**Supplementary material**

**Introduction**

Additional field and petrographic information concerning the Permian-Triassic tuffaceous sediments is summarized below. Tuffaceous rocks have previously been analysed by X-ray fluorescence and interpreted from the Stephens Group south of the Alpine Fault(Aitchison l984; Aitchison & Landis 1990)and from theChrome Creek Formation north of the Alpine Fault (Owen 1995), as outlined below. Some major-element XRF data already exist for the tuffaceous sediments from the Murihiku Terrane south of Alpine Fault and from the Willsher Group on the south coast (Jeans et al. 1997). In addition, cross plots of new major element data for each of the units studied here are illustrated and discussed. All of these data are taken into account in the interpretation of the tuffaceous sediments.

**Brook Street Terrane**

*Takitimu Mountains*

Felsic tuffs which were focused on during this study are volumetrically minor. However, mafic pyroclastic rocks occur more abundantly, as described by Houghton (1977), l981) and by Houghton & Landis (l989), as follows:

1. Crystal lithic tuff beds (0.5 to 2.0 m-thick), are rarely repetitive. Individual beds have irregular or sharp bases and include load and flame structure and other evidence of soft-sediment deformation. The beds are well sorted, normal-graded and pass gradationally upwards into volcanogenic mudstone. Rock fragments are concentrated near bed bases. Parallel lamination is visible in some of the finer-grained tuffaceous intervals. These basic tuffaceous rocks occur together with predominant black, non-vesicular, devitrified glassy basalt (with subordinate crystal and lithic material).

2. Basic lapilli tuff (up to 1 m thick) occurs rarely.

3. Brick-red vitric tuffs (< 10 cm thick) occur locally in the mid part of the succession (Heartbreak Formation and MacLean Peaks Formation). These tuffs are, in places, parallel laminated and micro-cross laminated, partially bioturbated and show evidence of small-scale slumping.

4. Crystal vitric tuff occurs, with rare plagioclase and clinopyroxene crystals and also shards, set in a matrix of altered glass with relict pyroclastic textures.

5. Minor agglomerate which is interpreted as the product of nearby volcanic vents.

6. Hyaloclastite, mostly in the lower part of the succession (Brunel Formation), which is typically made up of angular to subangular black vitric clasts (1 mm-1 cm). There are rare (<1%) red argillite or lithic fragments set in a green chloritized matrix. Individual depositional units exhibit normal-grading in maximum clast size over several metres. The hyaloclastite is interbedded with volcanogenic mudstones and sandstone gravity-flow deposits.

7. Finally, there are occasional occurrences of massive heterolithic tuff breccia.

**Maitai Group (Stephens Subgroup)**

*Countess Range*

Abundant tuffaceous rocks in the Countess Range (eastern Southland) were initially described by Landis (l974) and later by Aitchison (1984) (see also Aitchison & Landis 1990)

Landis (1974) emphasized the occurrence of plagioclase-rich crystal tuff on the east side Mt. Snowdon and vitric tuffs occur further northeast in the Countess Range (Mt. Snowdon and Tapara Peak). Although chert-like in the field, in thin section an original glassy texture can be inferred, with the growth of porphyroclastic pumpellyite and lawsonite in a very fine-grained quartz-albite groundmass. Vitric tuff contains spots of prehnite, pumpellyite and laumontite. An original dacitic ash fabric is largely replaced by a lawsonite-pumpellyite quartz-rich assemblage. A sample from further south, near Mossburn contains laumontite and pumpellyite. Felsic tuffs are interbedded with tuffaceous and volcaniclastic conglomerates and mudstone at Mt. Snowdon, in the Upukerora Valley and near the Mataura River.

*Richmond area*

In the Wairoa-Lee river area, fine-grained vitric tuffs include crystal tuff with abundant plagioclase, biotite and quartz, minor zircon and apatite (Owen l995). Rare fragments of gabbro, granite or biotite schist occur within the crystal tuff suggesting a continental basement. The andesitic-rhyolitic tuffs are interpreted as the product of explosive volcanism. The pyroclastic detritus is generally poor recrystallized. The highest part of the succession (Chrome Creek Formation) is generally tuffaceous and includes vitric, crystal and lithic varieties. Although most of primary eruptive texture is destroyed, gradations from vitric to crystal tuff, with plagioclase and possibly primary potassium feldspar are visible and cuspate textures are rarely retained.

Tuffaceous rocks were previously analysed for major elements from the Snowdon Formation (Aitchison & Landis 1990) and from the Chrome Creek Formation (Owen, l995). The Snowdon Formation tuffs range from basaltic to rhyolitic, whereas those of the Chrome Creek Formation range from andesitic to rhyolitic in composition. The Snowdon Formation tuffs represent a relatively low-titanium group. Within the Chrome Creek Formation, a tuffaceous interval (up to 40 m thick) includes, first a green to pale grey, mixed vitric crystal-lithic vitric tuff suite of andesitic to rhyolitic composition (relatively high in magnesium) and, secondly mostly pale grey lithic tuff of relatively alumina-rich, mainly andesitic composition.

**Murihiku Terrane**

*Southland*

The field relations, volcano-sedimentary features and petrography of felsic tuffaceous deposits have been documented throughout the Southland Syncline, from the south coast, though the Gore area (Wood 1956) to and including the Hokonui Mountains (Boles l971, l974).

The main components of the altered tuffs, as found in the North Range Group (Gavenwood Tuff) and the Taringatura Group (Bare Hill Tuff Zone) are as follows:

Heulandite-altered tuffs. These vary in colour from typically greenish or grayish-green to less commonly reddish or brownish and exhibit white to yellowish-grey rinds (< 5 mm). They fracture chonchoidally and are often fissile- weathering.

Analcite-replaced tuffs are paler-coloured, typically greenish, greyish or yellowish, typically with a white-weathering rind. They also fracture conchoidally, but are more massive- weathering compared to other varieties.

Laumontite-altered tuffs. These occur spasmodically in the North Range Group where they are greyish yellow to yellowish grey, made up of interlocking laumontite crystals, and exhibit rhomboidal jointing.

Albite-altered tuffs. The tuffs are rarely altered to albite and some quartz in the North Range Group (Gavenwood Tuffs).

Montmorillonite-altered tuffs. These are quite common in the North Range Group.

Vitric tuffs from the Murihiku Terrane include subordinate clinopyroxene, hornblende, biotite and/or magnetite. Hornblende, biotite, and volcanic quartz are conspicuous in the North Range Group, whereas clinopyroxene is more common in the stratigraphically higher Tarangatura Group, together with trace-amounts of sphene and plant fragments.

Associated tuffaceous sediments commonly contain authigenic quartz, albite and potassium feldspar (adularia). Many of tuffaceous layers are zeolitised in the form of analcite (crystal mosaics replacing shards), heulandite (lath-like) and laumontite (patch-like interlocking crystals replacing shards). Phrenite and/or pumpellite occur sporadically in small amounts. There are also minor and scattered occurrences of chlorite, celadonite, siderite, pyrite and montmorillonite. In some cases, early shard-replacing minerals (e.g. some zeolites) are replaced by regional metamorphic minerals (e.g. albite, quartz, alkali feldspar). The Bare Hill tuff zone includes localized intraclasts of dark-grey siltstone (up to 1 cm in size) and foreign tuff fragments (up to 4 cm across).

Previous major element data (six samples from the Hokonui Hills and one from Parks Cutting, south coast) indicate SiO2 values of mostly 68-74%. K2O and Na2O are strongly influenced by low-grade metamorphism and alteration. Electron probe analysis of feldspar indicates c. 90% plagioclase versus c. 10% alkali feldspar (Boles l971, l974).

The stratigraphically lower Mid-Triassic tuffs (North Range Group) are mainly dacitic, whereas the higher Late Triassic tuffs (Taringatura Group) vary from andesitic to dacitic. The composition of the late Triassic (Oretian) tuffs suggested a more highly evolved magma than at other times (Boles, 1971 l974).

The results of the present study suggest that some of the minerals identified using optical microscopy are present in very low abundances (<15) because not all were indicated by X-ray diffraction. In addition, the new chemical data from the Gavenwood and Bare Hill felsic tuffs do not indicate systematic compositional differences.

**Murihiku Terrane**

*Richmond area*

Felsic tuffaceous rocks occur at several levels of the Richmond Group (Owen l995).

The Mid-Triassic (Etalian) lowest formation (Te Arowhenua Formation) locally includes pale grey to pinkish zeolitic tuff with occasional dark grey silicified conchoidal-fracturing tuff layers. The overlying Mid-Late Triassic (Etalian-Kaihikuan) interval (Wantwood Formation) (Johnston l982; Owen 1995) includes minor red and green tuffs and tuffaceous sandstones. The interval above this (Kaihikuan-aged Wells Formation) (Johnston l982; Owen l995) includes potassium feldspar-rich sandstones and red and green tuffaceous sandstones. The overlying Late Triassic Kaihikuan-Oretian Saxton Conglomerate (Johnston l982a) is subdivided into an unfossiliferous conglomeratic interval (Saxton Conglomerate) and a fossil-bearing finer-grained laterally equivalent interval (Church Valley Formation (Owen l995). The overlying Garden Formation encompasses tuffaceous siltstones, fine-grained sandstones and occasional conglomerates with mudstone intraclasts, of Late Triassic (late Oretian) age. A well-known overlying bivalve-rich shell bed, which includes *Manticula problematica* is dated as Late Triassic (Otamitian) (see Johnston l982; Campbell 1974). Finally, the highest unit (Max Sandstone) is a brachiopod-fragment-rich coarse, locally pebbly sandstone of similar age (Otamitian).

**Major element chemistry**

Although the tuffaceous sediments are metamorphosed and variably altered, some interesting correlations of major element oxides emerged (see Supplementary Figs S1 & S2). There are clear positive correlations of SiO2 with several oxides (Fe2O3, MnO, MgO) in the Brook Street Terrane data set, whereas the plots for the Maitai Group and the Murihiku Terrane are more scattered. In general, the plots of the Maitai and Murihiku samples are more similar to each other for some oxide plots (e.g. MnO vs. SiO2, P2O5 vs. SiO2) than for the equivalent plots of the Brook Street terrane samples. A strong positive association of SiO2 vs. Al2O3 and of MgO vs. Fe2O3 suggests that metamorphism of up to upper greenschist facies has not resulted in significant chemical mobilization of these element oxides. However, the scattered nature of the SiO2 vs. Al2O3 plot and, particularly of plots involving K2O and Na2O is indicative of post-depositional alteration.

Overall, the major element oxide plots of the Brook Street Terrane tuffaceous sediments from south of the Alpine Fault are consistent with variable degrees of fractional crystallization of a mafic melt, as suggested by the SiO2 vs. Fe2O3, SiO2 vs. MgO plots. The Maitai and Murihiku tuff samples reflect fractional crystallization of both generally mafic and more felsic magmas.

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