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NEW ZEALAND'S DARRAN COMPLEX AND MACKAY INTRUSIVES—RB-SR WHOLE-ROCK ISOCHRONS IN THE MEDIAN TECTONIC ZONE

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ABSTRACT. The Cretaceous opening of the Tasman Sea, followed by uplift east of the Alpine Fault, has given access to the roots of a Mesozoic convergent Gondwana margin in western New Zealand. This long term margin contains the complex Median Tectonic Zone (MTZ) of recent authors and is perfectly exposed between Milford Sound and the Darran Range. In the western part of this profile, in the *Milford Gneiss Complex,* earlier MTZ history is obscured by Cretaceous metamorphism and structural transposition. However, the *Pembroke Granulite* is well preserved, and the metamorphic curtain gradually lifts toward the east. Rb-Sr whole-rock isochron dates and initial $^{87}Sr/^{86}Sr$ (I_o) values are presented. The *Darran Complex* yields a whole rock isochron of 133 ± 17 Ma, concordant with published zircon U-Pb *and* hornblende K-Ar results. The *Mackay Intrusives (Mistake Diorite* and *Hut Suite*) yield a whole rock isochron of 224 ± 4 Ma (MSWD = 1.21) in agreement with published U-Pb dates of *Mistake Diorite.* Rafts of *Christina Gneiss* in *Mackay Intrusives* were subject to partial melting at the time of the *Mackay* intrusive activity. However, the *Darran Complex* also appears spectacularly intruded by the Christina-Crosscut irruptives of *Mackay* granitoids, which plot precisely on the 224 Ma *Mackay* Rb-Sr whole rock isochron. Obvious ways of resolving this paradox are (1) that the *Darran Complex* has undergone thermal resetting *after* its intrusion by *Mackay* magma, and (2) that the Christina-Crosscut irruptives are late, back-intrusive, Darran differentiates containing assimilated *Mackay* material. These solutions fail on the grounds of heat transfer (*Mackay* isochron was not re-set) or of heat balance (surmised irruptives excessively contaminated for the available heat). A way past the constraints is the passive tectonic emplacement of the Mt. Crosscut irruptive as a dike-like roof pendant. The Mt. Christina irruptive is dated less reliably, is tectonically less modified, and may represent a late *Darran* liquid. A much older age and lower I_o of the *Darran* correlative *Rotoroa Complex* may be inherited from a common *Rotoroa/Darran* protolith. I_o increases systematically from *Rotoroa* to *Western Darran (Milford/Pembroke)*, to *Darran* rocks, and finally to *Western Fiordland Orthogneiss (WFO),* which is chemically distinct from the *Pembroke Granulite* and *Darran Complex.*

INTRODUCTION

The Paleozoic eastern margin of Gondwanaland was originally known in New Zealand as H. Fyfe's Line (Fleming, 1970) and by the associated Median Tectonic Line (Landis and Coombs, 1967). It was active in the Permian and early Triassic with the addition of the Brook Street island arc and related subduction zones (Coombs and others, 1976). Only in a fragmentary and telescoped form has this continental margin survived the Cretaceous formation of metamorphic core complexes (Tulloch and Kimbrough, 1989; Gibson, 1990), the opening of the Tasman Sea, and transcurrent faulting. Bradshaw (1993) and Kimbrough and others (1993, 1994) have defined the most chaotic part of this margin as the Median Tectonic Zone (MTZ), Bradshaw (1993) formulating as follows: ". . . a zone of small terranes, terrane shards, and stitching plutons

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[. . . which contain] evidence of the history of the Gondwana margin. . . ". Recently, Mortimer and others (1999a,b) have simplified the MTZ concept to "Median Batholith" perhaps underlining the fact that long lived continental margins do consist of accreted plutons and batholiths. However, the collage is varied (figs. 1 and 2). The *Mackay Intrusives* form the faulted eastern boundary of the MTZ against the *Brook Street Volcanics* to the east. Together with the associated *Largs Group* they have long been of uncertain status and require new dates and a reappraisal. As will be seen, apophyses of the *Mackay Intrusives* seem to intrude the eastern boundary of the *Darran Complex* in spite of its now accepted Cretaceous intrusion age. In the west an increasingly ductile *Darran Complex* grades metamorphically into the *Milford Gneiss Complex.* That intensely folded structure and possible metamorphic core complex is bounded westward by the subvertical *Anita Shear Zone.* As the *Western Fiordland Orthogneiss (WFO)* and *Separation Point Granite* are here missing or faulted out, the Anita Shear Zone and associated *Thurso Gneiss* are the likely western margins of the MTZ (Gibson, 1990; Hill, 1995).

We present new Rb-Sr whole rock isochron data and field relations of the *Mackay Intrusives,* the *Darran Complex,* and adjacent units to the west, including the *Rotoroa Complex* of Nelson. Rather than attempt an along-strike review of all MTZ tectonics, we present a detailed study of one particularly well exposed transect.

GEOLOGICAL SUMMARY OF HOLLYFORD-MILFORD TRANSECT

Mackay Intrusives

The field concept of the *Mackay Intrusives* has shown a pragmatic and increasingly ambivalent development. The Eglinton Volcanics of Grindley (1958) formed the eastern margin of the Darran Diorite map unit of Wood (1962) and the original *Mackay Intrusives* (Grindley, 1958; Wood, 1962) were isolated, largely granitoid, plutons within the Eglinton Volcanics. Later, Williams (1975) and Williams and Harper (1978) discovered additional, often migmatitic, diorites and granites, including the *Mistake Diorite,* which were an obvious northward extension of the *Mackay Intrusives.* As they observed "a continuous petrographic spectrum from leucogranite to dunite," Williams and Harper included with these extended *Mackay Intrusives* the gabbroic rocks of Wood's (1962) Darran Diorite, which they named Hollyford Gabbroic Suite. In this way all *Mackay Intrusives* would be an extension of the Darran Diorite (and hence of the *Darran Complex*). Somewhat farther north and in a similar zone of migmatization and syntexis, Blattner (1978) found significant intrusive contacts at Mts. Christina and Crosscut, *within* the Darran Diorite. His "Leucoquartzdiorite" intrudes the usually two-pyroxene gabbroic *Darran Complex* in a near vertical over 1 km long apophysis, connected to rocks very similar to the *Mistake Diorite.* A reasonably good tectonic match exists for this zone of *Mackay Intrusives* southward across the Upper Hollyford Valley, after restoration of about 10 km dextral offset on the Glade-Darran Fault. Thus, as *Nurse* and *Glade Suite* (cross pattern in fig. 2) are rare north of the Upper Hollyford Valley, and on the field evidence of Mt Crosscut, Bishop, Blattner, and Landis (1990) include with the *Mackay Intrusives* the entire granitoid sequence on the eastern margin of the *Darran* Complex. Only the Hollyford Gabbroic Suite among Williams and Harper's units is relegated to the *Darran Complex* (fig. 2). Here follows a summary of rock types after Williams and Harper (1978), slightly adapted and with comments, after extending the mapping to the north of the upper Hollyford Valley.

The *Mistake Diorite* is an elongate body of up to a few kilometers wide, which narrows northward to less than 100 m in the Upper Hollyford Valley, where Williams' (1975) map ends. The rock types range from common quartz bearing diorite to rarer granite, all with generally uniform grain size of 3 to 5 mm and unzoned or weakly zoned plagioclase of about An33. The main mafic minerals are biotite, augite, and magnetite/ilmenite (at the diorite end, predominantly in the west) and hornblende, largely chloritized biotite and characteristic titanite, with up to 15 percent K-feldspar and strongly altered plagioclase (at the more deuterically altered western, granitic end).

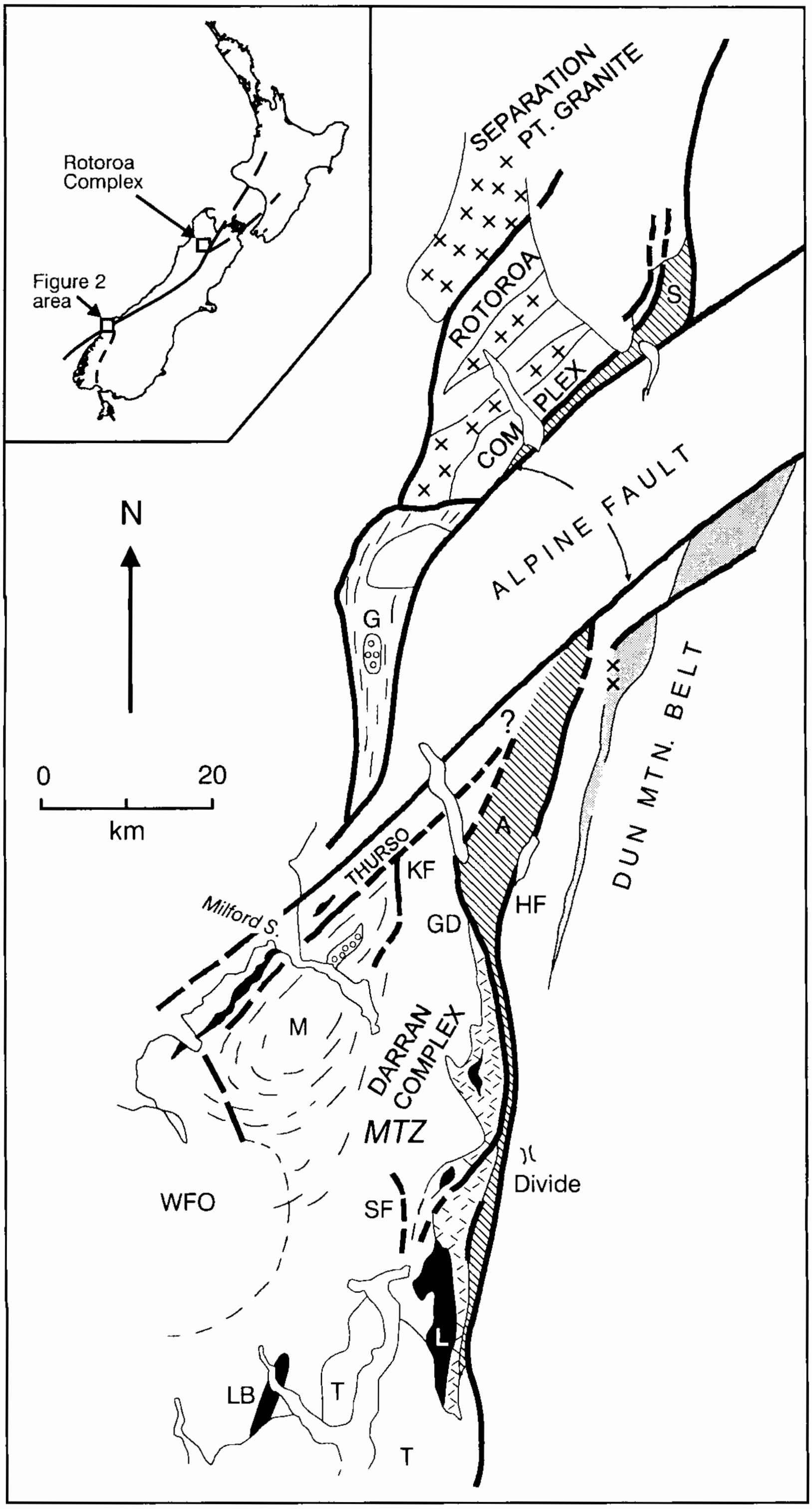

Fig. 1. Reconstruction of Alpine Fault, New Zealand, showing Mesozoic proximity of *Darran* and *Rotoroa Complexes*, as well as of *Milford Gneiss* (M) and *Glenroy Complex* (G); note circles for hornblende granulite. These four units form the western part of the MTZ. The *Anita Ultramafites* (black, across entrance of Milford Sound) also mark the Anita Shear Zone. The *Largs Group* (L) is also shown in black, associated with the stippled *Mackay Intrusives*, which mark the eastern end of the MTZ. Remaining key: KF Kaipo Fault, GD Glade Darran Fault, HF Hollyford Fault, *WFO Western Fiordland Orthogneiss*, A *Alabaster Group (Brook Street Terrane)*, SF Surprise Creek Fault, LB *Loch Burn Formation*, S Speargrass Fault Zone, T Tertiary cover.

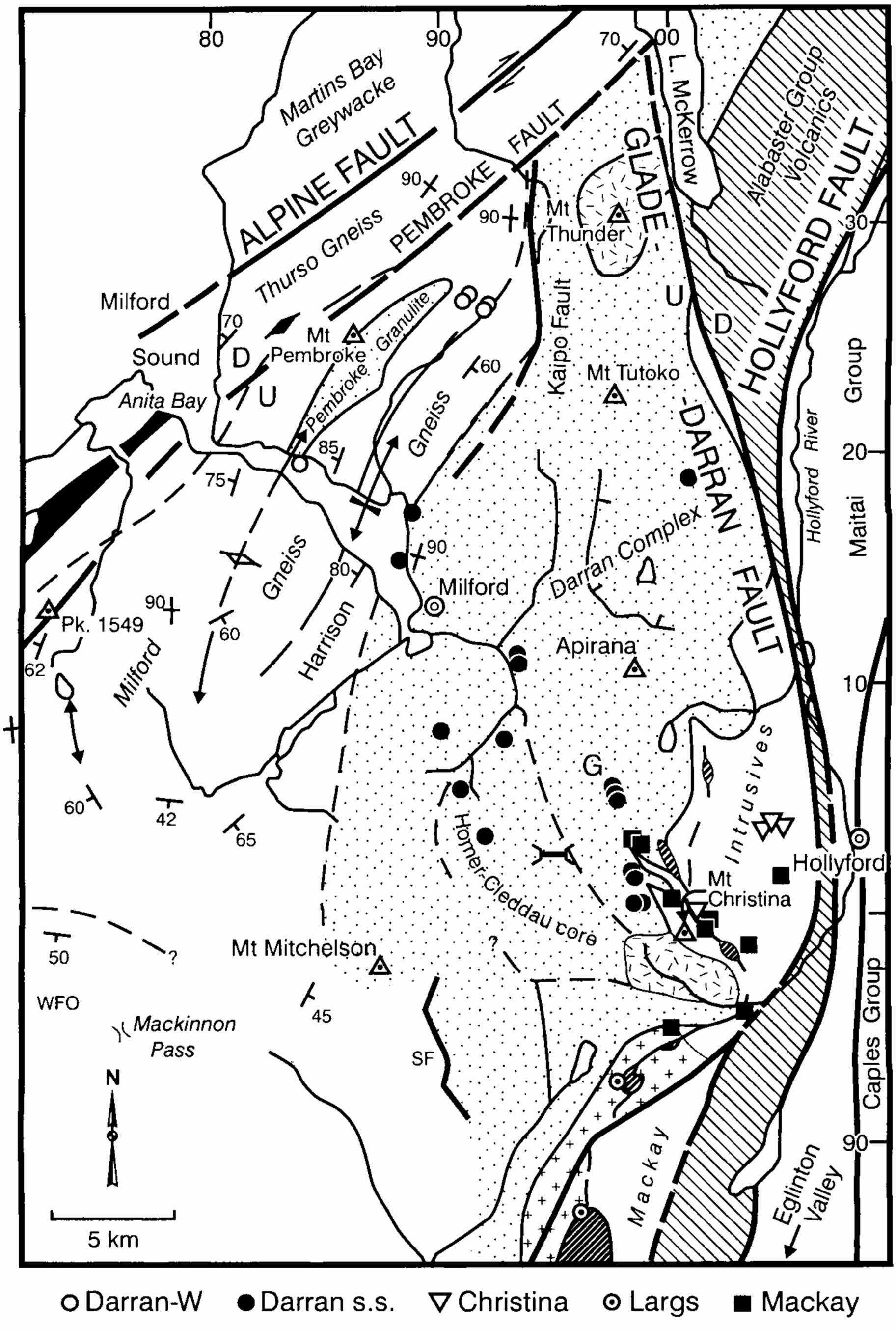

Fig. 2. Geological sketch map of northern Fiordland; the MTZ is contained between Anita Bay and Hollyford. *Anita Ultramafites* black, also marking core of Anita Shear Zone; *Largs Group* bold hatched; mafic *Darran* rocks are stippled near Mts. Thunder and Christina; *Nurse/Glade Suite* with cross pattern. Key to samples analysed for Sr isotopes at bottom. Mt. Crosscut is 3 km north-northwest of Mt. Christina, within the main (curved) apophysis. Not all samples near Gertrude Saddle (G) and Mt Christina are shown individually. Note bold mark of Homer Tunnel near "Homer-Cleddau Core"; from there the Cleddau River flows northwestward and the Upper Hollyford River to the southeast. The ductile deformation of the *Milford Gneiss Complex* lapses gradually near the *Darran* boundary and the Kaipo Fault has excised much of the *Milford* to *Darran* transition zone syn- to post-metamorphically. SF = Surprise Creek Fault; *WFO* = *Western Fiordland Orthogneiss.* The symbol just outside the western margin of this figure marks the recent discovery of massive marble and quartzite (see text). The map projection and grid correspond to the NZMS1 references in the tables.

North of the Upper Hollyford valley (that is, across the Glade-Darran Fault) the *Mistake Diorite* is widening again (in accordance with the above mentioned fault restoration), sometimes showing zoned plagioclase and steeply dipping cumulate layers. The *Hut Plutonic Suite* of Williams and Harper (1978) lies at the western margin of the *Mistake Diorite* and consists of 75 percent leucogranites (with less than 5 percent mafics, including up to 1 percent magnetite), and some quartz bearing diorites. Grain size is 3 to 5 mm. Such rocks also occur north of the Upper Hollyford Valley, forming a petrographic transition to the *Mistake Diorite.*

It is the *Nurse* and *Glade Suites* that, together with the *Darran Complex*, provided Williams and Harper (1978) with a full petrographic spectrum from granite to (*Darran*) dunite. They tend to occur west and south of the *Mistake Diorite* and have grain sizes near 1 mm, extensively zoned plagioclase, and show little alteration. They are likely to be part of the *Darran Complex.* The distinctive small grain size noted by Williams and Harper (1978) tends to increase significantly toward north (*see* also under *Darran Complex* below). Like the *Hut* and probably the *Mistake* granitoids, they can be in direct intrusive contact with *Largs* volcanics and contain *Largs* xenoliths in zones of assimilation. The pink leucogranite Bl 8706 (table 4) may be one of Williams and Harper's (1978) varieties of Nurse granitoids.

After consideration of the age data we will see that the term *Mackay Intrusives* should be confined to the *Mistake Diorite* and *Hut* granitoids, that is the *Mackay Intrusives* of Williams and Harper (1978) after removal of the *Nurse* and *Glade* units to the *Darran Complex.*

Mackay Irruptives at Mts. Crosscut and Christina

Blattner (1978) and Bishop, Blattner, and Landis (1990) mapped a single Christina-Crosscut "irruptive" of *Mackay Intrusives* into the *Darran Leucogabbro.* The name emphasises that field relations require a post-*Darran Complex* emplacement for that part of the *Mackay Intrusives.* A main 1 km long apophysis at Mt. Crosscut consists of leucogranite and petrographically strongly resembles the *Hut Suite* and some of the least altered examples of *Mistake Diorite.* Its overall structural integrity is well preserved (fig. 3A), although the root of the irruptive, that is, its connection to the main *Hut Suite/Mistake Diorite* body, is difficult to access in the subvertical southeast face of Mt. Crosscut. On closer examination from the air it is clear that the similar apophysis at Mt. Christina (fig. 3B) is separately rooted. In the Mt Crosscut irruptive internal flow structures are common (fig. 4), and figure 5 shows an alignment of shattered *Largs* xenoliths within the foliated rock. A typical southwestern margin of this irruptive is shown in figure 6: no original, crystallized intrusive contact is preserved, with both rocks foliated, sometimes with a low angle discordance. In figure 6, in addition, a boudin-shaped remainder of wall rock material is wedged in at the contact. The incipient foliation in the *Darran* wall rock is clearly a tectonic overprint and may have little to do with emplacement history. Across the width of the apophysis, some 40 m eastward, and after passing through inhomogeneities such as the schlieren and xenolith swarms of figures 4 and 5, the eastern contact of the irruptive seems transitional over a distance of meters, and homogeneous hybrids between *Darran Leucogabbro* and *Mackay* granite occur. Toward northwest the irruptive ends in one or more thinning-out strands (fig. 3A). The similar, at least 500 m long, independent "*Mackay*" apophysis of Mt Christina consists of almost pyroxene-free, finer grained leucoquartz-diorite. Its western contact is sharp; and a steady marginal accumulation of xenoliths, extending over some 100 m distance, indicates a degree of magmatic fluidity (fig. 3B).

Largs Group and Christina Gneiss

Williams (1975, 1978) subdivided Grindley's Eglinton Volcanics into the predominantly basaltic volcaniclastics of the Plato terrane and the generally andesitic and pyroclastic Largs terrane; for the latter we follow Mortimer and others' (1999a) usage of *Largs Group.* Williams suggested that hornfelsed xenoliths in the *Mackay Intrusives* (fig. 6; also Blattner and Williams, 1991, fig. 4) were themselves contact metamorphic *Largs* material. Williams also postulated a subaerial, terrestrial, deposition of the *Largs Group*

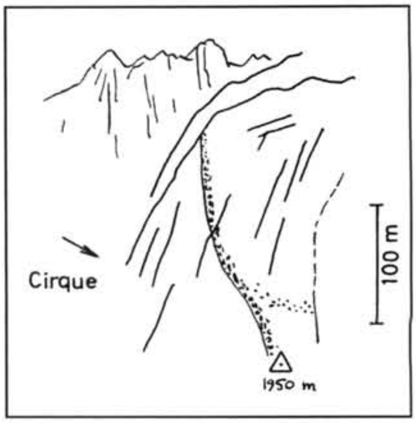

Fig. 3(A) Middle Peak of Mt Crosscut from the northwest, with shoulder towards right. View of the light coloured Mt.Crosscut irruptive. Internal septa of wall rock are visible in the rock face above the ice field. Figures 4–6 are from the area just below the ice field. The western contact (fig. 6) of the irruptive is on the right. (B) The Mt. Christina irruptive in the North Peak of Mt. Christina, with its sharp western contact, marked by an accumulation of xenoliths (different types of quartz diorite with sizes up to 1 m); a smaller xenolith swarm branches off. Mt Crosscut seen from the southeast is in the background. The irruptive there is indicated, and strikes to the right (re-interpretation 1998 of Blattner, 1978).

volcanics, and both ideas were confirmed by the significant oxygen isotope (^{18}O-) depletion of the conterminous *Largs Group* as well as of the rafts and xenoliths far to the north (Blattner and Williams 1991). Due to assimilation, the *Mackay Intrusives* (especially *Hut* leucogranites) can show a secondary isotopic signal of this depletion. The *Largs* xenoliths are contact metamorphic up to pyroxene-hornfels grade (K-feldspar, sillimanite, corundum; Bishop, Blattner, and Landis, 1990).

In view of their occurrence as rafts within the *Mackay Intrusives* and their polyphase migmatite fabric, the *Christina* medium grained biotite gneisses could be the statigraphically oldest rocks of the Darran Range (Blattner, 1978). They include veined gneiss and diatexite and occasional grossularite-rich calcsilicate nodules. On the map of Bishop, Blattner, and Landis (1990) two main occurrences are marked as "migmatites." The *Christina Gneiss*, including its primary quartz component, seems to match the oxygen isotope anomaly of the *Largs Group*. It may have a parallel in the *Rotoiti Gneiss* of Nelson, mapped by Johnston (1990) as a sliver of uncertain age in the Speargrass Fault Zone, that is at the eastern boundary of the MTZ there.

Darran Complex

The *Darran Complex* is what remains of the Darran Diorite of Wood (1962) after exclusion of the discordant, seemingly later emplaced, *Mackay Intrusives* (that is *Mistake*

Fig. 4. Schlieren with arrowhead structures in Mt. Crosscut irruptive, near center of figure 3A. Ice axe points towards top of Mt. Crosscut and the root of the irruptive in the main *Mackay (Hut/Mistake)* pluton.

Fig. 6. Western contact of Mt. Crosscut irruptive; the hammer is on *Darran Leucogabbro.* Both, irruptive and wall rock are gneissoid. The split-off and transported boudin shows banded structure and may be of a wall rock xenolith. On left, schlieren of similar composition as arrowheads of figure 4.

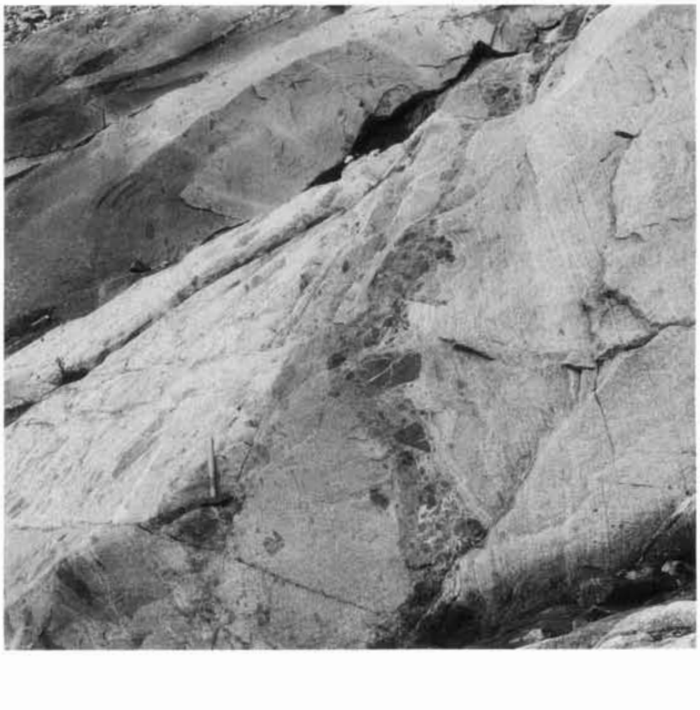

Fig. 5. Alignment of mafic xenoliths within the *Mackay* irruptive northwest of Mt. Crosscut, parallel to the foliation, and roughly parallel the easten contact of the irruptive, which is near the left margin of photo.

Diorite and *Hut Suite*). In view of its size (>100 km^2 outcrop area) and coherent igneous character the *Darran Complex* is a significant batholith in the strict sense. In addition to anorthosites and ultramafics, which occur in the massifs of Mt. Thunder and Mt. Christina (and farther to the southwest near Mt. Mitchelson; Bradshaw, 1990), it consists of the *Darran Leucogabbro,* which varies from leucogabbronorite to biotite-pyroxene-leucodiorite (Blattner 1978, 1991; Williams and Smith 1983). Mesoscopic primary layering is common but without a clear regional structure as yet. Small-scale differentiates or segregations, with a few percent quartz and up to 2 percent K-feldspar with myrmekite, also occur. The leucogabbro shows a regional compositional gradation with the chemically most primitive, unevolved fractions occurring to the southwest of the Cleddau-Upper Hollyford axis ("Homer-Cleddau Core", fig. 2). Here, samples have about 51 percent SiO_2, with only traces of biotite, whereas farther west and north (Apirana, Mt. Tutoko) the dominant fractions have up to 55 percent SiO_2 and several percent biotite. While overall igneous cumulate fabrics and textures are pervasive, grain size varies from 1 to 2 mm in the Homer-Cleddau Core, where feldspar is colored strongly gray to purple, to well over 5 mm near Mt. Tutoko. Progressively lighter colored feldspar occurs in the more evolved, coarser grained areas. Some minor and trace element concentrations in the *Darran Leucogabbro* are as follows (starting with "core" samples): K_2O, 0.2 to 2.2 percent; Rb, 2 to 70 ppm; Sr, 700 ± 100 ppm; Pb, 4 to 25 ppm; Zr, 10 to 100 ppm; Y, 10 to 30 ppm (Blattner, 1991 and thirty unpublished analyses). The strong magnetic anomaly of the Upper Hollyford Valley (Woodward and Hatherton, 1975) is shared by the central part of the *Darran Complex* and much of the *Mackay Intrusives,* which both contain up to 1 percent magnetite. The *Leucogabbro* suite as a whole and individual zoned feldspar grains straddle the An50 composition limit of plagioclase. Given the resulting choice, the term *gabbro* is preferred over diorite, because of the context of differentiation and the dominance of two pyroxenes among mafic minerals (see discussion in Streckeisen, 1976) and for contrast with such rocks as the Mistake *Diorite.*

A pattern of deuteric replacement of pyroxenes by hornblende is imposed on the primary *Darran Leucogabbro,* in that structural discontinuities (locus of veins and dikes as well as joint planes) have acted as conduits for hydrous fluid (Blattner, 1978). This alteration takes over progressively toward the west, as if part of the regional metamorphism, and a *regional* hornblende leucodiorite replaces the leucogabbro at the longitude of Milford (*Darran Hornblende Diorite,* Blattner 1991). Sizeable residues of leucogabbro can still be found as far as 1.5 km north-northwest of Milford village. Analysis of adjacent leucogabbro and hornblende diorite shows gain of H_2O and possible loss of Cl to be the only chemical changes in the transition. From Milford westward any original *Darran* boundary would be lost in a zone of increasing strain partitioning, boudinage, and re-mobilization, suggestive of a high-P/T tectonic mélange extending at least 2 km across strike, or just showing the onset of a different tectonic regime. This area shows few higher level faults or shear zones. Epidote/oligoclase, muscovite, and garnet appear very gradually (garnet clearly reaching into the *Darran Complex*) and magnetite reacts to rutile (Blattner, 1991). There is good evidence in Bradshaw (1990) and Blattner (1991) and from new mapping of sheeted intrusives, that the Cretaceous intrusions and injections of the *Indecision Creek Complex* continue northward into the *Harrison Gneiss,* although this is not easy to show on a small scale map (Turnbull and others, 2000).

Trondhjemite/adakite.–A swarm of up to 5 m wide subvertical dikes of trondhjemitic composition with occasional garnet crosses the *Darran Complex* in the upper Hollyford Valley (Bishop, Blattner, and Landis, 1990), and farther south and west (in Bradshaw's, 1990, Mt. Anau Complex), some merging into injection layers. Along the Milford road, Wandres and others (1998) find a surprisingly pervasive network of smaller veins of similar composition (adakites). They point out that these rocks, with usually <5 ppm Y, indicate a change to a garnet bearing magma source area.

Milford Gneiss Complex and Pembroke Granulite ("Western Darrans")

With their intermediate to deep crustal metamorphic fabric and textures, the *Thurso Gneiss*, *Milford Gneiss*, *Pembroke Granulite*, and *Harrison Gneiss* (fig. 2) form the *Milford Gneiss Complex.* Near the Alpine Fault this structure passes into and is cut by the Anita Shear Zone, interpreted by Hill (1995) as a middle Cretaceous, originally near horizontal, boundary to the western province or Tuhua sequence (Gondwana). Toward north the Milford basement buckles in a narrowing tectonic regime. The Kaipo Fault signals a mass deficit with the removal and perhaps subduction of the *Harrison Gneiss,* much of the *Milford Gneiss*, and thus the entire metamorphic and structural transition between *Darran Complex* and *Milford Gneiss.* It juxtaposes high grade strongly foliated gneisses and almost unaltered igneous fabrics (fig. 2). These characteristics are not fully shared by the Surprise Creek Fault (Koons, 1978; Bradshaw, 1990), which occurs 25 km farther south and has *Darran* type rocks on both sides (for example, the *Darran Hornblende Diorite* of Mt. Mitchelson).

In the Mt. Pembroke massif near the core of the Milford antiform, a several kilometers long residue of meta-igneous *Pembroke Granulite* is preserved, engulfed by its retrograded chemical equivalents in the *Milford Gneiss* unit. Protected from ductile deformation, the granulite has magmatic structures including cumulate layers, although from preceding more static metamorphism its feldspar textures are hypidiomorphic-granular, and its hypersthene is strongly pleochroic (Blattner, 1976, 1978). Clarke, Klepeis, and Daczko (2000) offer new P/T estimates on these rocks. In a new discovery some 8 km to the south-southwest of Peak 1549 m (fig.2), the dominantly meta-igneous *Milford Gneiss* contains (or borders on) massive layers of marble and quartzite (Spark, 1999). If the Anita Shear Zone is to be a major tectonic boundary, the relationship between this marble and the marbles of the *Thurso Gneiss* will require detailed attention.

Rotoroa Complex

The *Rotoroa Complex* of Nelson (fig. 1) lies to the northwest of the Alpine Fault and is widely regarded as a counterpart of the *Darran Complex*, so that the two would have constituted a *Darran-Rotoroa* proto-Complex (Challis and others 1994). A major unit of the *Rotoroa Complex* is the *Howard Gabbro*, which is petrographically very similar to the *Darran Leucogabbro.* On a regional scale it has interposed sheets of granite (fig. 1), which are considered to be part of the *Separation Point Granite* (Challis and others, 1994).

Magma Lineages and Tectonic Relations with Nelson

The *Pembroke Granulite* shares its network of planar garnet bearing alteration zones, indicating rapid and incomplete dehydration (Blattner, 1976; Blattner and Black, 1980) with the major granulite of Fiordland, the *WFO* (Bradshaw, 1989). However, there are substantial chemical differences between *Pembroke Granulite, WFO,* and *Darran Complex.* The *WFO* has about 30 percent more Na than the *Darran* rocks at similar Si and almost twice the amount of Sr as well as being very low in Y (Blattner, unpublished analyses; Muir and others, 1998). On these grounds, Muir and others (1995, 1998) regard the *WFO* (and the *Separation Point Granite)* as high pressure partial melts in the garnet stability field and with almost complete feldspar melting. In contrast, the *Darran* and *Rotoroa* magmas would be calc-alkaline partial melts of more shallow origin. For Kimbrough and others (1994) the *WFO* is a stitching pluton at the western margin of the MTZ. The *Pembroke Granulite* matches the *Darran Leucogabbro* exactly in its moderate Sr content (~800 ppm), although its Na and especially Y approach *WFO* values (Blattner 1991). Garnet-free granulites petrographically similar to the *Pembroke Granulite* have also been found in the *Glenroy Complex* (fig. 2) which could much enhance the correlation between North Fiordland and Nelson. The hornblende and apatite found in *Glenroy* hornblende granulites show elevated chlorine levels, equivalent to values theoretically restored for the pre-garnet zone and pre-dehydration *Pembroke Granulite* (P. Blattner and A.J.

Tulloch, unpublished data; Blattner, 1981). The *Rotoroa Complex* lies immediately east of the *Glenroy* area, as the *Darran Complex* lies to the east of the *Milford Gneiss.*

PREVIOUS ISOTOPIC DATING AND THE DARRAN-MACKAY RELATIONSHIP

Field geological interpretations require to be guided increasingly by isotopic dates, which in turn tend to become more scattered about the literature. It was mostly the work of Williams and Harper (1978) that brought isotopic methods to this area, and the following isotopic dates seem available for *Mackay Intrusives* at present (limits of error are mostly negligible for the purposes of this overview):

- For *Mistake Diorite*, two hornblende K-Ar dates of 180 and 186 Ma and three biotite K-Ar dates of 182, 208, and 208 Ma; also a date for *Hut Suite*, of 112 Ma (Williams and Harper 1978). We also report for the first time two further conventional K-Ar dates as follows (rocks as described in table 1): (1) for *Hut* leucogranite sample Bl 2502, 179.7 Ma (biotite), and (2) for *Mistake Diorite* sample Bl 2372, 180.8 Ma (biotite); see also Nathan, Thurlow, and Zucchetto (2000).
- Also for *Mistake Diorite*, Kimbrough and others (1994) report a zircon U-Pb date of 224 Ma, which is matched by a SHRIMP U-Pb date of 226 Ma published by Muir and others (1998). New $^{40}Ar/^{39}Ar$ dates by Mortimer and others (1999) approximate 220 Ma, supporting the zircon results.
- For one sample each of the *Nurse* and *Glade Suites* of Williams and Harper (1978), Kimbrough and others (1994) report zircon U-Pb dates of 141 and 142 Ma.
- Kimbrough and others (1994) report a single 195 Ma zircon U-Pb date from an ignimbrite of the *Loch Burn Formation*, whereas for a similar rock of the related *Largs Group* Mortimer and others (1999a) obtained 140 Ma by the same method. A whole rock K-Ar date for a different locality in the *Largs Group* is 189 Ma (Williams and Harper, 1978).

For the *Darran Complex* and the *Western Darrans,* the following results were available by 1980: K-Ar dates of 139 and 149 Ma for two coarse pegmatitic hornblendes from near the Homer Tunnel (Adams 1975); also, K-Ar dates of less than 136 Ma for five biotites, one hornblende, and one muscovite of Williams and Harper (1978).

In a profile across the *Milford Gneiss Complex* from east to west conventional K-Ar dates on hornblende, muscovite, and biotite range from *Darran* dates near 140 to less than 10 Ma close to the Alpine Fault. The fairly steady westward decrease, which largely reflects uplift on the Alpine Fault, is broken by *Darran* type 140 Ma K-Ar dates for hornblende in the massive *Pembroke Granulite* (Nathan, Thurlow, and Zucchetto, 2000).

The conventional K-Ar dates from the *Darran Complex* and therefore close to the area of metamorphism of Milford Sound had long been considered to be cooling or entirely re-set dates and were perhaps not taken seriously enough. It was therefore a surprise when zircon U-Pb dates of the *Darran Complex* came out near 137 Ma (Mattinson, Kimbrough, and Bradshaw, 1986; Kimbrough and others, 1994, Muir and others, 1998). For the *WFO* Mattinson, Kimbrough, and Bradshaw (1986) reported zircon U-Pb dates near 125 Ma, and McCulloch, Bradshaw, and Taylor (1987) a Rb-Sr whole rock isochron of 120 ± 15 Ma with an initial $^{87}Sr/^{86}Sr$ (I_o) of 0.70391. All these dates were interpreted as ages of emplacement and original magma formation, although the *WFO* also has depleted, probably mid-Paleozoic, $^{143}Nd/^{144}Nd$ ratios (McCulloch, Bradshaw, and Taylor, 1987). In the wake of Mattinson, Kimbrough, and Bradshaw (1986) the *Pembroke Granulite* was often presumed to be of the same age as the *WFO.* Its low Sr was an early warning, however, and Tulloch and others (2000) report Paleozoic as well as Cretaceous zircons in *Milford (Ortho-) Gneiss* and *Pembroke Granulite.* A discordant Paleozoic zircon date had already been reported by Bradshaw (1990) from the Arthur River Complex *(Milford Gneiss).* For the *Rotoroa Complex* Kimbrough and others (1993)

TABLE 1

Rb-Sr whole-rock isochron data for Mackay Intrusives

Field no. NS-R no.	NZMS260 &1 map coordinates	Rock type/ Mineralogy	Occurrence/ Relationships	Rb (ppm) Sr (ppm)	$^{87}Rb/^{86}Sr$ 2σ error	$^{87}Sr/^{86}Sr$ 2σ error
BI-2502 10401	D40/202901 S122/033973 Mt Christina	'Hut' leucogranodiorite; 3% green to brown biotite; ≤1% magnetite; titanite; quartz mortared; fsp. with sec. musc., epidote; med. to fine grained (<4mm)	Area >30m, cut by swarm of microdiorite dikes, W of L.Marian	169 180	2.719 0.054	0.71206 (5)
BI-8324 15977	D41/209873 S122/040942 Falls Ck bridge	do., noticeably tough fabric to split	Intruded by microdiorite some 20m away	163 217	2.175 0.044	0.71048 (5)
BI-8419 12418	D41/179852 S122/006920 Upper Falls Ck.	do., 5% green and brown biotite; ≤1% magnetite, 2% titanite	From 10m sized pod; part of late (?) liquid among diorite and hornfels	161 251	1.857 0.037	0.70941 [4]
BI-8860 15976	D40/166930 S122/994005 Mt. Crosscut	'Hut/Mistake' flow foliated (leuco-) granite; biotite; titanite; tr. magnetite; sec. musc., epi.; med. grained (<4mm)	Christina-Crosscut irruptive (nearest xenolith 5m)	134.7 289.5	1.347 0.013	0.70777 (8)
BI-2753 12572	D40/165929 S122/993004 Mt. Crosscut	do., finer grained (2 mm) plagioclase with mild zonation, some red/brown clouded; tr.cpx.	do., within 20cm of contact with Darran Leucogabbro	141 332	1.230 0.025	0.70749 (5)
BI-2441 10400	D40/191916 S122/021989 NW L.Marian	'Hut/Mistake' granodiorite; 5% brown and green biotite; titanite; magnetite; medium grained (4mm)	Migmatite with steep NE striking schlieren	108 369	0.847 0.017	0.70620 [7]
BI-2372 10399	D40/229924 S122/021989 E of Mt Lyttle	'Mistake Diorite': quartzmonzodiorite; 6% hornbl.; do. biotite; 2% titanite; some plag. zoned; med. grained	Area with few xenoliths	104 558	0.540 0.011	0.70517 [4]
BI 2578 12571	D40/177908 S122/005981 NW face, Mt Christina	Hornblende(leuco)quartzdiorite; plag. strongly zoned, with filled cores; tr. cpx., fine grained (≤1mm); 'Mistake Diorite', 'Nurse Suite'?	Christina-Crosscut irruptive near root; from homogeneous area near xenolithic margin	41 683	0.174 0.035	0.70409 (7)

Footnotes: errors on Rb, Sr, 2.0 and 1.0%. Errors on Sr ratios are 2 sigma (for the fifth decimal place). Square brackets give range of duplicate checks.

found zircon U-Pb dates near 156 Ma, significantly higher than for the *Darran Complex*, and still older discordant fractions.

The existing data thus indicate:

1. A *Darran* group of K-Ar and U-Pb dates in the vicinity of 140 Ma, including for *Nurse* and *Glade Suites,* with K-Ar dates ranging from 149 to 112 Ma.
2. Scattered 140 to 189 Ma dates for samples of the *Largs Group* and *Loch Burn* unit.
3. A *Mackay* (that is, *Hut/Mistake*) K-Ar group of dates ranging from 179 to 208 Ma. These are supported by $^{40}Ar/^{39}Ar$ dates near 220 Ma and are likely cooling ages, ranging downward from the zircon U-Pb based intrusion age near 225 Ma.
4. A number of strong indications of Paleozoic ages in the western part of the MTZ as well as in the *Christina Gneiss.*

The field boundary between the *granitoid Mackay Intrusives* and the largely gabbroid *Darran Complex* was drawn by Bishop, Blattner, and Landis (1990) casting the *Mackay Intrusives* as the late emplaced unit. The zircon dates (if not the earlier known K-Ar dates!) have put this fundamental relation into question. Kimbrough and others (1994) still combine (after Williams and Harper 1978) *Mackay Intrusives* and *Darran Complex* but in their table 1 have separated off the *Mistake Diorite.* No doubt this was done on the basis of the above cited 224 Ma zircon U-Pb date, confirmed since by Muir and others (1998). However, the *Mistake Diorite* and the *Hut Suite* leucogranite together form the one part of the *Mackay Intrusives* of Williams and Harper (1978) that substantially differs in its age and genesis from the *Darran Complex* and the *Darran*-related *Nurse* and *Glade Suites.* Since the *Mistake Diorite* is also the most extensive of the granitoid *Mackay Intrusives,* the name *Mackay Intrusives* should therefore continue for the *Mistake* and *Hut* units.

RB-SR GEOCHRONOLOGY

Experimental methods.–Rock samples of ~1 kg (in some cases of Christina Gneiss 20–50 g) were crushed in a tungsten-carbide TEMA swing mill and analyzed for Rb and Sr by XRF by the Analytical Facility, Victoria University of Wellington. Strontium for isotopic analysis was extracted using standard cation exchange methods and analyzed on a VG Micromass 30B mass spectrometer of the Nuclear Sciences Group, Lower Hutt, New Zealand; for details of procedures see Graham and White, 1990. Reference sample SRM-987 yields $^{87}Sr/^{86}Sr=0.71025$. Isochrons were calculated using method II of York (1969), using the decay constant $\lambda = 142 \times 10^{-11}\ a^{-1}$ recommended by Steiger and Jäger (1977).

Mackay Intrusives

A main objective of this work was to obtain a complete whole rock Rb-Sr isochron for the *Mistake Diorite* and *Hut Suite* granitoids, including the irruptives into the *Darran Complex.* The data for the eight samples of this isochron appear in table 1 in order of decreasing Rb/Sr ratios, with petrographic and structural details, using the nomenclature of Williams and Harper (1978) in quotes. The petrography is uniform, apart from the compositional differences due to fractional crystallization and one case of unusually fine grain size to be considered later.

Figure 7 shows the Mackay isochron, giving a homogenization age of 224 ± 4 Ma and an I_0 of 0.70350 ± 0.00003. In the past much has been made of the fact that a mixture of materials from two sources may show a whole rock Rb-Sr isochron with a "meaningless age" (Dickin, 1995). In such cases high MSWD values are expected (Munksgaard, 1974; Wendt, 1993). Here, in spite of the areal coverage of nearly 60 km^2 and the involvement of *Mackay Intrusives* in migmatite fabrics, the MSWD of 1.21 is close to the ideal 1.0. The agreement with the previous zircon U-Pb dates is remarkable, although the Rb-Sr isochron is most relevant for the *Hut* granitoids, not dated up to now by zircon methods. The Rb-Sr isochron and zircon U-Pb dates together confirm a close genetic relationship between the *Mistake* and *Hut* magmas.

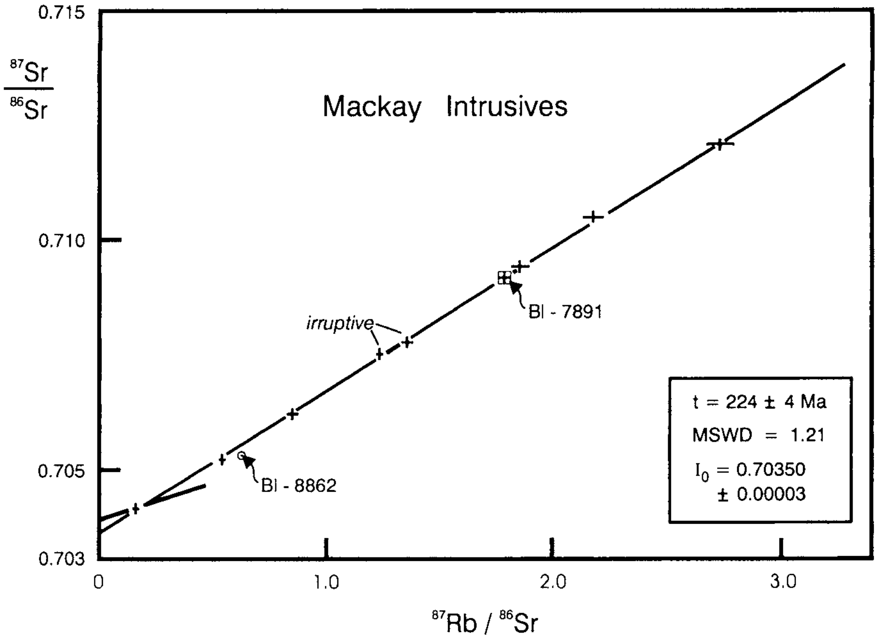

Fig. 7. Rb-Sr whole-rock isochron for the *Mackay Intrusives*, with actual errors (2σ), sometimes exaggerated for clarity. The samples from the Mt. Crosscut irruptive are marked. On the lower left the *Darran* isochron of figures 9 and 10 is shown to scale (bold line). Bl 8862 is a hybrid of *Mackay* and *Darran* material. Microdiorite dike Bl 7891 cuts *Christina Gneiss* but is not part of the isochron calculation.

Contamination at contacts with gabbroic rocks low in Rb/Sr and more so with the more radiogenic *Christina Gneiss* could have affected the Sr isotope systematics of *Mackay* type magmas. The irruptive granite sample Bl 2753 borders directly on the *Darran Complex*, but the more representative Bl 8860, collected in order to confirm the earlier result, is Sr-isotopically identical. For the hybrid rock Bl 8862 see under *Darran Complex* below. Also marked in figure 7 is the small microdiorite dike no. 7891, listed in table 4. A photo of this dike is shown in Bishop, Blattner, and Landis (1990, fig. 11), and it appears to be of *Mackay* parentage.

It is noted for six of the eight samples that make up the *Mackay* isochron, oxygen isotope data are available in Blattner and Williams (1991). Two closely similar granites at the high-Rb end (Bl 2502 and Bl 8419) vary by 7.4 permil $\delta^{18}O$, between 5.0 and -2.4 permil. The other four samples vary between 6.4 and -1.4 permil, seemingly at random, except that the three least negative and therefore least anomalous samples occur toward the east. The fact that these *Mackay* $\delta^{18}O$ results reach barely as low as the mean of *Largs* values (median at -4 permil; Blattner and Williams, 1991), strongly suggests that the hydrothermal alteration of some or all of the *Largs* and *Christina* oxygen isotope ratios occurred before the 224 Ma *Mackay* isochron date. In the original hydrothermal fluid-rock interaction, the Sr isotopes of the *Largs* rocks may have remained almost unchanged. However, if subsequently the oxygen signal was transferred from *Largs* rocks to *Mackay* magmas entirely through assimilation, the linear isochron suggests the I_o values for *Largs* and *Mackay* to have been almost identical.

Largs Group and Christina Gneiss

Five samples of the Permotriassic(?) *Largs* volcanics of Blattner and Williams (1991) were also analyzed. All have $^{87}Rb/^{86}Sr$ ratios below 0.4 and plot near the intersection of

TABLE 2

Rb-Sr whole-rock isotope data for Largs Group of Williams (1975)

Field no. NS-R no.	NZMS260 & 1 map coordinates	Rock type/ Mineralogy	Occurrence/ Relationships	Rb (ppm) Sr (ppm)	$^{87}Rb/^{86}Sr$ 2σ error	$^{87}Sr/^{86}Sr$ 2σ error
OU36225 14439	D41/162836 S122/988902	Feldsparphyric andesite	Raft in Mackay? (Glade or Hut)	17.5 523.2	0.097 0.001	0.70389 (7)
OU35403 14440	D41/142775 S122/965836	ditto, and clinopx. phenocrysts	Murcott Burn Andesites	26.5 846.9	0.091 0.001	0.70403 [3]
OU35426 14441	D41/143695 S131/964748	Lithic crystal tuff (albite)	Nurse Formation	47.2 551.4	0.248 0.002	0.70435 (8)
OU35474 14442	D41/136732 S131/957789	Flattened breccia	Waterfall Tuffs	66.0 480.1	0.398 0.004	0.70452 [4]
OU35476 14443	D41/124681 S131/943733	Feldsparphyric andesite	Raft in Nurse Suite	11.0 929.5	0.034 0.000	0.70363 (5)

Footnotes: see table 1.

the *Mackay* and the *Darran* isochrons (table 2). As in the case of the *Mackay Intrusives*, variously depleted $\delta^{18}O$ values of these samples (between 3.1 and −9.2 permil) do not correlate well with Sr isotope ratios.

Eight samples from *Christina Gneiss* rafts (table 3) yield a scattered isochron plot with an indicated date of 365 ± 90 Ma and a low I_o of 0.7022 ± 0.0007 (fig. 8). The calculation does not include the paired veins and host rocks Bl 2819A and B and Bl 9066A and B. The veins strongly resemble anatectic leucosomes, and, assuming feldspar isotopic equilibration *via* a fluid (Orville, 1963), the slopes of the vein/wall rock tie-lines indicate dates of 248 and 209 Ma. Allowing some imprecision due to the small size of the vein samples, each sample pair plots parallel to the 224 ± 4 Ma Mackay isochron (fig. 8), with the higher apparent I_o of ~0.7056 reflecting the ^{87}Rb decayed before the Mackay event at 224 Ma. The two sample pairs could provide valid whole rock information for a *Christina Gneiss* isochron, if each were re-combined to the exact weighted composite of melt and exchanged wall rock on the tie line. However, we do not know these proportions. Furthermore, each of the nine other whole rock samples of the *Christina* isochron plot may itself represent a fractionated portion of a larger exchanged subsystem of older gneiss, migmatized at about 224 Ma.

Darran Complex

Because of the shorter Rb/Sr range of the *Darran Complex*, a whole rock isochron date will be less precise than for the *Mackay Intrusives*. Table 4 lists several groups of Darran samples used for the Rb-Sr isochron. The two best sampled areas are Gertrude Saddle and the combined north and south side of Mt.Crosscut, including Christina-Crosscut Cirque. Together these two areas cover nearly 10 km^2. The Gertrude Saddle area and its perimeter contain no recognizable *Mackay Intrusives* and few, if any, xenoliths of *Largs Group* or *Christina Gneiss*, whereas Mt Crosscut does, and the leucogabbro there is generally less homogenous on the outcrop scale. Still, the isochron data from the two domains are statistically indistinguishable. Of course, as in the case of the *Mackay* isochron, a-typical samples were avoided as far as possible, but the agreement may have

TABLE 3

Rb-Sr whole-rock isochron data for Christina Gneiss

Field no. NS-R no.	NZMS260 & I map coordinates	Rock type/ Mineralogy	Occurrence/ Relationships	Rb (ppm) Sr (ppm)	$^{87}Rb/^{86}Sr$ 2σ error	$^{87}Sr/^{86}Sr$ 2σ error
BI-2436	D40/194907	Biotite gneiss with wispy veins and diatexite	(Float, Marian Creek)	116.2	1.083	0.70899
14362	S122/024998	K-spar concentrated in veins; fine grained		310.6	0.011	(6)
BI-2511	D41/192834	Wispy biotite gneiss with 15 % K-spar,		94.6	0.504	0.70506
14361	S122/020990	trace epidote and muscovite, fine grained	"	543.0	0.005	[4]
BI-2819A	) (	Biotite gneiss, c. 20 % K-spar, fine grained	)	164	1.947	0.71218
12421	)D40/218946(		) Mt. Gunn	244	0.039	[4]
BI-21819B	)122/051021 (	Pegmatoid vein in above; K-spar unevenly	) shoulder	120	1.178	0.70947
12420	) (	distributed, medium grained	)	295	0.024	(7)
BI-7892	D40/184917	Migmatite, finely veined or layered	Mt. Christina	132.6	0.972	0.70721
10592	S122/013991			394.8	0.010	[3]
BI-9059	D40/218945	Diatexite, evenly fine grained, on 5cm-	Fresh fallen blocks	151.1	1.758	0.71261
14353	S122/051021	shear zone in fine grained biotite gneiss	directly below cliff	248.9	0.018	(7)
			(East of Mt. Gunn)			
BI-9060		Biotite gneiss, fine grained with some		185.7	1.588	0.70929
14354	"	20 % granitoid veins	"	338.5	0.016	(5)
BI-9061		Granitoid with streaky biotite,		154.1	1.377	0.70844
14355	"	medium grained	"	324.0	0.014	(6)
BI-9063		Biotite gneiss to diatexite, fine grained		142.7	1.470	0.70960
14356	"		"	281.2	0.015	[8]
BI-9065		Diatexite with streaky residues; fine to		63.5	0.875	0.71121
14357	"	medium grained	"	210.1	0.009	[4]
BI-9066A	)	(Fine grained biotite gneiss)		169.7	1.640	0.71078
14358	)	( )		299.6	0.016	(5)
BI-9066B	) "	(Pegmatoid vein (similar BI-2819))	"	80.8	0.586	0.70765
14359	)	( )		399.0	0.006	(5)

Footnotes: see table 1.

been helped by the Sr-isotopic similarity of *Darran* and any assimilated *Largs* materials. The combined Gertrude-Crosscut (GC) isochron gives an age of 133 ± 17 Ma and I_0 = 0.70382 ±2 (fig. 9). Excluded from the isochron calculation is only the mixed *Darran-Mackay* sample Bl 8862 (see fig. 7, which shows the *Darran* and *Mackay* isochrons to scale). It has Rb/Sr significantly beyond the *Darran* range of values yet plots close to the *Mackay* isochron in figure 7, in good agreement with its explanation as a mixture and with the mixing model given in connection with figure 12.

Figure 10 shows all remaining *Darran* samples, covering a much larger area and a greater variety of leucogabbro types. Four samples of the Homer-Cleddau Core, mostly from ~5 km west of the Gertrude area and typically low in Rb, fit the GC isochron well, as do an evolved leucogabbrodiorite from nearer Mt Tutoko (Bl 8209) and the three *Darran Hornblende Diorites* analyzed. Three leucogabbro samples from the Donne River slip (locality also sampled by McCulloch, Bradshaw, and Taylor, 1987; Muir and others, 1998) show somewhat low Sr isotope ratios, tying in better with the lower I_0 of *Milford Gneiss* and *Rotoroa Complex*, but show poor homogeneity on the 5 m scale. A pink-colored granite from Mackay Creek well to the south of figure 2 (an original *Mackay Intrusive* of Grindley, 1958) plots close to the extrapolated *Darran* isochron of 133 Ma, being far more Rb-rich than any of the typical *Darran Complex* samples. and may be one of Williams and Harper's (1978) *Nurse* granitoids.

Western Darrans and *Rotoroa Complex*

Like the weakly evolved core of the *Darran Complex*, samples *of Milford Gneiss* and *Pembroke Granulite* have Rb near the detection limit and thus give close to I_0 values (table 5-1). Figures 10 and 11 show values significantly below those of the *Darran Complex.* Because of the similarity and potential tectonic correlation of the *Darran Complex* and the

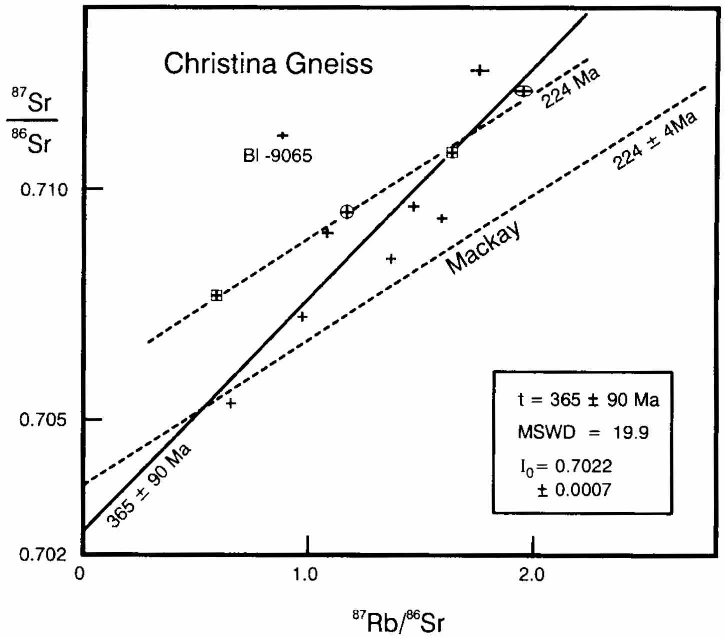

Fig. 8. Rb-Sr whole rock isochron plot for Christina Gneiss. Vein-host rock pairs are marked by ellipses(Bl-2819) and rectangles (Bl-9066). The 365 Ma scatterchron was calculated without outlier Bl 9065 and without the two vein-host rock pairs.

Rotoroa Complex of Nelson, a number of samples of *Howard Gabbro* were analyzed (table 5-2; fig. 11). Their spread of Rb/Sr is very limited, but there is a clear indication of an isochron different from the *Darran* isochron both in slope and I_0 value. The suggested 330 Ma age is significantly greater than either the *Mackay* date of 224 Ma or the 133 Ma *Darran* date. The I_0 of 0.7035 falls below that of any low-Rb *Darran* sample, although it is approached by the *Milford Gneiss* and *Pembroke Granulite (Western Darrans)* and arguably by the Homer-Cleddau Core samples (figs. 10 and 11).

CHRISTINA-CROSSCUT IRRUPTIVES: DISCUSSION

The Rb-Sr whole rock data presented here confirm the existing zircon U-Pb dates, as well as some K-Ar dates, for *Darran Complex* and *Mackay Intrusives* and put into question the field evidence of Mts. Christina and Crosscut. Paradoxically, the *Darran Leucogabbro*, which defines the *Darran* Rb-Sr isochron of 133 Ma, appears to be intruded by the Christina-Crosscut irruptive, dated by the precise 224 Ma *Mackay* isochron. Two initial options for solving the problem are as follows.

Option 1–Darran Isochron re-set at 130–140 Ma?

The Rb-Sr isochron of a magma originally homogeneous in $^{87}Sr/^{86}Sr$ can be reset to a new higher I_0 by convective and diffusional mixing and re-homogenization. A primary *Darran* isochron with a lower I_0 would have been tilted about its center of gravity (average composition of the exchanging domains) to the horizontal and to a new I_0 = 0.70382 at 133 Ma. Areas of a batholith not well connected by fluids and permeability would be reset less completely, which could explain part of the scatter of the *Darran* isochron of figure 9. The relatively low I_0 of the Homer-Cleddau Core and of possible western equivalents *(Milford Gneiss, Pembroke Granulite)* may be a relict of an original still

TABLE 4

Rb-Sr whole-rock isochron data for Darran Complex

Field no. NS-R no.	NZMS260 & I map coordinates	Rock type/ Mineralogy	Occurrence/ Relationships	Rb (ppm) Sr (ppm)	$^{87}Rb/^{86}Sr$ 2σ error	$^{87}Sr/^{86}Sr$ 2σ error
1. Gertrude Saddle						
BI-8503 10746	D40/154952 S122/981029	Biotite (3%)leucogabbronorite (lgn); rounded, 0.5m xenolith in autobreccia; plagioclase clear; fine grained (≤2 mm)	E of Gertrude Saddle area c. 100x200 m	5 815	0.018 0.000	0.70384 [4]
BI-8501 10745	"	Biotite(3%)leucogabbronorite, plag faintly clouded (red/brown); medium grained (≤5 mm)	"	9 772	0.034 0.001	0.70396 (5)
BI-8505 10748	"	Biotite(6%) lgn to hornblende leucodiorite; olive green hornbl.>pyroxene; plag. clouded; (<7 mm)	"	33 720	0.133 0.002	0.70399 [4]
BI-8504 10747	"	Biotite(7%) lgn to secondary hornbl. leucodiorite; plag. very slightly clouded; grain <6 mm)	(matrix of BI-8503 3 m distant)	65 516	0.365 0.007	0.70450 (6)
GS-1 6720	D40/146950 S122/981030	Biotite(4%)leucogabbronorite; plagioclase clouded; medium grained (4 mm)	W of Gertrude Saddle	25.0 779.5	0.093 0.001	0.70400 (4)
GS-3 6722	D40/154952 S122/981030	Biotite(3%)leucogabbronorite to hornblende leucodiorite; plag. slightly clouded; grain 4 mm	Gertrude Saddle	43.5 724.5	0.176 0.001	0.70424 [5]
2. Mt. Crosscut and Christina-Crosscut Cirque						
BI-8868 15983	D40/173919 S122/994005	Leucogabbronorite; 1% magnetite, plagioclase clear; medium to fine grained (2 mm)	Mt. Crosscut shoulder (fig. 3B)	4.2 978.2	0.012 0.000	0.70385 (5)
BI-8713 13529	D40/173919 S122/001993	(similar) Hornblende leucogabbronorite; pyroxene reacts to brown-green hornbl.; grain <5 mm	Christina-Crosscut Cirque	4.0 820.5	0.014 0.000	0.70387 (5)
BI-8865 15982	D40/166930 S122/994005	Biotite(10%)leucogabbronorite, or diorite, with some 3% K-feldspar; grain <7 mm	Mt. Crosscut shoulder; near a mafic patch	44.7 530.8	0.244 0.002	0.70436 (5)

TABLE 4
(continued)

Field no. NS-R no.	NZMS260 &1 map coordinates	Rock type/ Mineralogy	Occurrence/ Relationships	Rb (ppm) Sr (ppm)	$^{87}Rb/^{86}Sr$ 2σ error	$^{87}Sr/^{86}Sr$ 2σ error
2. Mt. Crosscut and Christina-Crosscut Cirque (continued)						
Bl-8710 13527	D40/175920 S122/004994	Biotite (5%)leucogabbronorite; 5% K-feldspar; medium grained (≤4 mm)	Christine-Crosscut Cirque (matrix of Bl-8711)	57.9 636.8	0.263 0.003	0.70429 [3]
Bl-8863 15981	D40/166930 S122/994005	Biotite(10%), hornbl.(leuco)diorite; trace pyroxene; plag. red/brown clouded (<4 mm)	Mt. Crosscut shoulder (SW wall of irruptive)	66.9 510.0	0.380 0.004	0.70455 (5)
Bl-8862 15961	"	Sim. nebulitic foliated rock; 30% of plag. clouded 2% K-feldspar; 1% magnetite; grain< 4 mm	Mt. Crosscut shoulder	99.6 442.4	0.652 0.007	0.70536 (6)
3. Homer-Cleddau Core						
Bl-2375 10885	D40/148913 S122/974987	Leucogabbronorite, to (secondary) hornbl. leucodiorite; hornbl. olive green; plag. slightly clouded; grain <6 mm	Base of Students Pk.	<2 869	≅0.003	0.70379 [5]
Bl-2461 10883	D40/110978 S122/933059	Leucogabbronorite; plagioclase weakly clouded; medium grained (<5mm)	Base of Mt. Isolation	<2 870	≅0.003	0.70375 (4)
Bl-8215 10588	D40/106942 S122/928020	Leucogabbronorite; pyrox. has olive hornbl. rims; very fresh; fine grained (<4mm)	South Branch of Cleddau River	<2 724.5	≅0.003	0.70383 (4)
Bl-8405 10884	D40/092957 S122/913036	Leucogabbronorite; minor hornbl.; minor alteration; fine grained (<3 mm)	Cleddau River	3 734	0.011 0.000	0.70380 (8)
4. Western Hornblende Diorite and/or Harrison Gneiss						
Bl-8535 10752	D40/067072 S113/888162	mafic epidote(10%)hornbl.diorite; plag.→albite, musc., epid.; pyrox.→hornbl.;magnetite→rutile; medium grained (≤3 mm), but clusters larger	Coast near Harrison River mouth	3 880	0.009 0.000	0.70378 [9]
Bl-2765 10585	D40/069061 S113/890150	Hornblende epidote biotite leuco(quartz)diorite, some titanite, medium grained (<3 mm)	Bridget Point	44 523	0.243 0.005	0.70425 (6)

BI-8232 10589	D40/082990 S122/903072	Biotite hornbl. leucodiorite; epidote, titanite; medium grained (<6 mm)	North Branch of Cleddau River	50 600	0.241 0.005	0.70436 (4)
5. Central and northern region						
BI-8521 10749	) D40/113012) S122/937096	Leucogabbronorite, some sec. hornbl.; plagioclase clouding resolved into discrete flakey inclusions; med.grained (≤6 mm)	Steep creek between Cleddau and Tutoko Rivers; samples 3m apart	(42 (670	0.181 0.004	0.70407 [3]
BI-8522 10750	)			(35 (680	0.149 0.003	0.70395 (4)
BI-8523 10751	)			(39 (659	0.171 0.003	0.70395 (4)
BI-8209 10753	D40/190090 S113/023180	Biotite (6%) leucogabbronorite, medium grained (≤7 mm)	Madeline Creek	57 658	0.251 0.005	0.70426 [7]
6. Miscellaneous dikes						
BI-2822 12573	D40/201956 S122/033033	Dark grey microdiorite; plagioclase dark clouded, in matrix (50%) with biotite and hornblende	Dike 2 m wide, in Mackay Intrusives	89 546	0.472 0.009	0.70450 (7)
BI-7891 10586	D40/184917 S122/013991	Biotite (35%)microdiorite; gneissoid; very fine grained	Small dike in Christina Gneiss BI-7892	217 351	1.789 0.036	0.70917 (4)
BI-8861 15975	D40/166930 S122/994005	Trondhjemite; plag. strongly zoned; qtz. mortared; med. grained (4 mm)	Dike 2 m wide; Mt Crosscut	89.9 621.1	0.419 0.004	0.70466 (8)
7. Eglinton Valley Granite						
BI 8706 13526	D40/156586 S131/976629	Pink/gray granite; feldspars, biotite altered; medium grained (4 mm)	Mackay Creek	157.7 217.4	2.100 0.021	0.70755 (6)

Footnotes: see table 1.

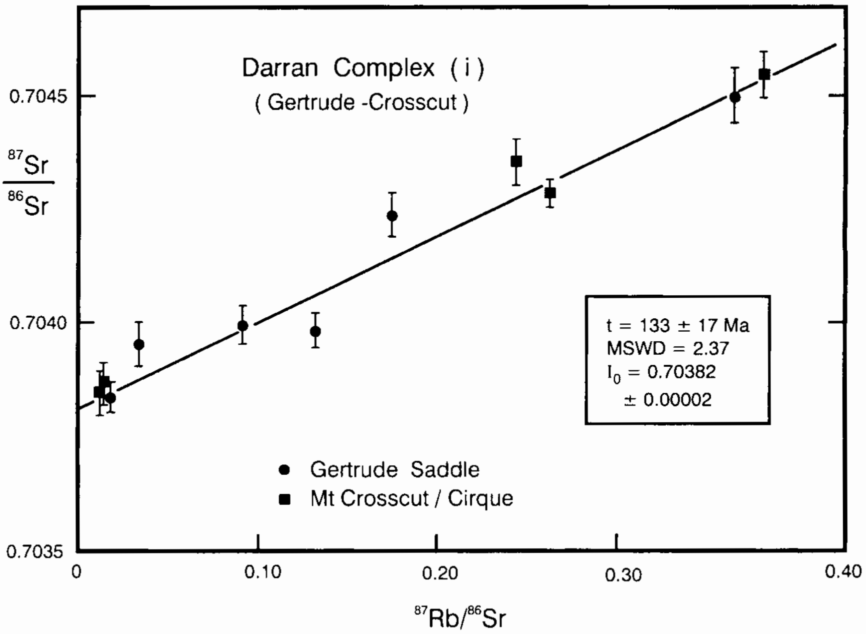

Fig. 9. Rb-Sr whole-rock isochron of the *Darran Complex*: Gertrude Saddle, Mt Crosscut and Christina-Crosscut Cirque areas. Data from the two areas are not distinguishable with present statistics.

lower I_0 of a *Darran-Rotoroa* proto-complex, partly preserved because these areas were relatively isolated from high-Rb fractions.

Difficulties for this interpretation are (1) the largely single-stage magmatic fabrics of the Darran Complex, combined with the current evidence that zircon requires substantially magmatic conditions for its re-setting, and (2) that in a process of re-setting the *Darran* isochron in the present position of the units, the irruptives themselves (Bl 2753 and Bl 8860) could hardly have remained unchanged on the *Mackay* isochron. Having rejected the re-setting of older *Darran* dates *after* a Triassic emplacement of the irruptives we nevertheless find evidence, to be discussed below, of Paleozoic events in the tectonic counterpart of the *Darran Complex* in Nelson.

Option 2–Mackay Isochron Coincidental

Could the "paradoxical" irruptive samples plot on the *Mackay* isochron by some coincidence? In their area Williams and Harper (1978) required little help from isotopic dating to regard the *Nurse and Glade Suites* as late fractions of the *Darran* magma. Such fractions could back-intrude major, already emplaced portions of a batholith, but should fall on a *Darran* Rb-Sr whole rock isochron. Alternatively they may have assimilated low melting *Mackay* granitoids. Mixed, hybrid compositions of *Darran* and *Mackay* material were mentioned (eastern contact of Mt. Crosscut irruptive; also no. Bl 8862), and if late *Darran* differentiates had assimilated a sufficient amount of *Mackay* material, their isotopic composition may have reached points on the *Mackay* isochron. In fact, it turns out that the I_0 of the *Darran* magma is just so much higher than that of *Mackay* magma that the most common evolved *Darran* composition ($^{87}Rb/^{86}Sr$ = 0.2 to 0.4) brackets the intersection with the 91 Ma old Mackay isochron at the postulated time of emplacement of the *Darran* magma 133 Ma ago (fig. 12). This would be partly the result of the *Darran* magma being drawn from a similar deep crustal environment as the *Mackay* magma had

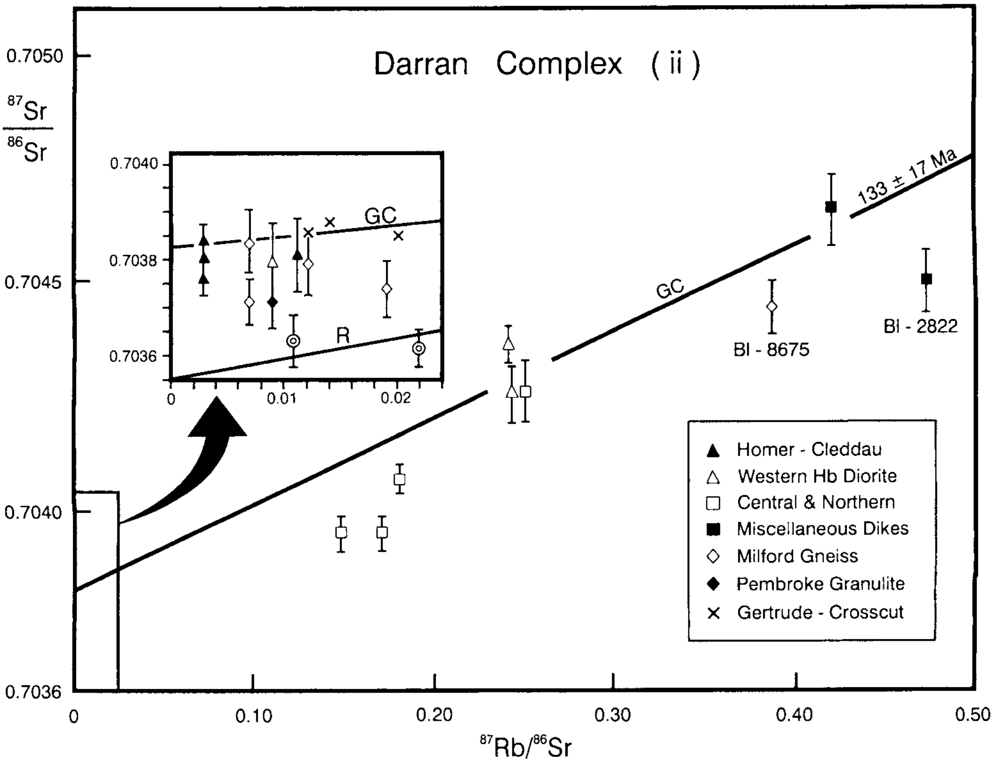

Fig. 10. Rb-Sr isochron plot for remainder of *Darran Complex*: Homer-Cleddau Core, *Darran Hornblende Diorite*, dikes, and gneiss and granulite of *Western Darrans*. The Largs samples of table 2, although more scattered, are generally similar to the *Darran* data of this figure. R = *Rotoroa Complex (Howard Gabbro;* see fig. 11).

been. Assimilation mixtures on the *Mackay* isochron are therefore possible and would evolve as part of the *Mackay* assemblage. Nevertheless, in order to match the "irruptive" samples of figure 7, a *Darran* differentiate had to achieve a ratio $^{87}Rb/^{86}Sr$ of 1.5. While the *Mackay/Hut* leucogranites have three to four times the $^{87}Rb/^{86}Sr$ of an average *Darran* magma, this factor would be diluted dramatically by the higher Sr contents of the *Darran* input. To plot on the *Mackay* isochron postulated mixtures such as Bl 2753 and Bl 8860 would therefore have to consist of *Darran* liquid with well over 50 percent *Mackay* contaminant (fig. 12). Since they should then still be capable of intrusion, most of the required heat for assimilation (DePaolo, 1981) would have to come from sources other than the *Darran* differentiates themselves, such as a regional heat flow, and it is difficult to see how it could be delivered selectively to the eastern contact of the newly emplaced complex.

A Dike-like Roof Pendant?

Events of geological history may leave opposing pieces of evidence in the record, and this has povoked terms such as "petrified nonsense" (used by H. Cloos to good effect for back-intrusion by reactivated granitoid gneiss) and "meaningless isochrons" (used by Field and Raheim 1979). Of course these expressions are misleading: in each case evidence needs only to be examined more completely. In the present case the *Mackay Isochron* is real enough, and it is unlikely that pre-Triassic *Darran* zircon and Rb-Sr dates

TABLE 5

Rb-Sr whole-rock isotope and isochron data for Western Darrans and Rotoroa Complex

Field no. NS-R no.	NZMS260 &1 map coordinates	Rock type/ Mineralogy	Rb (ppm) Sr (ppm)	$^{87}Rb/^{86}Sr$ 2σ error	$^{87}Sr/^{86}Sr$ 2σ error
1. Milford Gneiss and Pembroke Granulite					
H2 6725	D40/090166 S113/915265	Epidote hornblende gneiss to amphibolite, with magnetite and rutile; med./fine grain	2 822	0.007 0.000	0.70383 (7)
H5 6728	"	do., medium grained with large hornbl clusters (10 mm) and garnet porphyroblasts	3 746	0.012 0.000	0.70378 (7)
H17 6740	D40/099162 S133/925260	do., with rutile	6 916	0.019 0.000	0.70372 (6)
H18 6741	"	do. with rutile; fine grained (1mm) with 6mm clusters	2 846	0.007 0.000	0.70370 (5)
M22 6770	D40/021099 S112/838193	Hornbl.- two pyrox. granulite, reaction textures (pyrox.→hornbl.); with clusters	3 984	0.009 0.000	0.70369 (5)
2. Howard Gabbro (Rotoroa Complex)					
RC-131 15979	S26/059716 M29/821388	Leucogabbronorite, 4% magnetite; minor sec. hornbl.; plag. gray clouded; medium grained (5 mm)	3.1 828.1	0.011 0.000	0.70361 (6)
RC-139 10903	S26/065712 M29/826385	Olivine (2%)gabbronorite, plag. grey clouded ("black"); minor primary. hornbl.; med. grained	7 745	0.027 0.000	0.70359 [4]
RC-193 13524	S33/098694 M29/857369	Biotite (3%) leucogabbronorite; plagioclase "black"; some rust col'd alteration; med. grained	17.6 660.2	0.077 0.001	0.70391 (9)
RC-157 15978	S33/942659 M29/715334	Biotite (5%) leucogabbronorite; plagioclase gray clouded; medium grained	23.0 1176.2	0.057 0.001	0.70380 (4)
RC-577 13525	S33/043552 M29/809238	Partly hornblendised and chloritised leucogabbro; medium grained	26.3 856.1	0.089 0.001	0.70391 (5)

Footnotes: see table 1.

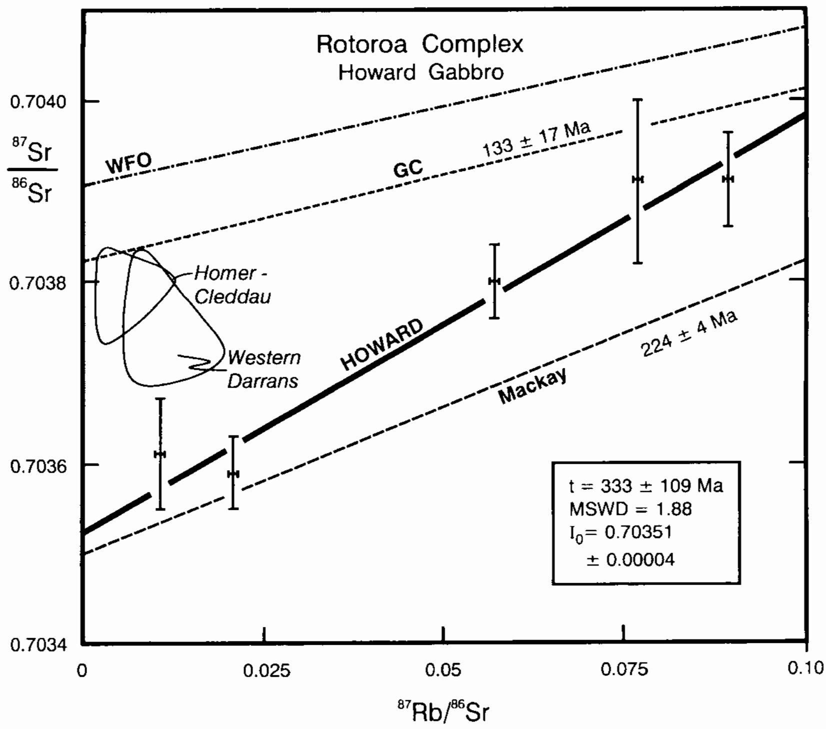

Fig. 11. Rb-Sr whole-rock isochron for *Howard Gabbro (Rotoroa Complex)* and comparison with other isochron or I_0 data. The line for *Western Fiordland Orthogneiss (WFO)* is the 120 Ma whole rock isochron of McCulloch, Bradshaw and Taylor (1987). GC=Gertrude-Crosscut (Darran) isochron

had been re-set after the emplacement of Triassic irruptives. Therefore the Mt. Crosscut irruptive of figure 3A, which maps out almost perfectly as a late intrusion into the *Darran Leucogabbro*, may need to be interpreted as a passive or partly tectonic emplacement in a perhaps already cooling *Darran Complex*. Once this requirement is established, parts of the evidence may appear in a different light. The gneissose fabric of the "apophysis" with perhaps conflicting signals of migmatization and tectonic overprinting, offer scope for argument and for viewing it as a roof pendant or tectonic projection. Only one margin of this irruptive is a well documented contact, the other (eastern) one showing some assimilation, although without detail this could work both ways (assimilation of *Mackay* or of *Darran* magma).

In contrast to Mt. Crosscut, the Mt. Christina irruptive shows little gneissosity and tectonic overprinting, and its prominent exposed southwestern contact is accompanied by an accumulation of xenoliths. This irruptive, more difficult of access, is relatively fine grained quartzdiorite and is dated by only one point (Bl 2578) close to the intersection of the *Mackay* with the *Darran* whole rock isochron. It could therefore be a *Darran* differentiate (*Glade Suite* of Williams and Harper, 1978) with largely ~135 Ma old zircon. As for other possible zircon U-Pb dates, it is probable that the *Hut* leucogranites, which provide the main input of the *Mackay* isochron, will return zircon dates near 224 Ma, as does the *Mistake Diorite* according to Kimbrough and others (1994) and Muir and others (1998). This is also suggested by the K-Ar date for *Hut* leucogranodiorite Bl 2502, which, like the available K-Ar dates for *Mistake Diorite*, lies between 180 and 208 Ma, whereas K-Ar dates from the *Darran Complex* are less than 150 Ma. If the Mt. Crosscut irruptive

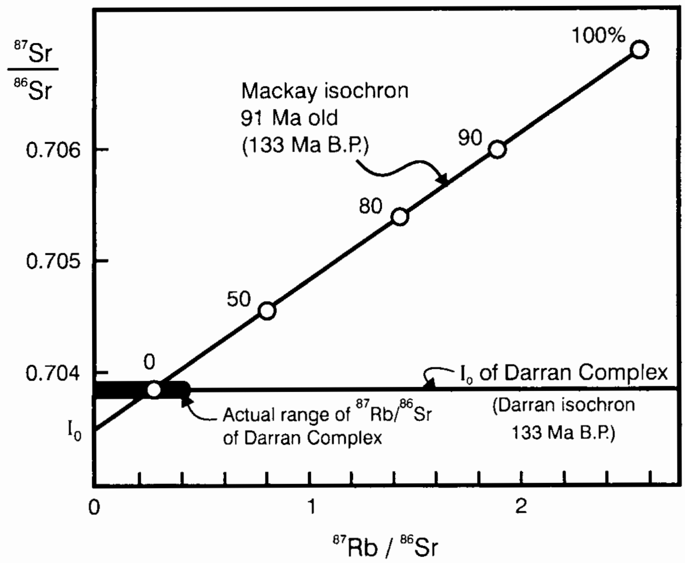

Fig. 12. The *Mackay* isochron and its possible incorporation of *Darran* differentiates 133 Ma ago. Due to their slightly higher I_0, *Darran* differentiates contaminated by *Mackay* material could plot exactly on the 91 Ma *Mackay* isochron and evolve with it oblivious of their different origin. However, in order to approach sufficiently *high* $^{87}Rb/^{86}Sr$, *Darran* differentiates would have to assimilate large amounts of *Mackay* material. Mixtures are calculated for an average *Mackay* granite (marked "100%").

were the late *Darran*, 50 percent *Mackay*-contaminated, differentiate of Option 2, it would contain a large (and scaled up) population of inherited 224 Ma zircon mixed up with Cretaceous *Darran* zircon. In contrast, a pendant or tectonic fragment could have 130 to 140 Ma zircons only at its margins. A more complete answer to the problem of *Darran-Mackay* syntexis and tectonism has to await further systematic work.

DARRAN, *ROTOROA*, AND *WFO* RB-SR ISOCHRONS AND I_0 VALUES

The *Howard Gabbro* of the *Rotoroa Complex* is petrographically, chemically, and in oxygen isotopes very similar to the *Darran Leucogabbro* (Challis and others, 1994; Bishop, Blattner, and Landis, 1990; Blattner, 1991); restoration of the Alpine Fault places it close to the present *Darran* unit prior to 25 Ma (fig. 1). The southeast side of the Alpine Fault has been uplifted relatively to the northwest, and we may therefore expect a higher temperature, deeper crustal (and more completely reset) environment to be represented by the *Darran* than by the *Howard* unit. This is potentially in accord with the lower, less equilibrated I_0 of ~0.7035 for the *Howard Gabbro,* which has preserved a correspondingly older Rb-Sr isochron. I_0 values including that for *WFO* determined by McCulloch, Bradshaw, and Taylor (1987) as 0.70391 form the sequence: *Rotoroa Complex* < *Western Darran* < Homer-Cleddau < Gertrude-Crosscut < *Western Fiordland Orthogneiss*, perhaps of decreasing Rb-Sr age inheritance and increasing completeness of melting at the magma generation stage (figs. 10 and 11). They also further emphasize the difference between *WFO* and *Pembroke Granulite.*

The Rb-Sr data from Nelson do not require a resetting of the *Darran* dates with the Christina-Crosscut irruptives already in place, since a *Darran* proto-isochron could have been reset well before emplacement, perhaps in the process of substantial partial melting of a protolith shared with or similar to that of the *Rotoroa Complex.* Zircon solubility depends on detailed magma chemistry (Watson and Harrison, 1983), and we do not know exactly how zircon would behave in the *Darran*, relatively chlorine-rich, gabbroic environment. Zircon U-Pb ages of the *Howard Gabbro* are near 156 Ma and include discordant inherited zircon, which has so far not been found in the *Darran Complex* (Kimbrough and others, 1993, 1994). It is therefore possible that the *Rotoroa Complex* was reactivated only barely sufficiently at 156 Ma to reset its zircon, but not its whole rock Rb-Sr system. In contrast, older zircon generations in the regenerated *Darran* magma may have been completely dissolved and recrystallized, and the whole rock Rb-Sr system reset imperfectly, as suggested by the *Darran* and *Western Darran* I_0 values.

CONCLUSION

The northern Fiordland crystalline basement has long been considered to be of largely Paleozoic age. The isotopic dating and especially the zircon U-Pb data have then drawn attention to Cretaceous magmatic and metamorphic activity. While the $^{143}Nd/^{144}Nd$ ratios of McCulloch, Bradshaw, and Taylor (1987) had already indicated a Paleozoic prehistory for the *WFO*, the present work brings a Paleozoic Rb-Sr isochron for the *Rotoroa Complex* and relatad variations in I_0 values in the *Darran Complex* itself. Bradshaw (1990) and Tulloch and others (2000) report evidence of Paleozoic events from the *Milford Complex*, including the *Pembroke Granulite*. Hopefully the re-focussing of dating interest on pre-Cretaceous events will add depth to the geological understanding of the area, in parallel with new structural studies (Klepeis, Daczko, and Clarke, 1999). Rafts of Christina Gneiss may equally be of mid-Paleozoic age. Isotopic dating has forced a re-interpretation of the apparent irruptive of *Mackay Intrusives* at Mt. Crosscut as a kind of roof pendant, thus undoing a perhaps overly simple field interpretation. One may speculate on the reliability of field interpretations in less perfectly exposed areas of similar rocks!

As emphasized by Bradshaw (1993) the MTZ is a long lived, highly complex zone of accretion, plutonic stitching, and metamorphism. According to Mortimer and others (1999b) it also "continues to defy simple and unified geological classification". The name Median Tectonic Zone emphasizes this state of affairs. In the present east-west profile the *eastern* part of the MTZ consists of medium level *Mackay* plutons of Triassic intrusion age and of the *Largs Group* which may yet have a range of ages. This assemblage is intruded again by the *Darran Complex.* The age of oxygen isotope anomalies in the wider and off-shore MTZ (Blattner, Grindley, and Adams, 1997) may extend from Triassic to Cretaceous. Mortimer and others (1999a) suggest, based on their own latest obtained zircon U-Pb date, that the entire *Largs Group* be of Cretaceous age. In doing so they may have ignored the fact that the *Hut* leucogranites that are part of the present 224 Ma *Mackay* isochron show an inherited signal of anomalous $\delta^{18}O$ values, with the granites always much less depleted than the intruded *Largs Group* itself (Blattner and Williams, 1991). Oxygen isotope anomalies originally present in the *Largs Group* and *Christina Gneiss* and inherited by the intrusive magmas provide a rare and unexpected opportunity to determine quantitative details of two consecutive periods of magmatic assimilation.

In the *western* part of the present MTZ profile any original western margins of the *Darran Complex* have been overprinted and structurally obliterated by the highly dynamical metamorphism of the *Milford Gneiss Complex*, with the intervention of an injection zone *(Harrison Gneiss* and *Indecision Creek Complex).* The limit of the *Milford Gneiss Complex* against the *Western Fiordland Orthogneiss* does not occur before the Anita Shear Zone. Instead, the *Milford Gneiss* is tectonically associated with *Thurso* marble of probable Paleozoic origin (Turnbull and others, 2000), and the MTZ is thus ending in a major shear zone close to the Alpine Fault. At the southern end of the *Milford Gneiss Complex* the *WFO* is possibly intrusive, but strongly deformed with much of the boundary probably faulted (Bradshaw 1990).

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References

Adams, C. J. D., 1975, New Zealand potassium-argon age list–2: New Zealand Journal of Geology and Geophysics, v. 18, p. 443–467.

Bishop, D. G., Blattner, P., and Landis, C. A., 1990, Geological map of the Hollyford area, 1:75,000: New Zealand Geological Survey, Miscellaneous Map Series.

Blattner, P., 1976, Replacement of hornblende by garnet in granulite facies assemblages near Milford Sound, New Zealand: Contributions to Mineralogy and Petrology, v. 55, p. 181–190.

——— 1978, Geology of the crystalline basement between Milford Sound and the Hollyford Valley, New Zealand: New Zealand Journal of Geology and Geophysics, v. 21, p. 33–47.

——— 1981, "Halogen geothermometry" and case for post-Devonian granolite in Fiordland, New Zealand: Bulletin de Mineralogie, v. 104, p. 811–816.

——— 1991, The North Fiordland transcurrent convergence: New Zealand Journal of Geology and Geophysics, v. 34, p. 533–542.

Blattner, P., and Black, P. M., 1980, Apatite and scapolite as petrogenetic indicators in granolites of Milford Sound, New Zealand: Contributions to Mineralogy and Petrology, v. 74, p. 339–348.

Blattner, P., Grindley, G. W., and Adams, C. J., 1997, Low-^{18}O terranes tracking Mesozoic polar climates in the South Pacific: Geochimica et Cosmochimica Acta, v. 61, p. 569–576.

Blattner, P., and Williams, J. G., 1991, The Largs high-latitude oxygen isotope anomaly (New Zealand) and climatic controls of oxygen isotopes in magma: Earth and Planetary Science Letters, v. 103, p. 270–284.

Bradshaw, J. D., 1993, A review of the Median Tectonic Zone: terrane boundaries and terrane amalgamation near the Median Tectonic Line: New Zealand Journal of Geology and Geophysics, v. 36, p. 117–125.

Bradshaw, J. Y., 1989, Early Cretaceous vein-related garnet granulite in Fiordland, southwest New Zealand: a case for infiltration of mantle-derived CO-2 rich fluids: Journal of Geology, v. 97, p. 697–717.

——— 1990, Geology of crystalline rocks of northern Fiordland: details of the granulite facies Western Fiordland Orthogneiss and associated rock units: New Zealand Journal of Geology and Geophysics, v. 33, p. 465–484.

Challis, G. A., Lauder, W. R., Johnston, M. R., and Suggate, R. P., 1994, Geology of the Lake Rotoroa area, Nelson: Lower Hutt, Institute of Geological and Nuclear Sciences, 1:50 000 geological map 8. 1 sheet, 32 p.

Clarke, G. L., Klepeis, K. A., and Daczko, N. R., 2000, Cretaceous high-P granulites at Milford Sound, New Zealand: metamorphic history and emplacement in a convergent margin setting: Journal of Metamorphic Geology, v. 18, p. 359–374.

Coombs, D. S., Norris, R. L., Sinton, J. M., Borns, D. J., and Craw, D., 1976, The Dun Mountain ophiolite belt, New Zealand, its tectonic setting constitution and origin, with special reference to the southern portion: American Journal of Science. v. 276, p. 561–603.

DePaolo, D. J., 1981, Trace element and isotopic effects of combined wall rock assimilation and fractional crystallization: Earth and Planetary Science Letters, v. 52, p. 177–184.

Dickin, A., 1995, Radiogenic Isotope Geology: Cambridge, United Kingdom, Cambridge University Press, 452 p.

Field, D., and Raheim, A., 1979, A geologically meaningless Rb-Sr total rock isochron: Nature, v. 282, p. 497–499.

Fleming, C. A., 1970, The Mesozoic of New Zealand: chapters in the history of the Circum-Pacific Mobile Belt: Journal of the Geological Society of London, v. 125, p. 125–170.

Gibson, G. M., 1990, Uplift and exhumation of middle and lower crustal rocks in an extensional tectonic setting, Fiordland, New Zealand, *in* Salisbury, M. H., and Fountain, D. M., editors, Exposed Cross Sections of the Continental Crust: Dordrecht, Kluwer Academic Publishers, NATO SAI Series, p. 71–101.

Graham, I. J., and White, P. J., 1990, Rb-Sr dating of Rahu Suite granitoids from the Paparoa Range, North Westland, New Zealand: New Zealand Journal of Geology and Geophysics, v. 33, p. 11–22.

Grindley, G. W., 1958, The Geology of the Eglinton Valley, Southland, New Zealand: New Zealand Geological Survey Bulletin 58, 68 p.

Hill, E. J., 1995, The Anita Shear Zone: a major middle Cretaceous tectonic boundary in northwestern Fiordland: New Zealand Journal of Geology and Geophysics, v. 38, p. 93–103.

Johnston, M. R., 1990, Geology of the St Arnaud District, southeast Nelson (Map Sheet NZ9): DSIR, New Zealand Geological Survey Bulletin 99, 119 p.

Kimbrough, D. L., Tulloch, A. J., Coombs, D. S., Landis, C. A., Johnston, M. R., Mattinson, J. M., 1994, Uranium-lead zircon ages from the Median Tectonic Zone, New Zealand: New Zealand Journal of Geology and Geophysics, v. 37, p. 393–419.

Kimbrough, D. L., Tulloch, A. J., Geary, E, Coombs, D. S., and Landis, C. A., 1993, Isotopic ages from the Nelson region of South Island, New Zealand: crustal structure and the definition of the Median Tectonic Zone: Tectonophysics, v. 225, p. 433–448.
Klepeis, K. A., Daczko, N. R., and Clarke, G. L., 1999, Kinematic Vorticity and tectonic significance of superposed mylonites in a major lower crustal shear zone, northern Fiordland, New Zealand: Journal of Structural Geology, v. 21, p. 1385–1405.
Koons, P. O., 1978, Aspects of the geology of the southern Darran Mountains: New Zealand Geological Survey Report G 26, 25 p.
Landis, C. A., and Coombs,D. S., 1967, Metamorphic belts and orogenesis in southern New Zealand: Tectonophysics, v. 4, p. 501–518.
Mattinson, J. M., Kimbrough, D. L., Bradshaw, J. Y, 1986, Western Fiordland Orthogneiss: early Cretaceous arc magmatism and granulite facies metamorphism, New Zealand: Contributions to Mineralogy and Petrology, v. 92, p. 383–392.
McCulloch, M. T., Bradshaw, J. Y, Taylor, S. R., 1987, Sm-Nd and Rb-Sr isotopic and geochemical systematics in Phanerozoic granulites from Fiordland, southwest New Zealand: Contributions to Mineralogy and Petrology, v. 97, p. 183–195.
Mortimer, N., Gans, Ph., Calvert, A., and Walker, N., 1999a, Geology and thermochronometry of the east edge of the Median Batholith (Median Tectonic Zone): a new perspective on Permian to Cretaceous crustal growth of New Zealand: The Island Arc, v. 8, p. 404–425.
Mortimer, N., Tulloch, A. J., Spark, R. N., Walker, N. W., Ladley, E., Allibone, A., and Kimbrough, D. L., 1999b, Overview of the Median Batholith, New Zealand: a new interpretation of the Median Tectonic Zone and adjacent rocks: Journal of African Earth Sciences, v. 257, p. 257–268.
Muir, R. J., Ireland, T. R., Weaver, S. D., Bradshaw, J. D., Evans, J. A., Eby, G. N, and Shelley, D., 1998, Geochronology and geochemistry of a Mesozoic magmatic arc system, Fiordland, New Zealand: Journal of the Geological Society of London, v. 155, p. 1037–1053.
Muir, R.J., Weaver, S. D., Bradshaw, J. D., Eby, G. N., and Evans, J. A., 1995, The Cretaceous Separation Point batholith, New Zealand: granitoid magmas formed by melting of mafic lithosphere: Journal of the Geological Society of London, v. 152, p. 689–701.
Munksgaard, N. C., 1984, High ^{18}O and possible pre-eruptional Rb-Sr isochrons in cordierite-bearing Neogene volcanics from SE Spain: Contributions to Mineralogy and Petrology, v. 87, p. 351–358.
Nathan, S., Thurlow, C., and Zucchetto, R., 2000, Geochronology database for New Zealand rocks (2nd edition): 1961–1999: Institute of Geological and Nuclear Sciences, Science Report 2000/11, xx p.
Orville, P. M., 1963, Alkali ion exchange between vapour and feldspar phases: American Journal of Science, v. 261, p. 201–237.
Spark, R., 1998, Field work, Milford Sound area: Institute of Geological and Nuclear Sciences, Immediate Report RNS 98/01, 12 p.
Steiger, R. H., and Jäger, E., 1977, Subcommission on Geochronology : Convention on the use of decay constants in geo- and cosmochronology: Earth and Planetary Science Letters, v. 36, p. 359–362.
Streckeisen, A. L., 1976, To each plutonic rock its proper name: Earth Science Reviews, v. 12, p. 1–33.
Tulloch, A. J., 1983, Granitoid rocks of New Zealand–A brief review: Geological Society of America, Memoir 159, p. 5–19.
Tulloch, A. J., Ireland, T. R., Walker, N. W., and Kimbrough, D. L., 2000, U-Pb zircon ages from the Milford Orthogneiss, Milford Sound, northern Fiordland: Paleozoic igneous emplacement and Early Cretaceous metamorphism: Institute of Geological and Nuclear Sciences, Science Report 2000/6, 13 pages plus figures.
Tulloch, A. J., and Kimbrough, D. L., 1989, The Paparoa metamorphic core complex, New Zealand. Cretaceous extension associated with fragmentation of the Pacific margin of Gondwana: Tectonics, v. 8, p. 1217–1234.
Turnbull, I. M., and compilers, 2000, Geology of the Lake Wakatipu area: Lower Hutt, Institute of Geological and Nuclear Sciences 1:250 000 geological map 18. 1 sheet + xx p. (in press).
Wandres, A. M., Weaver, S. D., Shelley, D, and Bradshaw, J. D, 1998, Change from calc-alkaline to adakitic magmatism recorded in the Early Cretaceous Darran Complex, Fiordland, New Zealand:. New Zealand Journal of Geology and Geophysics, v. 41, p. 1–14.
Watson, E. B., and Harrison, T. M., 1983, Zircon saturation revisited: temperature and composition effects in a variety of crustal magma types: Earth and Planetary Science Letters, v. 64, p. 295–304.
Wendt, I., 1993, Isochron or mixing line?: Chemical Geology, Isotope Geoscience Section, v. 104, p. 301–305.
Williams, J. G., ms, 1975, Geology of the upper Eglinton area: status of the Median Tectonic Line. Ph.D. thesis, University of Otago, Geology Department, Dunedin, 305 p.
—— 1978, Eglinton volcanics–stratigraphy, petrography, and metamorphism: New Zealand Journal of Geology and Geophysics, v. 21, p. 713–732.
Williams, J. G., and Harper, C. T., 1978, Age and status of the Mackay Intrusives in the Eglinton-upper Hollyford area: New Zealand Journal of Geology and Geophysics, v. 21, p. 733–742.
Williams, J. G., and Smith, I. E. M., 1983, The Hollyford Gabbronorite–a calcalkaline cumulate: New Zealand Journal of Geology and Geophysics: v. 26, p. 345–357.
Wood, B. L., 1962, Sheet 22-Wakatipu: Geological map of New Zealand, 1:250,000: DSIR, New Zealand Geological Survey.
Woodward, D. J, and Hatherton, T., 1975, Magnetic anomalies over southern New Zealand: New Zealand Journal of Geology and Geophysics, v. 18, p. 65–82.
York, D., 1969, Least squares fitting of a straight line with correlated errors: Earth and Planetary Science Letters, v. 5, p. 320–324.