 a-c), similar to those of the Central Intrusion.

These changes in fault orientation indicate a change in local stresses above and around the intrusions. As the intrusions pierced deeper strata, the stress from emplacement was enough
to overcome the regional stress regime, possibly due to thermal weakening of host rock, and radial faults, driven by magma overpressure, formed and propagated outward to at least 3 km. Above the intrusions, however, the local stresses of emplacement related to doming were not enough to overcome the regional stress regime and the radial faults begin, nearest the apex of the intrusions, as typical radial faults, but then veer into a pattern produced by the regional stress regime. It is also important to note a complete lack of radial faulting to the southeast of the Northern Intrusion is probably because deformation is accommodated by movement along the Parihaka Fault that lies next to the intrusion (Figs. 18 and 21).

These faults can also be used to constrain the time of emplacement. Previous estimates for ages of the Northern and Central Intrusions have not taken radial faulting within and above the dome into account and have, therefore, been dated incorrectly using only seismic stratigraphy or by assuming they are submarine volcanoes (Giba et al., 2013). Giba et al. (2013) dates these intrusions to between 14 and 10 Ma (Northern Intrusion) and 12 to 10 Ma (Central Intrusion) while Luke (2012) dated the Northern Intrusion to no younger than 10 Ma and the Central Intrusion to no younger than 5.3 Ma. Using our techniques to interpret radial faulting above both intrusions and the principle of cross-cutting relations, we see radial faults extending into the Ariki Formation (7-3.5 Ma) and, in the case of the Northern Intrusion, slightly piercing the base of the Giant Foresets Formation (3.5 Ma to recent). Piercing of the GFF by the Northern Intrusion puts timing of emplacement to around 3.5 Ma since the faults just slightly pierce it. Timing of the Central Intrusion using these faults places it between 5 and 4 Ma.

**Intrusive Structures**

All intrusions imaged in this seismic survey are interpreted as igneous intrusions, and not salt or mud diapirs, based on their association with other igneous bodies that are either exposed
onshore or seen in seismic data offshore. They correspond to a zone of positive magnetic anomaly. Large salt deposits have not been found anywhere in the Taranaki basin ruling out salt diapirs as a source. Also, mud diapirs are not likely given there is a lack of source rock from the depths the intrusions are located and there are no withdrawal features.

**Northern Intrusion**

The Northern Intrusion is located at the north end of the survey data (Fig. 13). This is the largest of the intrusions interpreted for this study and has a diameter of 4.7 km at its greatest extent. This diameter is measured in a NE to SW direction and follows the Parihaka Fault to the SW. The top of the intrusion lies at about 1800 ms TWT (~2 km), but the base is not resolvable (Fig. 14). It extends at least 9 km in depth and blends seismically with the surrounding Jurassic-Early Cretaceous basement rock at depth (Fig. 14). The volume of the interpreted part of the Northern Intrusion is approximately 32 km$^3$ (Fig. 22).

This igneous intrusion has steep sides, exhibits faulting above the intrusion, has no evident internal stratification, deforms flanking strata by faulting and folding, and has no strong reflector marking the base. This indicates that this body is a plutonic body and not a submarine volcano (Figs. 14 and 22). Attribute analysis, such as amplitude, connectivity and size differences in semblance data revealed no internal structure, unlike the nearby Southern Intrusive Complex, which has a composite structure of multiple intrusions as described by Luke (2012). The vertical “sheets” apparent in this interpretation are artifacts of the interpretation process and do not imply vertically emplaced dikes.

Deformation on the flanks of the intrusion has increased the dips of strata to over 45°. The strata returns to regional dip within 4 km of the sides of the intrusion. Intrusion-related faulting of strata adjacent to and above the intrusion occurs as described earlier. The amplitude
of doming, simply measured as the vertical change in depth of the Moki Formation as it is deformed above the intrusion, is 300 ms TWT (~650 m) (Fig. 10).

The Northern Intrusion is bounded to the southeast by the Parihaka Fault and follows this fault for the entire intrusion (Figs. 14 and 18). Regional faulting to the NW of the intrusion bounds the Northern intrusion’s dome (Fig. 18). The relationship between the intrusion and these faults limited the ability of radial faults to propagate to the NW across the dome’s NW bounding fault and SE across the Parihaka Fault and, therefore, there are no visible radial faults that extend in those directions (Figs. 18 and 21). Radial faulting can be seen above and around the top of the intrusion breaking the Giant Foresets Formation (Figs. 18 and 21).

The sequence of events written about in the previous paragraph and base on cross-cutting relations (Fig. 22) is the following: Faulting began creating the Parihaka Fault and reactivating older Cretaceous faults. Synthetic and antithetic faults formed near the Parihaka Fault at about the same time. Space created by extension along these faults allowed for the intrusion of magma directly adjacent to the Parihaka Fault, where a majority of the extension occurred. Movement along synthetic faults to the NW of the intrusion ceased around 5 Ma. Emplacement of the Northern Intrusion ceased around 3.5 Ma and movement along antithetic faults to the SE of the intrusion continued into the Pliocene and Pleistocene. The Parihaka Fault has experienced movement into the recent era with recorded earthquakes occurring within the last 30 years.

Doming of the rock above the intrusion is evident in different horizons with the upper limit of doming just above the top of the Mangaa-B horizon (Fig. 14). The Top of Eocene horizon exhibits the most dramatic doming, which uplifts the strata by about 450 m (Fig. 14).
Central Intrusion

Located between the Northern Intrusion and the Southern Intrusive Complex, this igneous body displays the same characteristics as the Northern Intrusion but is smaller – 2.6 km at its widest extent. The top is at about 2700 ms TWT (~3 km) depth and the base is not resolved but it extends to a depth of at least 9 km (Fig. 15). The interpreted height is about 4.5 km. The volume of this intrusion is approximately 16 km³ (Fig. 23).

The Central Intrusion, like the Northern Intrusion, has steep sides, exhibits faulting above and along the sides, has no evident internal stratification, deforms flanking strata by faulting and folding, and has no strong reflector at the base indicating that this body is a plutonic body and not a submarine volcano (Figs. 15 and 20). Attribute analysis, such as amplitude, connectivity and size differences in semblance data revealed no internal structure – it is more or less uniform throughout its extent like the Northern Intrusion. As before, the vertical “sheets” apparent in this interpretation are artifacts. Radial faulting around the intrusion does not break the Moki Formation. Faulting above the intrusion is radial directly above the intrusion, but the faults change direction to follow the regional stress direction of NE-SW (Figs. 18 and 20). These faults do not break the Giant Foresets Formation (Fig. 23). The amplitude of doming, simply measured as the vertical change in depth of the Moki Formation as it is deformed above the intrusion, is 200 ms TWT (~450 m).

Western Intrusion

Being the smallest of the three intrusions identified and studied for this paper, the Western Intrusion is less than a half kilometer across and is emplaced west of the other aligned intrusions (Figs. 13 and 16). This intrusion, and its associated underlying magma transfer column, has a columnar shape in cross-section and is circular in plan-view (Fig. 16). This
intrusion’s magma transfer column is a series of upward dipping reflectors beneath the intrusion that do not connect at the center of the column (Fig. 16). Imaging the intrusion’s conduit system is unique to this dataset since most intrusions’ systems blend in with the surrounding basement rock at depth and this may help us understand magmatic plumbing systems in the future (Jerram and Bryan, 2015). The actual magmatic body itself is located at the top of this column between 1660 ms TWT and 2250 ms TWT (Fig. 16). Doming and radial faulting can be clearly seen in the seismic data especially when viewing it using the semblance attribute. Timing of this intrusion can be constrained using cross-cutting relations of the dome and associated faults. Based on these relations and the cutting of the base of the Ariki Formation, the intrusion ceased emplacement between 4 and 5 Ma; it is about the same age as the Central Intrusion.

Other Intrusions

Within the Parihaka 3D dataset, and aside from the intrusions already discussed in this study and in Luke (2012), are two other igneous intrusions. The larger of the two, is located just east of the Northern Intrusion and extends beyond the seismic survey (Fig. 9). This one looks to be larger than the Northern Intrusion, but the complete size and shape cannot be deduced with the data currently available. The smaller of the two is located southwest of the Northern Intrusion. This one domes the Eocene, Paleocene, and Cretaceous horizons (Figs. 7-9).

Magnetic Anomaly Map

Magnetic anomaly data used in Luke (2012) also extends north into the area of the Northern and Central Intrusions. These data show a magnetic high extending from north to south beneath the Northern Intrusion, the small intrusion SW of the Northern Intrusion, and the Central Intrusion (Fig. 24). Magnetic anomalies have previously been used to interpret locations of igneous intrusions (e.g., Clark, 1999). This magnetic high is coincident with the intrusions in
this study and indicates that these are igneous bodies, as opposed to salt or shale diapirs, and that they may be part of a much larger, deeper composite igneous body that cannot be seen in the Parihaka 3D data (Fig. 24).

**Emplacement History**

Both the Northern (3.5 Ma) and Central (5-4 Ma) Intrusions are older than the Southern Intrusive Complex (1.5 Ma) based on cross-cutting relations and as discussed by Luke (2012). They follow the trend of older to younger from north to south in the Mohakatino Volcanic Centre. The Northern Intrusion was emplaced in the footwall block of the Parihaka Fault in the early Paleocene after the fault was reactivated in the late Miocene. Doming and deformation are evident into the late Miocene-Pliocene Mangaa Formation with radial faulting above the intrusion extending up into the late Pliocene-recent Giant Foresets Formation. This indicates emplacement ceased ca. 3.5 Ma.

Emplacement of the Central Intrusion occurred along the axis of the Northern Taranaki Graben. The intrusion breaks the Eocene horizon and domes and deforms the Moki and Mangaa horizons. Faulting above the intrusion extends into the Ariki Formation and, based on cross-cutting relations, indicates termination of emplacement occurred between 5 and 4 Ma.

Both the Northern and Central Intrusions’ geometries (e.g., steep sides, no internal stratification, and no strong reflector indicating a base) and relationships with pre-existing strata (e.g., doming of overlying rock, deformation of sidewall rocks, steep sides, lack of internal stratification, lack of base reflector, and faulting) suggest these are, in fact, intrusions and not submarine volcanoes as they have previously been described (e.g., Giba et al., 2013) (Figs. 14 and 15).
Emplacement Mechanisms

The Parihaka 3D dataset provides an excellent opportunity to investigate space-making mechanisms associated with igneous intrusions. Doming, extension (both regionally and locally), and thinning of strata played significant roles in emplacement, while others, such as stoping and floor subsidence, were not seismically resolvable with this data. The magmatism is mostly passive magmatism with extension dictating the plutons’ locations.

Doming

One of the most important space-making mechanisms is doming. Laccoliths, like those that form the Henry Mountains of Utah (Horsman et al., 2010), exhibit roof uplift as one of the primary emplacement mechanisms. In order to calculate the amount of space made by doming, a volume was determined from the top of the first seismically resolvable horizon (the bottom of the Moki Formation) above both the Northern and Central Intrusions to the base of the dome where the horizon is no longer deformed. Dome volume was calculated by multiplying the area of the dome at 25 ms intervals by the depth of those intervals based on Luke’s (2012) velocity data and then adding those volumes together. This volume is estimated to be about 2 km³ for the Central Intrusion and about 5 km³ for the Northern Intrusion. This space made by doming accounts for ~13% of the interpreted volume of the Central Intrusion and ~16% of the interpreted volume of the Northern Intrusion.

Extension and Faulting

Extension and its related faulting can be responsible for a large portion of space made for an intrusion. King and Thrasher (1996) calculated 2 km of regional extension over a distance of 50 km across the entire Taranaki Basin, not including the space filled by intrusions. Given the
intimate relationships of both the Northern and Central Intrusions to regional, normal faults, local extension may have played a significant role in opening space for these intrusions.

Fault heave was measured across two NW-SW seismic cross-sections for both the Northern and Central Intrusions (Fig. 6). Faulting near both intrusions was measured twice, once across the shallowest (highest-reaching) part of each intrusion along with a cross-section to the SW and off the intrusion completely in order to estimate differences. The second seismic cross-section for the Northern Intrusion was 2.5 km to the west and southwest and for the Central it was located 2.85 km to the west and southwest (Fig 6).

Horizontal heave across the Northern intrusion measured 1.35 km or 29% of the diameter of the 4.7 km-across Northern Intrusion. Heave along the intrusion-free cross-section amounted to 0.47 km or 0.88 km less. Heave at the Central Intrusion is 0.32 km or 12% of the diameter of the intrusion compared to 0.10 km of heave away from the intrusion or 0.22 km less than at the intrusion. These numbers indicate that the intrusion is creating space for itself by extension while taking advantage of space already created by regional normal faults.

Regional extension, which is taken up to a large extent by magmatic intrusion, is the main space-making mechanism. Total regional extension across the Northern Intrusions, including both horizontal heave and the width of the intrusion in the NW-SE direction is about 4.75 km, with 3.4 km or ~72% due to magmatic intrusion (magmatic extension) and the remaining 28% due to amagmatic extension. The amount of magmatic extension associated with the Central Intrusion is almost as much as the Northern Intrusion’s magmatic extension. Here the regional extension is 3.93 km and of that over 66% or 2.6 km is due to magmatic extension with the remaining 34% a result of amagmatic extension.
Extension expressed by thinning of strata is also seen in the seismic data. The Moki horizon is unbroken by the intrusions and can be traced across the domes. The amount of thinning and extension of this formation was measured by calculating the difference between the length of the horizon as it domes over the intrusions and the length of the horizon if it extended straight across the intrusion without being domed. The amount of extension for this horizon was measured at 3.5% for the Northern Intrusion and 4% for the Central Intrusion (Figs. 22 and 23).

*Shortening*

Shortening of wallrock could be a significant space-making mechanism for intrusions. In other studies, as much as 54% shortening in the contact aureole in the White Horse Pluton of central Nevada (Marko and Yoshinobu, 2011) and 20% of space needed for a granitic pluton in southern China due to ductile shortening of wallrock (Wang et al., 1999) has been described. However, after careful examination of the seismic data, looking for anticlines, synclines, or other forms of shortening, the margins of both the Northern and Central Intrusions appear to be free of these structures. Likewise, no significant thickening of strata is seen.

Luke (2012) described compaction of wet sediments as another type of horizontal shortening. He describes that possibly 23% of space for the Southern Intrusive Complex could have been made in the GFF because of high porosities and wet sediment. Porosities are probably not as high as the GFF’s at 2 km depth (23%) where the Northern and Central Intrusions lie, but the wallrocks were probably wet. However, given that there is no apparent change in bed thicknesses in the wallrocks of the Northern and Central Intrusions, this process is unlikely.

*Assimilation*

The process of magma absorbing its host rock is known as assimilation and is important in many magmatic systems, but the amount of assimilation is difficult to estimate even when a
pluton is exposed for geochemical analyses. Some materials are completely consumed as xenoliths of the wall rock. Most studies conclude about 1% of the volume of intrusions to be wallrock xenoliths (e.g., Wang et al., 2000).

Another common method to assess assimilation comes from stable (e.g., O) and radiogenic (e.g., Sr, Nd, Pb) isotopic studies. Perry et al. (1993) estimated that anywhere from 10 to 100% of silicic magmas are derived directly from crustal sources. Also, Wang et al. (2000) described 36% of the Huichizi granite as having a crustal origin or having assimilated crustal materials although they recognize that assimilation may have occurred below the level of emplacement at a much deeper level. Floor subsidence may have transferred this “space” to the shallower level of emplacement.

Also, assimilation is limited by thermal processes. Disaggregation of crustal material into hot basalt is limited to a few tens of percent (Glazner, 2007). Rates of assimilation will be much lower for cooler magmas. The chemical and isotopic evolution of andesites to rhyolites in New Zealand’s Taupo volcanic zone was studied by Graham et al. (1995). Their models used an assimilation to crystallization rate of 0.2 or 20%. Other studies (e.g., Reiners et al., 1995) have considered thermal budgets deep within the crust and showed assimilation rates may exceed 1 percent for deep, basaltic magmas. Taranaki volcanic rocks are usually andesitic and shallow so their assimilation rates should be in the lower range of assimilation (below 1 %).

Other Mechanisms

Space-making mechanisms such as stoping and floor-subsidence may have had a significant role in emplacement of the Northern and Central Intrusion, but they are not seismically resolvable. Stoping may have occurred, but stoped blocks lack seismic contrast, may be too small to be resolved, and the seismic waves are unable to return a coherent reflection from
within the intrusions. Floor subsidence cannot be seen due to the inability to resolve the base of these intrusions seismically.

Hydrocarbons

Gas Chimneys or Biogenic Gas

Near the sea floor, from 200 to 400 ms TWT, of the Parihaka 3D survey are several zones that show a seismic phase reversal signifying a slowing of seismic velocity at a single interface relative to the surrounding strata (Fig. 25). Ilg et al. (2012) identified zones similar to these in the southern Taranaki Basin, within 100 km of the Parihaka 3D survey, as gas chimneys. There, zones below these amplitude anomalies show a decrease in frequency below the anomaly and these changes in frequency and anomaly can be traced to Pliocene normal faults. Also, Ilg et al. (2012) identified circular, concave up or down structures within 200 ms TWT of the sea floor and pockmarks or mud volcanoes near or on the seafloor.

Similar anomalies appear above both the Northern Intrusion and the larger intrusion to the east, which is cut off by the edge of the dataset, are similar anomalies. These variations in seismic character are bound to the south by late Miocene-Pliocene normal faults (Fig. 25). While there is not any amplitude variation along these faults to suggest fluid flow, it is possible for these faults to be conduits for gas migration from lower gas reservoirs.

While the actual source of these anomalies is unknown, they are probably small gas reservoirs due to the “bright spot” formed by the slowing of the seismic wave as it crosses higher velocity cap rocks into a zone of slower velocity (Taner and Sheriff, 1997). The amplitude anomalies visible in the Parihaka survey appear the same near the surface. Concave upward and downward features are seen between 280 and 350 ms TWT and extend up to 2188 ms TWT, but
there are no surface expressions higher than 200 ms TWT (Fig. 25). In map-view they are plume-like features that trend NNE. They range in area from 19 km$^2$ to 2 km$^2$. Also, there is a frequency disruption below the anomalies, but the frequency recovers before reaching any normal faults. The main question is, what is the source of the gas? The Arawa-1 well, located within the survey area and near these anomalies, penetrates a gas reservoir of Miocene age indicating the presence of hydrocarbons in lower formations. Given that there does not appear to be an actual gas chimney visible below or near the anomalies indicates that most of these gas deposits are probably biogenic in origin. There is also a possibility that those bound by normal faults derive their gas from lower formations (Fig. 25).

**CONCLUSIONS**

Further constraints on emplacement and timing of intrusion in the Parihaka 3D seismic are reported with the aim of broadening our understanding of the geologic history of the Taranaki Basin of New Zealand. Three intrusions, the Northern Intrusion, Central Intrusion, and Western Intrusion are described in this study. All of these bodies are intrusive bodies without a cover of volcanics as previously described. They all have steep sides, no resolvable reflector at their bases, no internal stratification, and have significant doming and fracturing above and to the sides of the intrusions. Future studies of these intrusions should work to understand why these intrusions do not have volcanics associated with them as other igneous bodies within the Taranaki Basin do.

The Northern Intrusion, largest of the three studied, has a diameter of ~4.7 km, a volume of ~32 km$^3$, and extends from about 2 km depth to at least 9 km below the seafloor. Timing of emplacement based on cross-cutting relations ceased, after deposition of the GFF commenced, at
about 3.5 Ma (Fig. 21). Emplacement of the Northern Intrusion occurred directly adjacent to the Parihaka Fault, the main fault associated with the Cape Egmont Fault Zone in the northern Taranaki Basin. The emplacement occurred during a time of intra-arc extension from the end of the Miocene to the beginning of the Pliocene. During this extensional period, the Taranaki Basin was opening from the NW to SE producing NE-SW striking normal. Intrusion-related faults around and above the Northern Intrusion show the influence of this regional stress-regime; near the intrusion, faults have a typical radial pattern in all directions (with $\sigma_2$ and $\sigma_3$ about equal to each other), whereas the distal ends of the faults deviate to strike in a NE-SW direction, the same as regional normal faults, and have a $\sigma_2$ greater than $\sigma_3$. Radial faults occur in all orientations around the Northern Intrusion except in the direction of the Parihaka Fault. There are no faults that cut through to the southeast since all the stress in this direction was absorbed by movement along the Parihaka Fault. This indicates that movement along the fault was occurring simultaneously with magmatic emplacement. Both magmatic and amagmatic extension occurred with magmatic extension being the largest contributor.

South of the Northern Intrusion, located in the center of the Northern Graben of the Taranaki Basin, is the Central Intrusion. This intrusion has a smaller diameter of ~2.6 km, a volume of ~16 km$^3$, and extends from about 3 km depth to at least 9 km below the seafloor. Timing of emplacement of the Central Intrusion is dated between 5 and 4 Ma, slightly younger than previous estimates. The stress regime at the time of emplacement for the Central Intrusion was the same as for the Northern Intrusion. NE-SW-striking provided extension and opening of space in a NW-SE direction. Within the Northern Graben of the Taranaki Basin there are few major faults. The only two normal, regional faults occur at the Central Intrusion. This indicates a relationship between magmatism and extension. Intrusion-related faults have been separated
into two zones. Faults in the deeper zone extend in all directions in a typical radial pattern while those in the shallower zone begin near the intrusion with a typical radial pattern, but deviate from this pattern farther from the intrusion ending with strikes in a NE-SW direction just like those at the Northern Intrusion.

West of the Parihaka Fault is the Western Intrusion. This intrusion, and its associated magma conduit, has a cylindrical shape, extends from a depth of about 2 km to a depth of over 9 km, and has a diameter less than half of a kilometer. This intrusion, which is the smallest studied herein, is interesting in that there are no major faults directly bordering it as with the other intrusions. Normal faults are nearby, with one cut by the intrusion, but they do not look like they influence emplacement. There is a small dome and some intrusion-related faulting visible above this intrusion.

Emplacement of the Northern and Central Intrusions was made possible by several important space-making mechanisms. Typical mechanisms such as stoping, assimilation, and floor-subsidence were not able to be constrained by seismic data used for this study. Doming, extension (both regional and local), and thinning of roof strata can be constrained by the data and are major emplacement mechanisms for these intrusions. Space-making mechanisms for the interpreted portion of the Northern Intrusion account for the following volumes: Doming accounts for at least 16%, extension for 29%, and thinning for 4% for a total of 49% of the total volume (Fig. 21). Space-making mechanisms for the Central Intrusion are: Doming accounts for at least 13%, extension for 12%, and thinning for 4% for a total of 27% of the total volume (Fig. 22). These estimates for both intrusions only apply for the upper parts of the intrusions above a depth of about 9 km. The remaining 73-51% of space for these intrusions could have come from assimilation, floor subsidence, stoping, and compression as described above (Figs. 22
and 23), but the simplest explanation would be through magmatic extension. Magmatic extension allows for some of the extension normally achieved by faulting to be accomplished by the flowing of magma into created space.

Finally, we describe the effects of possible hydrocarbons observed within the Parihaka 3D dataset (Fig. 25). Interpreted hydrocarbons are either derived from lower gas reservoirs punctured by faults, which then flow up through gas chimneys or they are biogenic pockets of gas. They are all between 200 and 400 ms TWT and are all located north and west of the Parihaka Fault.

REFERENCES


King, P.R., 2000, Tectonic reconstructions of New Zealand 40 Ma to the present: New Zealand Journal of Geology and Geophysics, v. 43, p. 611-638.


Figure 1. Modified from Best and Christiansen (2001), this diagram shows important space-making mechanisms. Emplacement mechanisms are important in understanding how intrusions make room for themselves in the crust. The most important mechanisms are stoping, thinning of roof strata through stretching, faulting and extension, shortening of sidewall rocks, floor subsidence, assimilation, and stoping.
Figure 2. Well locations and seismic coverage in the Taranaki Basin (modified from Luke, 2012).
Figure 3. Index map of the Taranaki Basin. The outline of the Parihaka 3D seismic survey is outlined in yellow. The Taranaki Basin is bound on the east by the Taranaki Fault, to the south by the northern part of the South Island. Major fault zones of interest, including the Cape Egmont Fault Zone and the Turi Fault Zone, are shown cutting the survey. The Cape Egmont Fault Zone trends NNE-SSW with a left-stepping, en-echelon fault pattern. The Turi Fault Zone is a series of NE-SW trending normal faults. Modified from Luke (2012).
Figure 4. Stratigraphic column of the Parihaka 3D seismic survey area of the Taranaki Basin. Approximate depths were calculated by Luke (2012) from two-way traveltime correlated to the Arawa-1 well located within the data area. Interpreted seismic horizons are indicated on the right column of the figure. Modified from Luke (2012).
Figure 5. Map showing seismic vessel’s acquisition path for the Parihaka 3D survey. Locations of wells tied into the data set are also shown (modified from Luke, 2012).
Figure 6. Seismic cross-sections where heave was measured a) SW of the Central Intrusion, b) across the Central Intrusion, c) SW of the Northern Intrusion, and d) across the Northern Intrusion. The map above shows the location of the cross-sections with white lines. Vertical scale is from 0 sec. to 6 sec. TWT. Vertical exaggeration is 3x.
Figure 7. Top of the Cretaceous is shown in (A) as amplitude with a color overlay showing depth in TWT and (B) as semblance. This horizon is not laterally extensive throughout the Parihaka 3D survey. In this horizon the Northern, Central Intrusion, and Western intrusions all break through. Also seen in this horizon are crystalline basement highs and lows (horsts and grabens) formed during extension and break-up of Gondwana when Taranaki Basin was initially formed about 80 Ma.
Figure 8. Top of the Paleocene is shown in (A) as amplitude with a color overlay showing depth and (B) as semblance. This horizon is laterally extensive throughout the Parihaka 3D survey. The Northern, Central, and Western Intrusions all break this horizon. (Modified from Luke, 2012).
Figure 9. Top of the Eocene is shown in (A) as amplitude with a color overlay showing depth and (B) as semblance. This horizon is laterally extensive throughout the Parihaka 3D survey. In these images radial faulting and doming can be seen above both the Northern and Central Intrusions. The Western Intrusion can be seen as a hole in the data in the western portion of the data just over half-way from the top. The Northern and Central Intrusions both pierce the top of the Eocene.
Figure 10. Base of the Moki Formation is shown in (A) as amplitude with a color overlay showing depth and (B) as semblance. The Moki is laterally extensive throughout the Parihaka 3D survey. In these images radial faulting and doming can be seen above both the Northern and Central Intrusions. The Western Intrusion can be seen as a hole in the data in the western portion of the data.
Figure 11. Base of the Mangaa Formation is shown in (A) as amplitude with a color overlay showing depth and (B) as semblance. The Mangaa is nearly laterally extensive throughout the Parihaka 3D survey. In these images radial faulting can be seen above the Central Intrusion. The Western Intrusion is shown by a hole in the data in the western portion of the survey area.
Figure 12. Bottom of Giant Foresets Formation (GFF) shown as (A) amplitude with a color overlay showing depth and (B) as semblance. The GFF is laterally extensive throughout the Parihaka 3D survey. The two apophyses described in the Southern Intrusive Complex can be seen at the southern end of the data. No doming by intrusions interpreted for this study is visible in this horizon, but doming is visible on older horizons. (Modified from Luke, 2012)
Figure 13. Locations of interpreted igneous intrusions are shown on the Parihaka 3D seismic data. Time-slice is at 3870 ms TWT. The intrusions are shown as red bodies within the data. (A) shows the data in amplitude and (B) is semblance.
Figure 14. A-A’ cross-section of the Northern Intrusion shows the relationship between the Parihaka Fault (Part of the CEFZ) and the intrusion. Note the intrusion’s steep sides and lack of base reflector. This intrusion breaks through into Miocene age rocks and domes and fractures strata as young as 3.5 million years. Location is indicated by a white line. Vertical exaggeration is 3x.
Figure 15. B-B’ cross-section of the Central Intrusion shows the relationship between the Parihaka Fault (part of the Cape Egmont Fault Zone) and the igneous intrusions in the Parihaka 3D seismic survey. The Central Intrusion, while not associated with the main Parihaka Fault, is associated with normal faulting. There are local relationships between normal faults and this intrusion possibly due to thermal weakening of the host rock by the pluton. Vertical exaggeration is 3x.
Figure 16. As seen in this cross-section of the Western Intrusion, the shape of this intrusion (red) and its underlying magma transfer zone (dark grey) is rod-shaped. It protrudes through the Moki Fm and domes the Ariki Fm putting emplacement of this intrusion at about the same time as the Central Intrusion (5-4 Ma). Vertical exaggeration is 3x.
Figure 17. Modified from Giba et al. (2012), part A) shows the location of the Taranaki Basin, Parihaka Fault, and the outline of the Parihaka 3D seismic survey. It also shows the evolution of faults and direction of extension during the Late Cretaceous, Early Pliocene and Pleistocene (red arrows). Igneous intrusions studied and interpreted for this study, as well as the Southern Intrusive Complex studied by Luke (2012), are in red within the “Early Pliocene” window indicating their emplacement timing. The grey shaded region highlights the Parihaka Fault and its evolution from a NNE-trending fault at the end of the Cretaceous to a NE-trending fault in Early Pliocene and Pleistocene. B) is a schematic drawing of fault blocks within the Taranaki Basin. The large, bold arrows show the direction of extension within the basin during emplacement of igneous intrusions in the Northern Graben. $\sigma_1$ is vertical, $\sigma_2$ has a NE-SW direction, and $\sigma_3$ is in a NW-SE direction and is the same as direction of extension.
Figure 18. Schematic fault maps with both regional and intrusion-related faults. A) shows intrusion-related faulting from 2000-2500 ms. These faults reorient with increasing distance from the intrusions and trend NE. B) indicates the locations of intrusion related faulting from 2500-3000 ms. These faults exhibit a radial pattern. Northern Intrusion-related faulting is absent to the SE and much of the NE due to the presence of larger, regional faults that accommodated the pluton emplacement. Intrusive bodies are in red. C) is a schematic representation of the difference between a fault and a fault zone. Fault zones (grey) are broader areas that incorporate many individual faults (black lines) with the same trend. The Parihaka 3D seismic data contains portions of two fault zones - the Cape Egmont Fault Zone and the Turi Fault Zone. The zone without major faulting is the Northern Graben of the Taranaki Basin. The location of faults has a significant impact on the locations of intrusions indicating that faults preceded the intrusions.
Figure 19. Timeslice at 1000 ms showing the relationship between regional en-echelon faults and horsetail splays. A) is the area inside the white box from the inset map above showing a close-up view of the Parihaka Fault’s en-echelon pattern including relay zones and horsetail splays. Horse-tail splays are visible from 500 to 2100 ms TWT in semblance volume. B) is a schematic image showing a simplified version of A). Parihaka Fault segments are in black, relay zone faults in green, and horsetail splays are in blue. C) shows the main Parihaka Fault segments in black, relay faults in green, and splays in blue. The location of the seismic cross-section is shown by the inset map and seismic box taken from the Parihaka 3D seismic data. Vertical exaggeration in C) is 3x.
Figure 20. Intrusion-related faults around the Central Intrusion were measured for their strike in three segments each for both the shallower series of faults (above the intrusion) and the deeper series (adjacent to the intrusion) and are displayed as rose diagrams. The Central Intrusion’s shallower series of intrusion-related faults were measured in the following increments from the center of the intrusion: a) <0.5 km, b) 0.5 to 1.5 km, and c) >1.5 km. The Central Intrusion’s deeper series of intrusion-related faults were measured in the following increments: d) <1 km, e) 1 to 2 km, and f) >2 km. A schematic cross-section in g) displays the increments for both series visually. Petals indicate number and trend of faults. Rainbow-shaded regions around the perimeters of the diagrams indicate where fault strikes are focused with blues being low and reds represent high concentrations. Radial faults around the intrusion in the deeper series display a typical radial pattern while the faults in the shallower series display a radial pattern nearest the intrusion, but reorient into the \( \sigma_2 \) direction (NE-SW) with distance from the intrusion as described in the text and Figure 17. The radial pattern in the lower faults may be a result of local thermal weakening allowing regional extension to have a greater impact on this area and creating greater variation in fault direction.
Figure 21. Intrusion-related faults around the Northern Intrusion were measured for their strike in three segments each for both the shallower series of faults (above the intrusion) and the deeper series (adjacent to the intrusion) and are displayed as rose diagrams. The Northern Intrusion’s shallower series of intrusion-related faults were measured in the following increments: a) <0.5 km, b) 0.5 to 1.5 km, and c) >1.5 km. The deeper series of intrusion-related faults were measured in the following increments: d) <1.5 km, e) 1.5 to 2.5 km, and f) >2.5 km. A schematic cross-section in g) displays how increments for both series of faults visually. The pink hued sections represent the area to the SE of the intrusion where there are no radial faults due to the presence of the Parihaka Fault. Petals indicate number and trend of faults. Rainbow-shaded regions around the perimeters of the diagrams indicate where fault strikes are focused with blues being low and reds represent high concentrations. Fault strikes prefer a NE-SW direction, especially at the end segments.
Figure 22. Schematic cross-section of the Northern Intrusion summarizing the percentage of volume created by space-making mechanisms. Percentages are the percent that each mechanism contributed to the overall volume of the pluton. Also shown are major horizons and their ages. Cross-section location shown by the white line on the map to the left. Depths (both TWT and km) and ages are modified from Luke (2012).
Figure 23. Schematic cross-section of the Central Intrusion summarizing the percentage of volume created by space-making mechanisms. Percentages are the percent that each mechanism contributed to the overall volume of the pluton. Also shown are major horizons and their ages. Cross-section location shown by the white line on the map to the left. Depths (both TWT and km) and ages are modified from Luke (2012).
Figure 24. Reduced-to-pole magnetic anomaly map from the Taranaki Basin. Locations of interpreted igneous intrusions are outlined in black. The thick black lines indicate the location of en-echelon, left-stepping segments of the Parihaka Fault and faults within the Turi Fault Zone. There is a significant aeromagnetic high extending between the Northern and Central Intrusions. This is probably due to a larger igneous intrusion at depth that cannot be resolved in the seismic data used for this study. This deeper intrusion follows the same general trend as the rest of the Mohakatino Volcanic Center. The intrusions that are resolveable may be apophyses or off-shoots of this deeper composite intrusion. (Data from Fugro Robertson Incorporated, 2007)
Figure 25. Top image shows the locations of possible gas chimneys or biogenic gas accumulations with a SW to NE trend with fault locations marked in red. a) Shows a cross-section of one possible gas chimney (second from left in top figure). Yellow outlines the chimney and red indicates a normal fault creating a conduit for gas movement. The gas chimneys are located on the down-thrown fault block when they are not above intrusions. b) Shows a cross-section of a possible gas chimney above the Northern Intrusion. Yellow outlines the possible area of the chimneys, red indicates the location of a major fault, and pink indicates the location of the Northern Intrusion. This gas chimney is located in the normal fault’s footwall, is bound on the left by the normal fault, and may be associated with faulting that occurred as the pluton intruded. c) is modified from Ilg et al. (2012) and shows their interpretation of a gas chimney located about 75 km south of the Parihaka 3D survey. Data from both studies are similar in that there is an amplitude disruption where the chimney may be located. If this gas is biogenic in origin then a similar disruption could occur with the disruption dissipating with depth as under-shooting by seismic waves occurs when collecting the data.