Desktop study documenting the occurrence and geological characteristics of known VMS deposits associated with Northland’s Tangihua Complex

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ABSTRACT

The Tangihua Complex of Northland comprises a series of fault-bounded massifs that contain ophiolite sequences of basaltic pillow lavas with local intercalated siliceous mudstone and micritic limestone, and subvolcanic intrusives of gabbro and dolerite. The intercalated sediments are of Late Cretaceous to Late Paleocene age on limited fossil evidence. The Tangihua Complex contains volcanic massive sulphide (VMS) copper deposits at Pupuke, Pakotai and Parakao that were mined historically. These deposits are associated with sedimentary lenses in the ophiolitic basalt sequences. The Tangihua Complex forms part of the Northland Allochthon, which was obducted by gravity sliding from the north east as a series of thrust sheets in the Early Miocene. Many of the massifs appear to have a similar gross stratigraphy, consisting of a lower part of basaltic pillow lavas with intercalated siliceous and/or calcareous mudstones, overlain by sequences of basaltic pillow lavas and intrusive rocks, within which mudstones are very rare or absent. Low-angle faults, shear zones and broken formation are present throughout the sequences, but are most common where mudstone is relatively abundant.

GNS Science was contracted by the Ministry of Economic Development to carry out a desktop study documenting the occurrence and geological characteristics of known VMS deposits associated with the Tangihua Complex. Historic mining and exploration of the known VMS deposits has been small scale. The Pupuke deposits were discovered in 1892 and were worked in the early 1900s, Pakotai was worked from 1944-51 and Parakao was discovered and worked in 1962-63. In the 1970s, mineral exploration was conducted over the Pakotai and Parakao deposits and on a Cu prospect at Purua. We have compiled relevant information from university theses, open file mining company reports, geological mapping and geochemical data, and magnetic and radiometric data from the recent Aeroquest Northland regional geophysical survey, in a Geographic Information System (GIS).

At Pupuke, small, irregular, tectonically disturbed lensoidal bodies of cupriferous sulphide are enclosed in weathered mudstone intercalated with basaltic lavas within a small (~1 km²) block of Tangihua Complex rocks. The sulphide lenses consist mainly of pyrite and chalcopyrite, locally with marcasite, and minor sphalerite and rare galena. Geochemically the Pupuke sulphide mineralisation is rich in Cu (up to 6.3%), with minor Zn (up to 1.37%), low Pb and low Au (0.12 ppm). At Pakotai, discontinuous sulphide lenses occur in mudstone intercalated with and are overlain by basalt and dolerite near the southern margin of the large Mangakahia massif. The sulphide lenses contain pyrite + chalcopyrite + marcasite + sphalerite with rare galena, and are geochemically rich in Cu (up to 40.2%) and Au (6.4-21.5 g/t), with minor Zn (up to 0.83%) and Pb (up to 0.5%). At Parakao a small lens of massive sulphide in sheared tuffaceous and siliceous mudstone is overlain by basaltic volcanics near the northern margin of the small (~12 km²) Pekapekarau massif. The primary ore consists of pyrite + chalcopyrite + marcasite, with minor sphalerite and rare galena, and geochemically it is rich in Cu (up to 19.0%) and Au (5.1-18.0 g/t), with minor Zn (up to 0.5%) and Pb (up to 0.5%).

The known VMS deposits at Pupuke, Pakotai and Parakao do not appear to have any consistent magnetic or radiometric signatures, although individually the Pakotai deposit is associated with a linear Th anomaly that may represent a sedimentary unit, and the Parakao VMS deposit is coincident with a small magnetic low that may represent a hydrothermal demagnetisation anomaly within a larger magnetic high representing Tangihua rocks. These known deposits exhibit a variable geochemical response in stream sediment geochemical exploration surveys, suggesting that geochemically quiet areas in the data may still be
prospective for VMS deposits. An analysis of the data has highlighted several geochemical anomalies in areas of Tangihua Complex rocks away from known areas of mineralisation.

The small size of the known VMS deposits and extensive deformation of the host sediments and volcanics, suggests that potential additional deposits in the Tangihua Complex will be small, though copper grades can be high and gold may also be present.

Further work to determine the potential for Cu-rich VMS deposits in the Tangihua Complex is recommended.

KEYWORDS

Volcanogenic massive sulphide deposits, Northland, Pupuke, Pakotai, Parakao, Purua, airborne magnetics, airborne radiometrics, Th, geochemistry, Cu, Zn, Pb
1.0 INTRODUCTION

In 2011, the Ministry of Economic Development, Northland Regional Council and Far North District Council funded an airborne magnetic and radiometric survey by Aeroquest over the Northland region to provide information that would encourage and assist mineral exploration of the region. A geological interpretation of the data was undertaken by GNS Science and is described by Stagpoole et al. (2012). Additionally, GNS Science was contracted by the Ministry of Economic Development to carry out a desktop study documenting the occurrence and geological characteristics of known VMS deposits associated with Northland’s Tangihua Complex and to see if the new airborne geophysical survey data would assist in their exploration. The brief for the study was as follows:

a) create a GIS incorporating QMAP geology with: existing knowledge of VMS deposits in Northland, including: information derived from a review of relevant publications, university theses, open file mining company reports; unpublished literature and other publically available information; and data from the Geological Resource Map (GERM), Regional Geochemistry (REGCHEM), PETLAB and Crown Minerals’ geochemical (report MR4510) databases;

b) analyse and interpret the Aeroquest Survey Data, as acquired in 2011 by a fixed wing aeromagnetic and radiometric survey of the Northland region, for magnetic and radiometric signatures characteristic of hydrothermal alteration zones and siliceous sedimentary rocks associated with VMS deposits;

c) assess geochemical data for the presence of characteristic geochemical signatures of VMS deposits;

d) update the GIS described in clause (a) with the analysis completed in clauses b) & c);

e) use the updated GIS to assess the exploration potential for VMS deposits associated with the Tangihua Complex in Northland; and

f) make a recommendation for any further technical work that may assist in realising any economic potential of this style of deposit in Northland.

The GIS is contained on the accompanying DVD and its themes are described in the separate “Description of files on this DVD” file on the DVD. The GIS is the same as that included with Stagpoole et al. (2012) and the reader should consult that reference for a detailed description of the geophysical data themes.

2.0 TANGIHUA COMPLEX

Small volcanic massive sulphide (VMS) copper deposits at Pupuke, Pakotai and Parakao in Northland (Figure 1) are associated with sediment lenses in ophiolitic basalt sequences of the Tangihua Complex of Northland (Mason and Kobe 1989; Christie and Brathwaite 2006). These ophiolite sequences are composed of basaltic pillow lavas, with intercalated siliceous mudstone and micritic limestone, and subvolcanic intrusives of gabbro and dolerite. The Tangihua Complex is part of the Northland Allochthon, which was obducted by gravity sliding from the north east as a series of thrust sheets in the Early Miocene (e.g. Ballance and Spörli 1979; Isaac et al. 1994; Edbrooke and Brook 2009). In northern Northland, the Allochthon consists of large mappable thrust sheets, whereas further south it is broken up into smaller, less discrete blocks, consistent with greater fracturing and deformation over a longer
The major Tangihua Complex massifs are numbered and named after Figure 4.7 in Isaac et al. (1994).
Table 1  Summary of the Geology of the Tangihua Massifs.

<table>
<thead>
<tr>
<th>Massif name</th>
<th>Size</th>
<th>Dominant rock types</th>
<th>Sediments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reinga</td>
<td>Large</td>
<td>Basalt lavas, dolerite</td>
<td>sil mdst, mic lst</td>
</tr>
<tr>
<td>Te Rake</td>
<td>Small</td>
<td>Basalt lavas</td>
<td>sil mdst</td>
</tr>
<tr>
<td>North Cape</td>
<td>Small</td>
<td>Peridotite, gabbro, dolerite</td>
<td></td>
</tr>
<tr>
<td>Waipahiriere</td>
<td>Small</td>
<td>Basalt lavas, dolerite</td>
<td></td>
</tr>
<tr>
<td>Te Kao</td>
<td>Small</td>
<td>Basalt lavas, dolerite</td>
<td></td>
</tr>
<tr>
<td>Ahipara</td>
<td>Large</td>
<td>Basalt lavas, gabbro</td>
<td>sil mdst</td>
</tr>
<tr>
<td>Maungtaniwha</td>
<td>Large</td>
<td>Basalt lavas, gabbro</td>
<td></td>
</tr>
<tr>
<td>Omaunu</td>
<td>Small</td>
<td>Basalt lavas</td>
<td></td>
</tr>
<tr>
<td>Whangape</td>
<td>Medium</td>
<td>Basalt lavas, dolerite</td>
<td>siltstone, tuff</td>
</tr>
<tr>
<td>Warawara</td>
<td>Medium</td>
<td>Basalt lavas, dolerite</td>
<td>sil mdst</td>
</tr>
<tr>
<td>Waima</td>
<td>Medium</td>
<td>Basalt lavas, dolerite</td>
<td></td>
</tr>
<tr>
<td>Mangakahia</td>
<td>Large</td>
<td>Basalt lavas, dolerite</td>
<td>sil mdst, chert, lst</td>
</tr>
<tr>
<td>Motatau</td>
<td>Small</td>
<td>Basalt lavas</td>
<td></td>
</tr>
<tr>
<td>Purua</td>
<td>Small</td>
<td>Basalt lavas, gabbro</td>
<td></td>
</tr>
<tr>
<td>Pekapekararu</td>
<td>Small</td>
<td>Basalt lavas, gabbro</td>
<td>sil mdst</td>
</tr>
<tr>
<td>Houtu</td>
<td>Medium</td>
<td>Basalt lavas, gabbro</td>
<td></td>
</tr>
<tr>
<td>Waihue</td>
<td>Small</td>
<td>Basalt lavas, gabbro</td>
<td></td>
</tr>
<tr>
<td>Maungaru</td>
<td>Small</td>
<td>Basalt lavas, gabbro</td>
<td>sil mdst</td>
</tr>
<tr>
<td>Tangihua</td>
<td>Medium</td>
<td>Basalt lavas</td>
<td>sil mdst</td>
</tr>
<tr>
<td>Mt Braeme &amp; Flat Top Hill</td>
<td>Small</td>
<td>Basalt lavas</td>
<td>sil mdst</td>
</tr>
</tbody>
</table>

Abbreviations: mic lst = micritic limestone, sil mdst = siliceous mudstone
Isaac et al. (1994) noted that many of the massifs appear to have a similar gross stratigraphy (Figure 2), consisting of a lower part of basaltic pillow lavas with intercalated siliceous and/or calcareous mudstones, overlain by sequences of basaltic pillow lavas and intrusive rocks, within which mudstones are very rare or absent. Low-angle faults, shear zones and broken formation are present throughout the sequences, but are most common where mudstone is relatively abundant (Isaac et al. 1994).

The age of the ophiolites is poorly constrained as Late Cretaceous to Late Paleocene from fossils in the intercalated sediments (e.g. Hollis and Hanson 1991; Isaac et al. 1994) and Late Cretaceous to Oligocene (~100 to 27 Ma) from K-Ar dating (Brothers and Delaloye 1982). On the basis of limited U-Pb and Ar-Ar dating, Whattam et al. (2005, 2006, 2008) suggested that in Northland there was a volumetrically dominant 32-26 Ma tholeiitic suite and an older basaltic ocean floor terrane of pillow lavas intercalated with Late Cretaceous to Paleocene sediments. However, from Ar-Ar dating of alteration/metamorphic events in the Tangihua Complex, Nicholson et al. (2007) concluded that the bulk of the Tangihua Complex is older than 50 Ma, which is consistent with the Late Cretaceous and early Cenozoic fossil ages of the intercalated sediments. The issue of the relative abundance of Cretaceous versus Oligocene igneous material in the Tangihua Complex remains unresolved.

Recent geochemical trace and rare earth element studies have indicated that Tangihua ophiolites contain island arc tholeiites in addition to mid-ocean ridge basalts (MORB), and were formed in a suprasubduction zone setting (e.g. Nicholson et al. 2000; Nicholson and Black 2004; Whattam et al. 2004, 2005).

Roser (1983) and Brathwaite and Pirajno (1993) noted that the VMS sulphide deposits of Northland and East Cape allochthons were similar to modern East Pacific Rise massive sulphide mineralisation and to Cyprus-type VMS deposits. The term Cyprus-type has now
been superseded by Ophiolite-hosted VMS deposits (Galley and Koski 1999), which are formed in the black smoker environment of mid-oceanic ridges or back-arc basin spreading centres, where hydrothermal systems are generated by basaltic volcanic and intrusive activity.

3.0 MINING AND EXPLORATION HISTORY FOR VMS DEPOSITS ASSOCIATED WITH THE TANGIHUA COMPLEX

At Pupuke near Kaeo (Figure 3), lensoidal bodies of pyrite + chalcopyrite, enclosed in mudstone intercalated with basaltic lavas, were discovered in 1892 and were worked in the early 1900s by the Hare-Ratjen Company, and Charles Ratjen (Table 2). Bell and Clarke (1909, p 84) noted that one 12 t shipment of ore contained 5.9% Cu, 0.5 g/t Au and 15 g/t Ag. Bell and Clarke (1909, p 82) listed seven analyses from the Hare-Ratjen workings which average 0.1 g/t Au, 3.6 g/t Ag and 0.9% Cu, with the best sample assaying 0.1 g/t Au, 11.5 g/t Ag and 4.2% Cu. A representative sample taken from a 7.3 m strike-length exposure of ore in the nearby Fergusson workings assayed 0.4 g/t Au, 15.0 g/t Ag and 5.4% Cu (Bell & Clarke, 1909, p. 83). Some prospecting and mining of small quantities of ore were carried out by Hazelbrook Mines from 1964 to 1968. A sampling campaign by City Resources NZ Ltd in 1989, reported eight grab samples of massive sulphide ore that assayed <0.01-0.9 g/t Au, <1.0-5.3 g/t Ag, 0.08-3.8% Cu, and 0.005-0.04% Ba (Licence 1989).

Table 2  Mining and exploration history for VMS deposits in the Tangihua Complex.

<table>
<thead>
<tr>
<th>Area</th>
<th>Year</th>
<th>Company</th>
<th>Activity</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pupuke</td>
<td>1892-1910</td>
<td>Hare-Ratjen</td>
<td>Mining and prospecting</td>
<td>Bell &amp; Clarke (1909)</td>
</tr>
<tr>
<td></td>
<td>1964-68</td>
<td>Hazelbrook Mines</td>
<td>Mining and prospecting</td>
<td>Bowen (1963, 1965)</td>
</tr>
<tr>
<td></td>
<td>1989</td>
<td>City Services</td>
<td>Sampling and assaying</td>
<td>Licence (1989)</td>
</tr>
<tr>
<td>Pakotai</td>
<td>1944-51</td>
<td>Cloudesley Mines</td>
<td>Mining, prospecting and drilling</td>
<td>Landreth et al. (1947), Hay (1960)</td>
</tr>
<tr>
<td></td>
<td>1979</td>
<td>Gold Mines NZ Ltd</td>
<td>Review</td>
<td>Pirajno (1979)</td>
</tr>
<tr>
<td></td>
<td>1989</td>
<td>City Resources</td>
<td>Sampling and assaying</td>
<td>Licence (1989)</td>
</tr>
<tr>
<td>Parakao</td>
<td>1962-63</td>
<td>Copper Queen Mine</td>
<td>Mining and prospecting</td>
<td>Rowe (1963)</td>
</tr>
<tr>
<td></td>
<td>1989</td>
<td>City Services</td>
<td>Sampling and assaying</td>
<td>Licence (1989)</td>
</tr>
<tr>
<td></td>
<td>1978-79</td>
<td>Developments</td>
<td>Sampling and assaying</td>
<td>Bell (1978, 1979)</td>
</tr>
</tbody>
</table>

The Pakotai Cu deposit was discovered in 1944 and produced about 1400 t of copper ore between 1947 and 1951 (Hay 1960). It consists of small discontinuous sulphide lenses in mudstone intercalated with and overlain by basalt and dolerite near the southern margin of the Mangakahia massif (Hay 1960; Clifton 1972; Pirajno 1979). Assays of shipped ore averaged 12.7% Cu, 57 g/t Ag and 5.8 g/t Au (Hay 1960). During 1971, Mines Exploration Pty Ltd (Clifton 1972) carried out geological mapping, soil geochemical sampling, geophysical surveys and drilling of three holes totalling 277 m. Licence (1989) reported seven grab samples of massive sulphide ore that assayed 0.9-21.5 g/t Au, 15-155 g/t Ag, 0.5-35% Cu, 0.018-0.5% Pb, 0.01-0.5% Zn, and 0.015-0.067% Ba.

On the eastern side of the Purua Tangihua massif, trenching of geochemical Cu anomalies exposed a 5 m thick basalt lava unit containing oxidised copper minerals derived from disseminated chalcopyrite-pyrite mineralisation (Bell 1971, 1972, 1973, 1978, 1979; Mason
and Kobe 1989). Channel samples from trenches returned assays of up to 3.5% Cu over 1.0 m, and drill core assayed up to 2.1% Cu.

The Copper Queen mine, near Parakao on the northern margin of the Pekapekara Tangihua massif, was discovered and worked in the 1960s (Rowe 1963; Bowen 1966). A small lens of massive pyrite + chalcopyrite in sheared tuffaceous and siliceous mudstone is overlain by basaltic volcanics. Oxidised and secondary enriched ores were mined between 1961 and 1966, and produced about 1040 t of copper ore. Reconnaissance exploration by Kaiser Mining and Development Ltd failed to locate extensions to the known orebody (Lalor and Purvis 1971). Licence (1989) reported three grab samples of massive sulphide ore that assayed 5.1-19.5 g/t Au, 20-24 g/t Ag, 11-19% Cu, 0.006-0.5% Pb, 0.1-0.5% Zn, and 0.01-0.1% Ba.

4.0 TANGIHUA MASSIFS

We have compiled notes from the published literature and MSc theses on the lithology of the individual Tangihua Complex massifs. In particular we have noted the occurrence of sedimentary lenses within the volcanic sequences (see Table 3), because VMS deposits are typically hosted by argillaceous or siliceous sediments.

4.1 REINGA

This large massif is predominantly composed of augite basalt pillow lavas and dolerite sills, with associated massive lavas, breccia and siliceous mudstone (Brook 1989). Siliceous mudstone and red micritic limestone (Pandora Member) occur near the top of the Reinga massif. At Pandora a c. 10 m thick unit of sheared red, green and grey calcareous siltstones and limestones is underlain by dolerite and overlain by pillow basalt (F.J. Brook pers com. 2007; Brathwaite and Christie 2008).

4.2 TE RAKE

This small massif is exposed along the coast between Cape Reinga and Cape Brett and consists mainly of pillowed basalt flows and dolerite sills, with minor basaltic breccia (Brook 1989).

4.3 NORTH CAPE

This massif contains the basal part of an ophiolite complex, with a thick plutonic sequence of serpentinised peridotite (at least 7800 m thick), overlain by gabbro with microgabbro and microdiorite sills (900 m) which form a sheeted intrusion complex (400 m) at the top of the exposed massif (Isaac et al. 1994). This plutonic sequence is overlain by fault-bounded thrust slices of sheeted basalt and dolerite dikes, with minor intercalated pillow basalt screens, and basaltic pillow lava with intercalated dolerite and basaltic sills. Isaac et al. (1994) noted that this is the only known occurrence of sheeted dikes within the Tangihua Complex.
Figure 3   A. Location of volcanogenic massive sulphide deposits and Tangihua Complex rocks; B. total magnetic intensity, reduced to pole, analytic image; and C. thorium counts image. B and C are data from the 2011 airborne geophysical survey (see section 8.0).
Table 3  Tangihua Complex masses: lithologies and VMS mineralisation.

<table>
<thead>
<tr>
<th>Location</th>
<th>Grid Ref</th>
<th>Sediments</th>
<th>Igneous rocks</th>
<th>Mineralisation</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reinga Massif</td>
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<td>basalt breccia, tuff</td>
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<td>sil mdst?</td>
<td>basalt breccia, tuff</td>
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</tbody>
</table>
4.4 **TE KAO**

This small massif is mapped as basalt pillow lavas with a fault-bounded occurrence of wehrlite on the south margin of the massif (Isaac 1996).

4.5 **MAUNGATANIWHA**

This large massif is well exposed along the coast between Te Reinga Bay and Tokomatu as a sequence of: pillow basalts with red and green mudstone intercalations (800 m thick), overlain by intercalated pillow basalt and mudstone intruded by volumetrically dominant gabbro (1100 m thick), and pillow basalt with dikes and sills of dolerite and basalt (1500 m thick) (Martin 1988; Isaac et al. 1994).

On the southeastern side of the Maungataniwha massif between Camp and Taupo bays, a 42 m thick unit of relatively undeformed basalt pillow lavas, with intercalated micritic limestone and chert, is overlain by a c. 1 km thick igneous complex of mylonitic basalt, dolerite, microgabbro and diorite (Hanson 1991; Hollis and Hanson 1991). At Camp Bay (P4/753918), pockets and lenses of red limestones, green argillite and red chert occur within the pillow lava unit (Hanson 1991). Clots of pyrite-chalcopyrite-pyrrhotite occur in a fissile fault rock at a nearby site in the overlying mylonite complex.

4.6 **AHIPARA, WHANGAPE AND WARAWARA**

These three discrete but adjacent massifs extend along the coast west of Kaitaia, southwest to Matihetihie (Isaac 1996). The Ahipara massif is composed predominantly of porphyritic pyroxene basalt occurring as pillow lavas, pillow lava breccias and massive flows, with gabbro mainly at Shipwreck Bay, and thin lenses of siliceous mudstones and cherts (Baskett 1970; Larsen 1987; Larsen and Parker 1989; Larsen and Spörli 1989). Brathwaite and Christie (2008) described small lenses (<5 m in length) and blocks of red and green cherts within a sequence of basaltic pillow lavas and hyaloclastic breccias along the coast to the west of Shipwreck Bay. Baskett (1970) noted that the gabbroic rocks contained disseminated grains of pyrrhotite, pyrite and chalcopyrite.

In the Whangape massif, highly sheared basalt flows make up about 70% of exposures, and pillow lavas and pillow breccias account for a further 20% (Maxwell 1968). Small gabbro and dolerite intrusions occur along the northern margins of the massif, whereas pillow lavas and pyroclastic deposits are mainly limited to the southern margins. Maxwell (1968) described bedded tuffs overlying sheared basalts on the coast (N5/281520), north of Kuia Bay (N5/269531) and on the foreshore at Whangape (O5/316508), and a lens of sheared siltstone 3.2 km north of the Whangape Heads (N5/293499). A fine ash bed (2 m thick) at the top of the sequence at Whangape contains about 60% mordenite.

In the Warawara (Maungapohatu) massif, a lower unit of aphyric pyroxene basalts with thin argillaceous sediments intercalated or in tectonic lenses, passes upwards into a dike swarm which is overlain by intercalated basalt pillow lavas, autoclastic breccias and hyaloclastite (Ardern 1988). The aphyric basalts are locally intruded by gabbro and diorite. Ardern (1988) described siliceous mudstone intercalated with pillow lavas and pillow breccias in Waikare (O5/344442) and Taikarawa (O5/356422) streams, and argillaceous limestone in Otangaroa Stream (O5/411518).
4.7 WAIMA

This is a relatively large oval shaped (17 x 5 km) massif on the southern side of Hokianga Harbour. It is mapped as undifferentiated Tangihua Complex by Isaac (1996).

4.8 MANGAKAHIA

This large massif forms the Mangakahia, Oputeke, Okahara and Karaka ranges. In the southeastern part of the Mangakahia Range the dominant rock type is porphyritic pyroxene basalt occurring as pillow lavas, pillow lava breccias and massive flows (Soffe 1986). Lesser dolerites occur mainly at lower elevations in valley floors. Minor sediment lenses, including red, green and brown siliceous shales (quartz-albite-illite), chert (quartz-chlorite) and red limestone (calcite-hematite), are generally found in association with dolerite bodies. The dolerite/sediment contacts are commonly marked by fault zones.

Briggs (1969) mapped the southwestern sector of the Mangakahia massif, comprising the Oputeke, Okahara and Karaka ranges, as predominantly pyroxene basalt pillow lavas and pillow lava breccias, with minor intrusions of dolerite and gabbro. The Okahara Range is bounded on the south by a dolerite intrusion about 5 km in length. The only sediments recorded were a small lens of volcanic sandstone along a lava/dolerite contact on the northern end of the Karaka Range.

A small lens of massive sulphide, in sheared tuffaceous and siliceous mudstone overlain by basaltic volcanics near Pakotai on the southern margin of the Mangakahia massif, was worked in the 1960s as the Copper Queen mine (Rowe 1963; Bowen 1966).

4.9 MOTATAU AND PURUA

The Motatau and nearby Purua massifs are relatively small bodies of undifferentiated Tangihua Complex (Hay 1960; Edbrooke and Brook 2009) that lie to the east of Mangakahia massif.

On the eastern side of the Purua massif, prospecting trenches exposed a 5 m thick basalt lava unit containing disseminated chalcopyrite-pyrite mineralisation (Bell 1973, 1978, 1979; Mason and Kobe 1989).

4.10 PEKAPEKARAU

This is a relatively small massif (~12 km²) composed of basalt pillow lavas with gabbro at the western end (Hughes 1966).

Small discontinuous sulphide lenses occur in mudstone intercalated with and overlain by basalt and dolerite near Parakao on the western margin of the Pekapekarau massif (Hay 1960; Clifton 1972; Pirajno 1979).

4.11 HOUTU

This massif consists of two small subcircular bodies of basalt pillow lavas surrounded by dolerite and gabbro. Hughes (1966) described two samples of sedimentary rocks, sample AU9398 (P07/000029) is shale and limestone cut by calcite-barite veins with laths of barite in the shale, and AU9402 (P07/096036) is a siliceous sediment with argillaceous layers rich in muscovite.
4.12 **WAIHUE**

This massif forms a group of low hills, about 15 km north of Dargaville, that are composed of pillow lavas and pillow lava breccias overlain by a breccia, with clasts of basalt and dolerite, which grades into volcaniclastic grits and sandstones (Fortune 1968). Yellow-brown chert and rare green mudstone locally occupy interstices between pillows. There are some lenses of siliceous siltstone and mudstone tectonically emplaced along contacts of intrusive dolerite. No sulphide mineralisation has been reported.

4.13 **MAUNGAR**

This massif forms the Maungaru Range with the northern and southern ends being composed of basaltic breccias and the central part being pillow lavas (Hughes 1966). Hughes (1966) described two samples of sedimentary rocks. Sample (AU9401) (Tangowahine in Table 2) is a hard white siliceous rock composed of quartz with minor alkali feldspar and muscovite. Sample AU9396 from near the northeastern boundary of the massif (P07/949025) is a siliceous sediment with quartz and feldspar and barite in a calcite-rich matrix cut by calcite-barite veins.

4.14 **TANGIHUA**

This elliptical fault-bounded massif is predominantly composed of pyroxene basalt pillows lavas with pillow lava breccias on the southern flank of the range. Hughes (1966) mapped small occurrences of siliceous sediment in Tauroa and Pikiwahine streams.

4.15 **MT BRAEME AND FLAT TOP HILL**

These two small isolated bodies are the southernmost occurrences of the Tangihua Complex. They are composed of fractured and sheared basalt lavas, with minor intercalated siliceous mudstone and basaltic intrusives (Edbrooke 2001).
5.0 CU-RICH VMS DEPOSIT MODEL

As described by Singer (1986, USGS model 24a) and Høy (1995, BCGS model M03), this deposit type typically comprises one or more lenses of massive pyrite-chalcopyrite associated with mafic volcanic rocks and underlain by a well-developed pipe-shaped stockwork zone. The sulphide lenses are commonly found in tholeiitic or calcalkaline marine basalts, typically pillowed, near a transition with overlying argillaceous sediments. Host rocks include pillow and flow basalts, basaltic tuff, chert and argillite. Many lenses appear to be structurally controlled, aligned near steep normal faults. The main minerals are pyrite, chalcopyrite, magnetite and sphalerite, with lesser marcasite, galena and pyrrhotite. The sulphide lenses are commonly overlain by “umbers”, consisting of ochre (Mn-poor, Fe-rich bedded mudstone containing goethite, hematite and quartz) and/or chert.

International examples include: Cyprus; York Harbour and Betts Cove, Newfoundland, Canada; Turner-Albright, USA; and Lokken, Norway. In USGS model 24a, the 50th percentile = 1.6 Mt at 1.7% Cu, with byproduct Ag, Au, Pb and/or Zn (0-33 g/t Ag; 0-1.9 g/t Au, 0-2.1 % Zn) (Singer 1986).

6.0 GEOLOGY AND MINERALOGY OF NORTHLAND VMS DEPOSITS

6.1.1 Pupuke

At Pupuke, small, irregular, tectonically disturbed lensoidal bodies of cupriferous sulphide are enclosed in weathered mudstone (Figure 4A) intercalated with basaltic lavas within a small (~ 1 km²) block of Tangihua Complex rocks on the slopes of Mt. Maungamiemie. The sulphide lenses consist mainly of pyrite and chalcopyrite, locally with marcasite and minor sphalerite and rare galena (Roser 1983; Mason and Kobe 1989). Secondary copper minerals include covellite, malachite, bornite, native copper and chalcocite. Brathwaite and Christie (2008) described a sample of massive sulphide from a tributary of Ohia Stream, consisting of aggregates of pyrite and spongy chalcopyrite in a matrix of fine grained quartz and minor illite. The chalcopyrite is locally replaced by covellite along grain margins. Most of the pyrite is in broken crystals indicating that the sulphides have undergone cataclastic deformation. A float sample of red chert (P77604) from the vicinity of this sulphide outcrop consists of fine grained quartz and red limonite. As listed in Table 4, sulphide dump samples are rich in Cu (up to 6.3%), with minor Zn (up to 1.37%), low Pb and low Au (0.09-0.132 ppm) (Roser 1983, Licence 1989).
Figure 4  
A, outcrop of weathered and oxidised massive sulphide lens hosted in weathered mudstone in the bank of a small stream at Pupuke. B, oxidised massive sulphide lens hosted in siliceous mudstone exposed in a shallow open cut at the abandoned Copper Queen mine, Parakao.
Table 4  Metal analyses of sulphide grab samples from Pupuke, Pakotai and Parakao.

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<th>Cu %</th>
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Analyses are from Roser (1983) (VU16533 etc.) and Licence (1989) (PK4 etc.). na = not analysed.

6.1.2  Pakotai

Small discontinuous sulphide lenses occur in mudstone intercalated with and overlain by basalt and dolerite on the southern margin of the Mangakahia massif near Oputeke Road (Hay 1960; Clifton 1972; Pirajno 1979). The lenses contain pyrite + chalcopyrite + marcasite + sphalerite with rare galena (Roser 1983; Mason and Kobe 1989). Dump samples of sulphide ore are rich in Cu (up to 40.2%) and Au (0.9-21.5 g/t), with minor Zn (up to 0.83%) and Pb (up to 0.5%) (Table 4; Roser 1983; Licence 1989).

6.1.3  Parakao

A small lens of massive sulphide, in sheared tuffaceous and siliceous mudstone (Figure 3B) overlain by basaltic volcanics near the northern margin of the small (~12 km²) Pekapekarau massif, was worked in the 1960s as the Copper Queen mine (Rowe 1963; Bowen 1966). A surface limonite gossan passes down into an oxidised zone with azurite, malachite and minor native copper and cuprite. Below this at a depth of about 5 m, pyritic lode material contains secondary sulphides. The primary ore consists of pyrite + chalcopyrite + marcasite, with minor sphalerite and rare galena (Roser 1983; Mason and Kobe 1989). Brathwaite and Christie (2008) described dump samples of massive sulphide consisting of marcasite and sphalerite with minor chalcopyrite locally replaced by covellite. Dump samples of sulphide ore are rich in Cu (up to 19.0%) and Au (5.1-18.0 g/t), with minor Zn (up to 0.5%) and Pb (up to 0.5%) (Table 4; Roser 1983; Licence 1989).
7.0 COMPARISON OF NORTHLAND VMS DEPOSITS WITH MODERN OCEAN FLOOR VMS DEPOSITS

The pyrite + chalcopyrite ± sphalerite massive sulphide mineralisation at Pupuke is similar in mineralogy to the sulphide mineralisation deposited at high temperatures (300 to >400°C) on some spreading ridges in the Pacific and Atlantic oceans (Herzig and Hannington 1995). This high temperature mineralisation has low gold values (≤0.2 ppm) (Hannington et al. 1991), as also seems to be the case for the single Pupuke sample analysed for gold (0.12 ppm Au; Licence 1989). The presence of sphalerite in some samples at Pupuke is reflected by Zn contents of up to 1.37% (Roser 1983). Geochemically the Pupuke sulphide mineralisation is very low in Pb relative to Cu and clearly plots in the field of oceanic crust deposits on a Cu-Zn-Pb ternary diagram (Figure 5). Most of the Pupuke samples plot near the Cu apex in the same part of the oceanic crust field as the pyrite-pyrrhotite-chalcopyrite mineralisation at Upokongaruru near Lottin Point in the Matakaoa Volcanics (Brathwaite et al. 2008).

The Pakotai and Parakao mineralisation is different, consisting of pyrite + chalcopyrite + marcasite + sphalerite, rare galena and elevated gold (6.4-18.0 ppm; Licence 1989). This mineralisation is comparable with lower temperature (200-300°C) pyrite-marcasite-sphalerite/wurtzite-chalcopyrite mineralisation, relatively enriched in Zn, Pb and Au, which is found in some spreading centres (e.g. the Galapagos Rift; the East Pacific Rise at 11°N, 13°N and 21°N; the Endeavour Ridge) in the Pacific Ocean (Hannington et al. 1991). On the Cu-Pb-Zn diagram (Figure 5), the Pakotai and Parakao samples mainly plot away from the oceanic crust field toward the continental crust field, which reflects the presence of traces of galena represented by Pb contents of up to 0.5% (Roser 1983; Licence 1989). However, the Pakotai and Parakao samples differ from continental crust affiliated deposits, such as those at the Brothers caldera, in being relatively rich in Cu (Figure 5).

![Figure 5 Cu-Pb-Zn ternary diagram (after de Ronde et al. 2005) showing the compositions of the sulphide mineralisation at Pupuke, Pakotai and Parakao in relation to ocean floor VMS deposits from different volcanic/tectonic settings, including data from the Matakaoa Volcanics (Upokongaruru and B13 creek) and the Brothers caldera (see Brathwaite and Christie 2008 for details).]
8.0 GEOPHYSICAL SIGNATURES OF THE TANGIHKUA COMPLEX AND THE KNOWN VMS DEPOSITS

Airborne geophysical surveys were flown by Aeroquest Airborne (formerly UTS Aeroquest) using a CRESCO-08-600 fixed wing survey aircraft with tail stinger magnetometer installation, operated by Kiwi Air Ltd (Aeroquest 2011). The survey was flown using a 200 m line spacing orientated 045° to 225° and sensor height of 60 m, with tie lines spaced at 2000 m and orientated 135° to 325°, for a total of 80,710 line km. The processed magnetic and radiometric data (e.g. Figure 3B and 3C) was made into a series of images and viewed in an ArcGIS database as georeferenced jpeg images along with geological, geochemical and other relevant spatial data sets. This digital data is presented on a DVD that accompanies the report by Stagpoole et al. (2012).

A series of positive magnetic anomalies correlate with Tangihua Complex massifs and some smaller blocks that comprise igneous rocks present mainly at the top of the Northland Allochthon thrust sequence (Stagpoole et al. 2012). Each anomaly is almost an exact match for the outline of the present day massif, indicating that there are no concealed massifs.

The magnetic and radiometric data acquired by the geophysical survey have also been examined for magnetic and radiometric signatures of hydrothermal alteration zones and siliceous sedimentary rocks that may be associated with the known VMS deposits. Specifically, hydrothermal alteration zones may be represented by zones with flat magnetic patterns resulting from the alteration of magnetite in the mafic igneous rocks associated with the VMS deposits. Also, lenses of siliceous sediments may show up as K, Th and U radiometric anomalies relative to the enclosing mafic igneous rocks. In the correlative Matakapoa Volcanics of the East Coast Allochthon (Figure 1), lenses of sediment were defined from their relatively high Th and K values in an airborne radiometric survey (Christie et al. 2005; Brathwaite et al. 2008). In the Northland radiometric dataset, Th appears to most reliably differentiate major units within the Northland Allochthon (Stagpoole et al. 2012). The Tangihua rocks are characterised by consistently low Th counts, siliceous mudstones of the Whangai Formation have moderately low Th, whereas the extensive Punakitere Sandstone unit has predominantly high Th counts.

In this context, we have examined the magnetic and Th signals for the Pupuke, Pakotai-Parakao and Purua areas. We have used an analytic version of the reduced to pole magnetics (rtp_analytic) because it offers some improved detail of mainly shallow anomalies (Stagpoole et al. 2012).

8.1.1 Pupuke (Figures 6 and 7)

The VMS deposits at Pupuke occur around the edge of a bipolar magnetic anomaly (Figure 6B), typical of the Tangihua Complex mafic igneous rocks.

The thorium data for Pupuke (Figure 6C) exhibits low counts for Tangihua rocks and moderate to high counts for the surrounding sedimentary rocks. The scale of the survey is too coarse to allow small lenses of sedimentary rocks within the Tangihua rocks to be distinguished radiometrically by their Th or K signals.

8.1.2 Pakotai and Parakao (Figures 8 and 9)

As shown by the magnetic data (Figure 8B), the VMS deposit at Pakotai occurs towards the southern margin of a large Tangihua massif (Mangakahia) and the Parakao VMS deposit is
located near the northern margin of a small Tangihua massif (Pekapekarau). The Th data (Figure 8C) shows the Pakotai VMS deposit on the edge of a northwest-trending zone with moderate Th counts that may represent an intercalation of sedimentary rocks within the Tangihua rocks. At Parakao there is an east-west trending trough within the magnetic high that may be related to a zone of hydrothermal alteration or lenses of sedimentary rock, although at the scale of the radiometric survey, the Th data (Figure 8C) indicates that Pekapekarau massif is entirely composed of Tangihua rocks.

8.1.3 Purua (Figures 10 and 11)

As shown by the magnetic and Th data (Figure 10), the Purua Cu prospect is located near the western margin of a small Tangihua massif (Purua). There are no obvious magnetic or Th anomalies associated with the Purua Cu prospect.
Figure 6  Pupuke:  A. Digital elevation model and area of Tangihua complex rocks. B. Magnetic data (rtp-analytic), showing pronounced positive anomaly (red) for Tangihua rocks in sharp contact with non-magnetic sedimentary rocks (blue). C. Thorium data (counts) showing low counts (blue) for Tangihua rocks and moderate to high counts (yellow-red) for the surrounding sedimentary rocks. The location of the Pupuke VMS deposit is shown by the pink dot near the centre of the image. See Figure 7 for Cu, Zn and Pb geochemical data.
Figure 7 Contours of the concentration of Cu (A), Pb (B) and Zn (C) in stream sediment samples recorded in the REGCHEM database for the Pupuke area. Uncoloured areas have no data. The geochemical data are described in section 9.1.1.
Figure 8  Pakotai and Parakao: A. Digital elevation model and area of Tangihua complex rocks. B. Magnetic data (rtp-analytic) showing pronounced positive anomalies (red) for Tangihua rocks in sharp contact with non-magnetic sedimentary rocks (blue). C. Thorium data (counts) for Pakotai-Parakao, showing low counts (blue) for Tangihua rocks and moderate to high counts (green-yellow-red) for the sedimentary rocks. See Figure 9 for Cu, Zn and Pb geochemical data.
Figure 9  Contours of the concentration of Cu (A), Zn (B) and Pb (C) in stream sediment samples recorded in the REGCHEM database for the Pakotai and Parakao area. Uncoloured areas have no data. The geochemical data are described in section 9.1.1.
Figure 10  Purua: **A.** Digital elevation model and area of Tangihua complex rocks. **B.** Magnetic data (rtp-analytic) showing pronounced positive anomalies (red) for Tangihua rocks in sharp contact with non-magnetic sedimentary rocks (blue). **C.** Thorium data (counts) showing low counts (blue) for Tangihua rocks and moderate to high counts (green-yellow-red) for the surrounding sedimentary rocks. The location of the Purua Cu prospect is shown by the pink dot near the centre of the image. See Figure 11 for Cu, Zn and Pb geochemical data.
Figure 11 Contours of the concentration of Cu (A), Zn (B) and Pb (C) in stream sediment samples recorded in the REGCHEM database for the Purua area. Uncoloured areas have no data. The geochemical data are described in section 9.1.1.
9.0 GEOCHEMISTRY

Stream sediment geochemical analyses listed in open-file mineral exploration reports have been compiled in the REGCHEM (Warnes and Christie 1995) and Crown Minerals (2009) databases and are included as themes in the Northland GIS. The data date mostly from the 1970s and 1980s and generally have high detection limits by today’s standards. The data should be used with caution because they have been grouped from many surveys with some variations in sampling and analytical methods. We suggest that they be used in a positive sense, i.e. the areas of high geochemical values of elements are of interest, but areas where values are generally low should not be considered non-prospective.

Carver (2011) statistically analysed the data and assembled contour maps for Cu, Zn, Pb and Ni (Figure 12-14). Thresholds for anomalous values were 80 ppm Cu, 160 ppm Zn and 40 ppm Pb. No anomalous Ni values were identified.
Figure 12  Contours of Cu in stream sediments assembled by Carver (2011) based on data from the REGCHEM (Warnes and Christie 1995) and Crown Minerals (2009) databases. Values ≥80 ppm Cu are statistically anomalous. Areas of Tangihua Complex rocks are outlined.
Figure 13  Contours of Zn in stream sediments assembled by Carver (2011) based on data from the REGCHEM (Warnes and Christie 1995) and Crown Minerals (2009) databases. Values ≥160 ppm Zn are statistically anomalous. Areas of Tangihua Complex rocks are outlined.
Figure 14 Contours of Pb in stream sediments assembled by Carver (2011) based on data from the REGCHEM (Warnes and Christie 1995) and Crown Minerals (2009) databases. Values ≥40 ppm Pb are statistically anomalous. Areas of Tangihua Complex rocks are outlined.
Figure 15  Contours of Ni in stream sediments assembled by Carver (2011) based on data from the REGCHEM (Warnes and Christie 1995) and Crown Minerals (2009) databases. No anomalous values of Ni were identified by statistical analysis. Areas of Tangihua Complex rocks are outlined.
9.1.1 Geochemical signatures of known deposits

Figure 7, Figure 9 and Figure 11 show enlargements of the stream sediment contour maps for Pupuke, Pakotai and Parakao, and Purua respectively. Pupuke exhibits anomalous Cu, but not Zn and Pb (Figure 7), whereas Parakao has anomalies of Cu, Zn and Pb (Figure 9). This is as expected from the mineralogy and rock geochemistry described in section 6.0.

Pakotai (Figure 9) and Purua (Figure 11) fail to exhibit any anomalies for Cu, Zn or Pb. This suggests that the absence of anomalous Cu, Zn and Pb values does not necessarily preclude the presence of VMS deposits.

9.1.2 Geochemical anomalies away from known deposits

Several anomalous values of Cu, Pb and Zn are present in stream sediments in areas of Tangihua Complex rocks away from the known deposits. These are anomalies associated with the Reinga, Te Rake, Maungataniwha, Ahipara and Waima massifs (Figure 16-23).

A comparison of the stream sediment contour maps with the magnetic and Th counts maps presented in Figure 16-23 fails to reveal any obvious coincidence of features in the geophysical data that explains the location of the anomalies. Many of the stream sediment anomalies appear to be in areas of the Tangihua Complex with slightly elevated Th count response, but this is not consistent. Nevertheless, the stream sediment geochemistry does highlight some areas for targeting follow-up exploration as shown by the red coloured anomalies in Figure 16, Figure 18, Figure 20 and Figure 22.
Figure 16  Contours of the concentration of Cu (A), Zn (B) and Pb (C) in stream sediment samples recorded in the REGCHEM database for Reinga (left) and Te Rake (upper centre) massifs. There is a coincident Cu and Pb anomaly in the Reinga massif and copper anomalies downstream and south of the Te Rake massif.
Figure 17 RTP analytical signal magnetics (A), Th counts (B) and DEM (C) images for the areas of the Reinga and Te Rake massifs also shown in Figure 16.
Figure 18  Contours of the concentration of Cu (A), Zn (B) and Pb (C) in stream sediment samples recorded in the REGCHEM database for the Maungataniwha massif. Isolated Cu, Zn (coincident with Cu) and Pb anomalies are present in the northwestern part of the massif.
Figure 19  RTP analytical signal magnetics (A), Th counts (B) and DEM (C) images for part of the Maungataniwha massif also shown in Figure 18.
Isolated Cu, Zn and Pb anomalies are present in the central and northeastern part of the massif.
Figure 21  RTP analytical signal magnetics (A), Th counts (B) and DEM (C) images for the Ahipara massif also shown in Figure 20.
Figure 22  Contours of the concentration of Cu (A), Zn (B) and Pb (C) in stream sediment samples recorded in the REGCHEM database for the Waima massif. Isolated Pb anomalies are present in the western part of the massif and there are Cu anomalies south of the central part of the massif.
Figure 23  
RTP analytical signal magnetics (A), Th counts (B) and DEM (C) images for the Waima massif also shown in Figure 22.
10.0 PROSPECTIVITY FOR VMS DEPOSITS IN NORTHLAND

The large area of Tangihua Complex ocean floor volcanics in Northland suggests that there is good potential for ocean floor VMS mineralisation in addition to the known deposits (Christie and Barker 2007). The known VMS deposits (Pupuke, Pakotai and Parakao) are associated with siliceous mudstones and cherts, which are intercalated with basaltic lavas. This stratigraphic sequence of a lower part of basaltic pillow lavas with intercalated siliceous and/or calcareous mudstones, overlain by sequences of basaltic pillow lavas and intrusive rocks, also occurs in the Reinga, Maungataniwha, Ahipara, Maungaru, Houto, Tangihau and Waihue massifs (Isaac et al. 1994). Therefore the sedimentary intercalations in the lower parts of these other massifs may be prospective for the occurrence of similar VMS deposits to those at Pupuke and Pakotai.

At a local scale, Fe-rich sediments associated with VMS mineralisation at Pupuke have a strong hydrothermal signature (Brathwaite and Christie 2008), compared with very weak or absent hydrothermal signatures in the sediments in the Matakaoa Volcanics. This enhances the prospectivity of the Tangihua Complex massifs in the Pupuke area.

The occurrence of samples relatively rich in chalcopyrite + sphalerite, with elevated gold values at Pakotai and Parakao suggests that the mineralisation at these sites could contain economic zinc and gold ore in addition to the previously mined copper ore (Brathwaite and Christie 2008).

We have been unable to identify a consistent and characteristic magnetic or radiometric signature associated with the known VMS deposits at Pupuke, Pakotai and Parakao. However, individually the Pakotai deposit is associated with a linear Th anomaly that may represent a sedimentary unit and the Parakao VMS deposit is coincident with a small magnetic low that may represent a hydrothermal demagnetisation anomaly within a larger magnetic high representing Tangihua rocks.

An analysis of open-file stream sediment geochemical exploration data has highlighted several geochemical anomalies in areas of Tangihua Complex rocks away from known areas of mineralisation.

11.0 CONCLUSIONS

The Pupuke VMS deposit has no obvious associated hydrothermal demagnetisation or radiometric anomalies. The Pakotai VMS deposit has no associated hydrothermal demagnetisation anomaly, but is associated with a linear Th anomaly that may represent sedimentary rocks. The Parakao VMS deposit is coincident with a small magnetic low within a larger magnetic high representing Tangihua rocks.

The known deposits exhibit a variable geochemical response in stream sediment surveys, suggesting that geochemically quiet areas may still be prospective for VMS deposits.

The small size of the known deposits and extensive deformation of the host sediments and volcanics, are negative prospectivity factors (e.g. Christie and Barker 2007). The new airborne geophysical survey data has shown that the extent of the Tangihua Complex rocks is as previously geologically mapped and that there are no large areas of Tangihua Complex rocks buried beneath cover rocks. However, some of the known deposits have high grades of Cu and Au, and there are several Cu, Zn and Pb geochemical anomalies identified in previous exploration that could be followed up. There is potential for trial of other types of
geophysical surveys, particularly electromagnetic (EM) surveys that may image massive sulphide deposits directly, because of their high conductivity (Christie et al. 2008). Electromagnetic surveys were not included in the 2011 airborne geophysical survey programme because of their high cost. Airborne or ground based EM surveys could be undertaken over specific areas selected on the basis of a more rigorous evaluation of the existing data than possible under the scope of this project.

12.0 ACKNOWLEDGEMENTS

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Carolyn Hume drafted Figure 2. David Skinner and Richard Barker reviewed the manuscript and provided helpful suggestions.

13.0 REFERENCES


Edbrooke, S.W. and Brook, F.J. (compilers) 2009. Geology of the Whangarei area. GNS Science 1:250,000 geological map 2. Lower Hutt, New Zealand.


