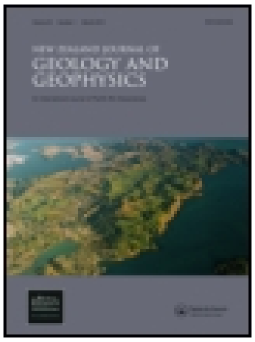

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The Chrystalls Beach–Brighton block, southeast Otago, New Zealand: petrography, geochemistry, and terrane correlation

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Abstract The Chrystalls Beach–Brighton coastal block in southeast Otago has commonly has been placed in Caples Terrane, but has recently been described as a geochemically anomalous area of uncertain terrane affinity. Data points on discriminant diagrams occupy fields centred between those for type Caples Group and Torlesse Terrane, overlapping both. The psammites average 71.9% SiO_2, closely comparable to Torlesse Terrane psammites, in contrast to the majority of type Caples Group psammites (av. 64.3%) and Waipapa Terrane psammites (64.4%). QFL plots show the Chrystalls Beach psammites as a petrofacies distinct from those described hitherto for Torlesse Terrane (lithic feldsarenites) and Caples Group and Murihiku Terrane (volcarenites).

Phosphatic nodules in melange zones associated with metabasites and cherts in the Chrystalls Beach Complex contain Middle Triassic radiolarians. Middle–Late Triassic tube fossils *Torlessia* sp. and *Titahia corrugata* Webby occur in the Chrystalls Beach Complex as in the Torlesse Terrane, but are unknown in type Caples Group sediments in which the only dated fossils are Permian.

Both the trench or trench-slope Chrystalls Beach–Brighton psammites and the late Middle to early Late Triassic Kaihikuan sediments of the Murihiku Terrane were derived from regions of largely felsic volcanism with underlying granitoids. The geochemical match is imperfect and the sedimentary facies are different. The Chrystalls Beach–Brighton block is unlikely to be a tectonically introduced and atypical part of the Torlesse Terrane. It may be: (1) an atypical and geochemically more evolved part of the Caples Terrane, younger than dated rocks preserved in the type area, or (2) a separate terrane fragment with a different history from its neighbours. A suggested correlation with the North Island Waipapa Terrane invites questions as to the true terrane affinity of the rocks concerned and of Caples–Waipapa relationships in general.

Keywords Caples Terrane; Torlesse Terrane; Chrystalls Beach Complex; Murihiku Terrane; geochemistry; Otago Schist; Waipapa Terrane

INTRODUCTION

Terranes relevant to the origin of Otago Schist

It is widely accepted that the Otago Schist, part of the Haast Schist in southern New Zealand, results from a metamorphic overprint on a suture zone involving two separate terranes (Fig. 1)—the Torlesse Terrane on the north and east, and the Caples Terrane to the south and west (e.g., Bishop et al. 1985; Frost & Coombs 1989; Roser & Cooper 1990). However, the terrane affinity of the coastal block in southeast Otago has become a matter of debate (Mortimer & Roser 1992; Roser et al. 1993; Adams & Graham 1997; Adams et al. 1999; Landis et al. 1999).

The Torlesse Terrane includes a vast pile of imbricated slices consisting mainly of quartzofeldspathic turbidites (e.g., MacKinnon 1983), together with localised terrestrial beds and widely scattered pillow lava, chert, and other pelagic sediments. Many of the cherty rocks are manganiferous (e.g., Coombs et al. 1996). The age is Permian–Cretaceous but extends back to Carboniferous if the Kakahu area of South Canterbury is included (Hitching 1979; Bishop et al. 1985).

Blake et al. (1974) mapped a "Caples-Croisilles-Pelorus terrane" from South Otago to the Alpine Fault and thence through Nelson and the central North Island to Northland, and described its essential characteristics. Caples Terrane (Bishop et al. 1976), termed "Caples-Pelorus terrane" by Coombs et al. (1976b), was defined by Bishop et al. (1985) as a belt "of relatively low-grade graywacke-type sediments with local development of thick (meta) volcanic and pelitic

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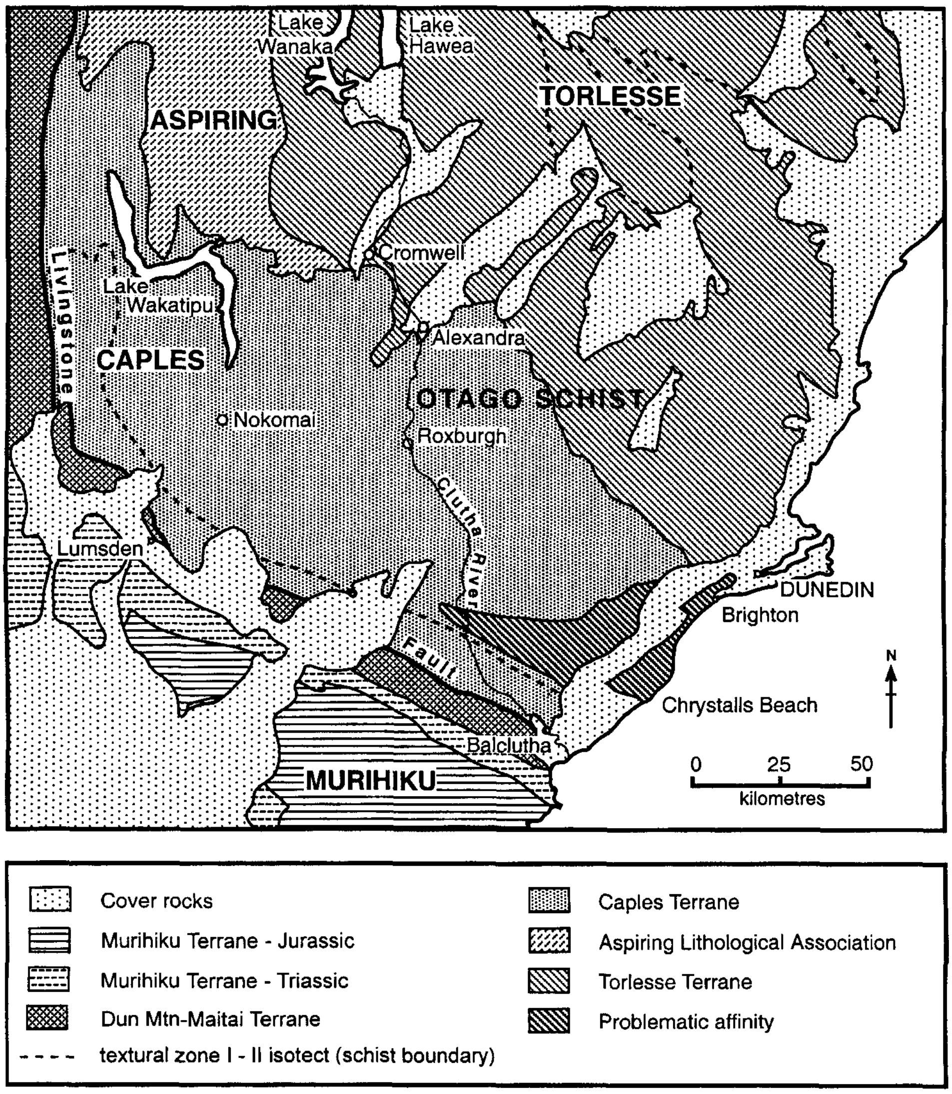


Fig. 1 Terranes in part of South Island, New Zealand. The area of problematic affinity (Mortimer & Roser 1992; Roser et al. 1993) includes the Chrystalls Beach–Brighton block of southeast Otago (other poorly defined problematic areas are shown by Mortimer & Roser 1992). A metamorphic overprint on the juxtaposed Caples and Torlesse Terranes has produced the Otago Schist between the textural zone I–II isotects (Mortimer 1993b), shown on its southwestern and north-eastern flanks.

units ... that outcrop between the Haast Schist and the Dun Mountain ophiolite", with an eastern boundary with the Torlesse Terrane somewhere within the Haast Schist. Rocks variously known as Tuapeka Group in South Otago, as Caples Group south and west of Lake Wakatipu, and as Pelorus Group in the northern part of the South Island were included. Sedimentary facies within the terrane were interpreted by Turnbull (1980) as representing a largely volcaniclastic submarine fan complex deposited on a lower trench slope and possibly a trench floor, together with pelagic ocean-floor sediment and metabasites of oceanic crustal origin.

Boulders of limestone consisting of atomodesmatinid prisms and containing the Permian form *Atomodesma* sp. aff. *trechmanni* occur in Bold Peak Formation within the Caples Group in northern Southland (Turnbull 1979a). Limestone consisting of atomodesmatinid fragments also occurs within the same formation in a volcanogenic horizon which has been interpreted as possibly olistolithic by Turnbull (1979a). Similar rocks to the southeast mapped as a melange zone contain late Early to Middle Permian conodonts (Fischer 1998; Ford et al. 1999) near Nokomai. Type Caples Group sediments and their inferred southeastern extension thus contain Permian detritus and may themselves be of Permian age, at least in part. Other datable fossils within Caples Group sediments are so far unknown.

An oceanic association of metapelites, psammitic schist, relatively abundant greenschists (metabasites), manganiferous and other metacherts, minor marble, and small ultramafic bodies exposed between Torlesse and Caples Terrane derivatives in northwest Otago was described by Craw (1984). He referred to it as the Aspiring lithologic association. Norris & Craw (1987) recognised this suite as a distinct terrane, the Aspiring Terrane, in underthrust relationship (Roser & Cooper 1990) to the adjacent terranes. Mortimer & Roser (1992) showed that the geochemistry of metapsammites and metapelites is of Torlesse type, and included the Aspiring lithologic association as a subunit of the Torlesse Terrane.

The Waipapa Terrane (Spörli 1978) is a diverse assemblage of largely turbiditic terrigenous sediments west of the Torlesse Terrane in central and northern North Island. These rocks had been included by Blake et al. (1974, fig. 7) in their Caples-Croisilles-Pelorus terrane. Distribution of facies and dated occurrences, mostly Late Jurassic, are reviewed by Black (1994). Psammites contain a high proportion of volcanic detritus, commonly mafic to intermediate, but quartzofeldspathic sandstones have also been reported. Chert in melange zones at Kawakawa Bay near Auckland (Hunua facies) contains Late Triassic and Early Jurassic radiolarians interpreted as of low-latitude Tethyan origin, whereas juxtaposed green argillite contains Middle and Late Jurassic radiolarians of dominantly high-latitude, non-Tethyan affinity (Spörli et al. 1989). Permian faunas are known from the Bay of Islands region (Hunua facies), and Aita & Bragin (1999) report high-latitude, non-Tethyan Middle Triassic radiolarians in phosphatic nodules on the Mahinepua peninsula, east of Whangaroa.

In the southern South Island (Fig. 1), Caples Terrane adjoins the Dun Mountain-Maitai Terrane along the Livingstone Fault. It is followed farther to the south and west by the Murihiku Terrane containing a sequence c. 10 km thick of Early Triassic to Middle Jurassic sediments derived from an active volcanic belt with older crystalline basement (e.g., Frost & Coombs 1989). Beyond the Murihiku is the Brook Street Terrane of Permian arc-derived sediments and related intrusives.

The Chrystalls Beach–Brighton block of problematic affinity

A coastal section through the southern flank of the Otago Schist is exposed in wave-cut platforms from Brighton to Chrystalls Beach, southwest of Dunedin (Fig. 1). The part of the section between Chrystalls Beach and Taieri Mouth was referred to by Nelson (1982) as the Chrystalls Beach Complex. This consists predominantly of deformed greywacke-type sandstone-argillite turbidites with lesser amounts of chert, conspicuous grey, pink, and greenish shales or phyllites, mafic volcanics including pillow lava (Hada et al. 1988; Suzuki & Suzuki 1988), and manganiferous horizons (e.g., Read & Reay 1971; Sameshima & Kawachi 1991). Associations involving variably coloured shales, manganiferous beds, and/or mafic volcanics are sandwiched between more coherent sandstone-grey mudstone turbidite suites and units consisting of amalgamated sandstones. With the supporting evidence of soft-sediment pull-aparts, weakly developed slaty cleavage, folds in dismembered bedding, and quartz-fibre lineated surfaces, Nelson (1982) interpreted these occurrences as accretionary melange. Intimate mixes are found at numerous localities of pelagic or hemipelagic argillite, metasiltstone or sandstone, and sometimes chert, with phosphatic nodules typically a few centimetres in diameter scattered through the argillites. The slabs of the more resistant rock types are commonly a few centimetres thick and may be tightly interfolded with the finer grained sediments. We interpret these units as olistostromal, the products of slurry-like soft-sediment slumping in a trench-slope environment. More coherent sandstone-argillite sequences occur as broken formation. Interpretation is complicated by later disruption and transposition of bedding.

Mud-clast conglomerates containing intraformational sedimentary rip-up clasts are developed at a number of localities and are attributed to gravity flows generated by sediment failure and erosion on submarine slopes (Maejima et al. 1992; Tanaka et al. 1992). A few such sheets 0.1–1.5 m thick, occurring in amalgamated sandstones on the southwestern side of Quoin Point, contain scattered well-rounded small pebbles and granules of exotic origin. We suggest that for these, turbidite transport was initiated by land-derived flood waters or by slope collapse in shallow water. A similar but much more highly metamorphosed conglomerate on the northern side of Reids Stream contains deformed, greatly stretched cobbles and pebbles of igneous origin (Norris & Bishop 1990).

Two distinct tube fossils are locally abundant in the terrigenous sediments—*Titahia corrugata* Webby on the southwestern side of Quoin Point, and *Torlessia* sp. at numerous localities between Watsons Beach and Bull Creek and inland thereof (Fig. 2) (Campbell & Campbell 1970). From the widespread occurrence of these remains in parts of the Torlesse Terrane where the closest dated fossils are of Late Triassic age, Campbell & Campbell (1970) inferred a probable Late Triassic age for the Chrystalls Beach Complex. Campbell & Pringle (1982) later found *Torlessia* to co-exist with a fauna dated as late Middle or early Late Triassic. A Middle to early Late Triassic correlation is thus plausible for the terrigenous sediments of the Chrystalls Beach section.

Radiolarians extracted from phosphatic nodules led to a provisional Triassic and possible Middle–Late Jurassic age assignment for a pelagic component in the Chrystalls Beach Complex (Hada et al. 1988). This has since been revised to Middle Triassic with no Jurassic (Kuranaga 1994; Aita & Bragin 1999; Ito et al. 2000, this issue). Largely on the basis of differences within the radiolarian faunas and differences in structural style, Ito et al. distinguish a southern unit which includes the *Torlessia* occurrences, and a northern unit which includes the *Titahia* occurrences. A northwest-trending fault zone on the southwestern side of Watsons Beach (Fig. 2) is taken as the boundary between these units.

The grade of metamorphism increases progressively northeastwards (Fig. 2) from textural zone IIA near Chrystalls Beach in the south to IIIB and IV in the north (Mortimer 1993b; Bishop & Turnbull 1996). Mineral facies range from indeterminate low-grade in the south to biotite zone of the greenschist facies near Brighton (Robinson 1958; Craw et al. 1982; Adams & Robinson 1993; Li et al. in press; Nishimura et al. in press).

Largely on the basis of its position on the south flank of the Otago schists, this coastal block was included as part of the Caples Terrane in the original terrane definitions described above. However, on the basis of geochemical criteria, Mortimer & Roser (1992) sketched a wedge-shaped area of problematic affinity including the Chrystalls Beach–Brighton coast and extending almost 70 km inland (Fig. 1). Roser et al. (1993) showed the same area as being of Torlesse affinity within the Caples Terrane. Adams & Graham (1997) reported initial $^{87}Sr/^{86}Sr$ ratios for this block intermediate between those for known Torlesse and Caples values. Adams et al. (1999) further suggested the possibility that the zone of uncertain affinity could correlate with the Waipapa Terrane as interpreted by them in the central North Island.

Tectonostratigraphic terranes have been defined by Howell et al. (1985) as fault-bounded packages of rocks of regional extent characterised by a geologic history that differs from that of neighbouring terranes. Clearly, a range of sedimentary ages and lithologies is to be expected in any one terrane. Furthermore, a variety of sources may contribute to the sedimentary rocks found in any one terrane. In spite of variations resulting from such factors, petrography and geochemistry of the sediments provide powerful tools for constraining terrane affiliations (e.g., MacKinnon 1983; Roser & Cooper 1990).

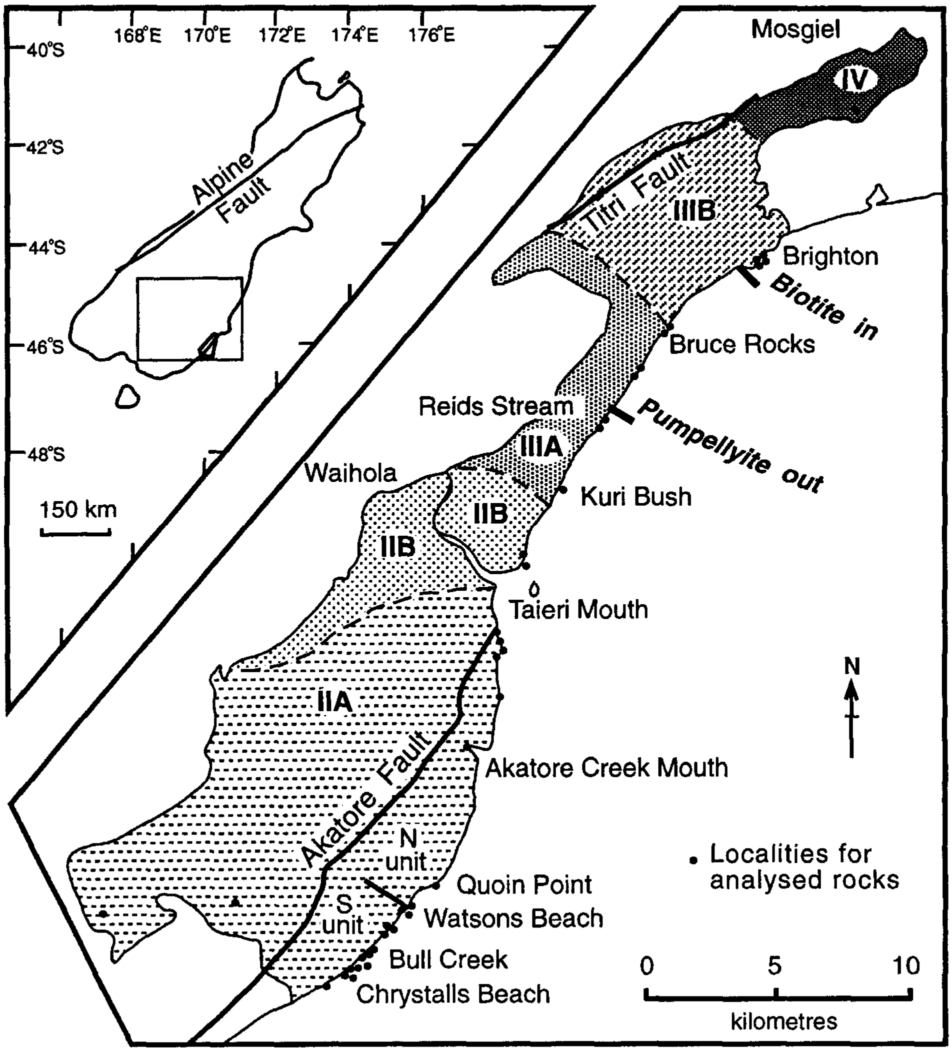


Fig. 2 Locality map for Fig. 1 and map of the coastal Chrystalls Beach–Brighton block of southeast Otago, showing localities for analysed rocks and approximate position of isotects (Mortimer 1993b; Bishop & Turnbull 1996) and of pumpellyite-out and biotite-in isograds.

In this paper, we discuss the terrane relationship of the Chrystalls Beach–Brighton block in the light of new petrographic and geochemical data and radiolarian age determinations.

METHODS

New major-element and minor-element analyses were carried out by X-ray fluorescence in the Geology Department, University of Otago, by R. D. Johnstone, using the methods of Norrish & Hutton (1969). The specimens concerned were collected by Hada et al. (1988) from between Chrystalls Beach and Taieri Mouth. Specimens were trimmed and washed in distilled water for 24–48 h. Analyses from Palmer et al. (1991) are also considered as well as major-element XRF analyses of pelitic and semi-pelitic rocks carried out at the University of Michigan, Ann Arbor, United States (Li et al. in press). Data for a carbonate-rich rock, OU68566, are included in Fig. 3 and 4, but are omitted from other plots presented. Discriminant functions are calculated as described by Roser & Korsch (1986, 1988), data being normalised for the purpose on a 100% loss-on-ignition-free (LOI-free) basis. Localities for analysed specimens are shown in Fig. 2.

Point-count analyses were carried out on sandstone thin sections which were stained for potassic feldspar, with a minimum of 500 points per section. Following Dickinson (1970), sand-sized grains in lithic clasts were counted according to their mineral identification for plotting on QFL plots. As a result of reconstitution, it was not possible to distinguish "pseudomatrix", consisting of some of the deformed and recrystallised lithic clasts (Dickinson 1970), from true original matrix. A single category, "matrix and indeterminate", has been used to include such material as well as introduced or completely recrystallised products of doubtful origin.

Five-figure (OU) reference numbers in the text and tables refer to specimens in the collection of the Geology Department, University of Otago.

PETROGRAPHY

Conglomerates

Well-rounded pebbles and granules of exotic origin occur within thin sheets of rip-up clast conglomerate near Quoin Point within the northern unit of Ito et al. (2000). While not necessarily fully representative, these provide important information on the nature of the source region for Chrystalls

Beach Complex sediments. All pebbles, granules, and sand grains larger than 1 mm with well-rounded edges and well-defined resistant faces were counted in several large thin sections from each of two of the conglomeratic sheets. Typical rip-up clasts with frayed ends and indentations were ignored.

Felsic volcanics are the most abundant rock types represented (Table 1). Groundmasses of most of these are of extremely fine, <20 μm grain size, with quartz, albite, and varying amounts of illite or phengite ± minor chlorite, stilpnomelane, and rarely pumpellyite. Phenocrysts include albitised plagioclase and much less commonly quartz and/or potassic alkali feldspar. Such clasts are believed to be derived from dacites, rhyolites, and rhyolitic ignimbrite. As a result of the metamorphic overprint, many smaller clasts lacking phenocrysts could not reliably be identified as igneous. A small proportion of felsic clasts have coarser grained textures, some spherulitic, typical of rhyolites and ignimbrites. Others are fluxional, with laths of feldspar and alteration products suggestive of an original felsic andesite composition. Approximately 18% of the clasts are granitoid, some with typical granophyric texture, most others micro-grained or medium grained with localised granophyric intergrowths. Potassic alkali feldspar is perthitic, and plagioclase is albitised and variably dusted with secondary minerals. The absence of muscovite and the presence of biotite indicate I-type granites, but hornblende was not seen.

Rounded sedimentary clasts are also abundant (Table 1). Some have textures indistinguishable from those of rip-up clasts and other sediments in the Chrystalls Beach Complex apart from the presence of predepositional quartzose veinlets. An intraformational origin involving rounding during transport is not precluded for some of the sedimentary clasts in which there are no such veinlets. Clasts of irregularly textured impure quartzite of uncertain origin were also observed.

Felsic volcanics and granophyric and other granitoids are prominent in textural zone IIIA matrix-supported conglomeratic schist near Reids Stream (Norris & Bishop 1990), but intense penetrative deformation and recrystallisation, especially of the finer grained volcanic and sedimentary clasts, precludes their detailed interpretation.

Psammites

Quartz grains are the most abundant of the detrital mineral clasts. Typically of medium sand grade and angular outline, some are monocrystalline, but, towards the north of the section, they are increasingly broken, granulated, and recrystallised as a result of penetrative deformation and metamorphism. Plagioclase is of albite composition. Some grains are almost free of inclusions and show well-preserved twinning, but most are clouded or disguised by inclusions of mica, chlorite, and, in some, pumpellyite. Potassic feldspar clasts are preserved in psammites at least as far north as Taieri Mouth, perthitic texture commonly being preserved in the lower grade rocks. Composite quartz-potassic feldspar ± plagioclase grains, often with granophyric texture, are recognisable in most thin sections, but microcline suggestive of a deeper seated granitic origin was not observed. With advancing metamorphism, potassic feldspar is destroyed, but even in some of the lowest grade rocks examined (e.g., OU43140, Table 2), potassic feldspar and granitoid clasts are rare or absent (cf. Suzuki & Suzuki 1988). The observations suggest that potassic feldspar was derived largely from high-level granitoids rather than volcanic rocks, and that the contribution of these to the sediments was variable.

Other clasts include copious lithics, degraded biotite, epidote, epidote-quartz ± chlorite, zircon, apatite, tourmaline, and quartz-tourmaline. Detrital muscovite is rare in psammites but occurs as small flakes in pelites. Detrital augite has not been observed, and hornblende only rarely.

Lithic clasts predominate in the psammites. Most are fine-grained siliceous aggregates containing albite and quartz with some secondary white mica and chlorite. Even where phenocrysts provide unequivocal evidence of volcanic origin, potassic feldspar is seldom present in the groundmass, as confirmed by staining tests. From Bull Creek north, pumpellyite and/or stilpnomelane are additional products of neocrystallisation. Even at the lowest grades of metamorphism, it is not always possible to distinguish clasts from reconstituted and penetratively deformed matrix. Some clearly volcanic clasts with euhedral phenocrysts are remarkably similar in groundmass texture to fine-grained siliceous sediments of the Chrystalls Beach Complex, and the origin of many fine-grained clasts is thus indeterminate.

Table 1 Rock types (%) represented by coarse sand grains (>1 mm), granules, and pebbles, with well-rounded edges and resistant faces, in matrix-supported rip-up clast conglomerates, Chrystalls Beach Complex; also stretched cobbles in matrix-supported metaconglomerate near Reids Stream.

OU number	69045 W side of Quoin Point	69049–51 300 m W of Quoin Point	1 km NE of Reids Stm
Grid reference, I45	912466	910465	974639
Clasts counted	80	81[1]	
Granite and microgranite, mostly granophyric, some with biotite	14	16	present
Felsic and felsic-intermediate volcanics	31	40	present
Intermediate to basic volcanics	5	10	–
Sedimentary including very low grade metamorphic	31	17	?
?Felsic volcanic or sedimentary	19	12[2]	present
Impure quartzitic of doubtful origin	–	5	–

[1] One heavy shell fragment (4 mm) and epidote-quartz-rich sand grains (<1 mm) also noted.
[2] Includes one altered, partly tourmalinised granule.

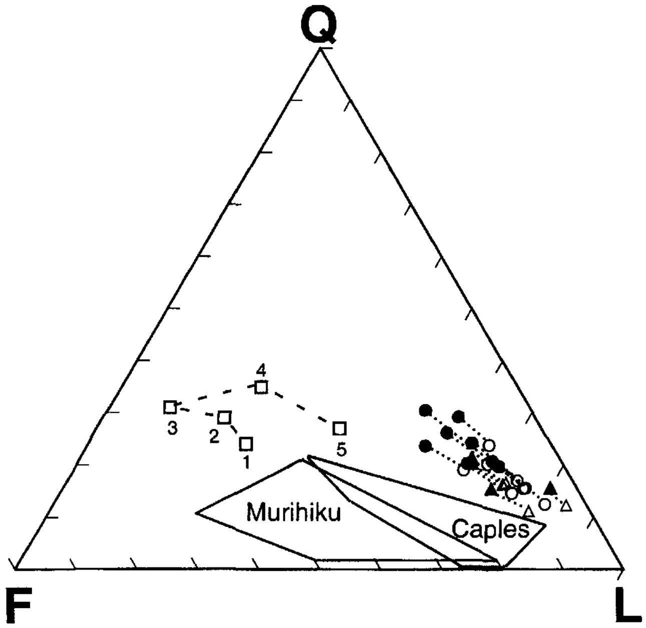


Fig. 3 QFL diagram for Chrystalls Beach Complex psammites. Triangles = southern unit. Circles = northern unit. Solid symbols are point-counted; open symbols are normalised to 10% matrix, treating "matrix" in excess of 10% as recrystallised fine-grained lithics. Points 1–5 are mean values for Torlesse Terrane petrofacies of MacKinnon (1983); petrofacies 1 of likely Permian age; 2 and 3, Middle to early Late Triassic as for the Chrystalls Beach Complex; 4, Late Triassic; 5, Late Jurassic to Early Cretaceous. Full lines enclose the fields of sandstones from the Murihiku and Caples Terranes (MacKinnon 1983).

Some impure cherty beds in the coastal section may be recrystallisation products of very fine grained siliceous ash beds, and some of the lithic clasts could have a similar origin. Blocky clasts consisting of almost monomineralic phengite or of quartz and feldspar, are possibly alteration products of volcanic glass. Apart from intraformational rip-up clasts in some sandstones, clearly sedimentary lithic clasts are a minor component, as are volcanic clasts with a texture suggestive of andesitic or more mafic origin.

Point-count analyses of representative sandstones are shown in Table 2 and in a QFL diagram (Fig. 3). Reconstitution makes the distinction of fine-grained sedimentary clasts, volcanic clasts, and matrix difficult or impracticable. Almost certainly, matrix has been overestimated at the expense of deformed and partly recrystallised fine-grained lithic clasts. For each analysis, a second point (open symbol) has therefore been plotted representing matrix normalised to an arbitrary 10%, the excess matrix being recalculated as fine-grained lithics. The appropriate positions on a QFL plot at the time of sedimentation may have fallen on the dotted lines linking the pairs of points generated in this way. Neocrystallisation products in strain shadows have been counted as matrix.

As shown in Fig. 3, lithic contents are much higher, and quartz and feldspar contents much lower than in Torlesse Terrane rocks reported by MacKinnon (1983). The spread of data points also differs from that shown by MacKinnon for Murihiku Terrane sandstones of Middle Triassic–Jurassic age and for Caples Terrane sandstones. Points plotted from the southern and northern units of the Chrystalls Beach Complex occupy overlapping fields in the same distinctive, narrow band.

Metamorphic overprint

Phacoidal trails of matrix are commonly wrapped around clasts in the psammites of lower metamorphic grade. Together with trails of fine-grained mica along zones of slip, these help define a pervasive crude foliation subparallel to transposed bedding and axial planes of folds, even in the rocks of lowest metamorphic grade.

All rocks contain hair-fracture or larger quartzose veinlets, often with albite, phengite and/or chlorite, calcite, pumpellyite, stilpnomelane, and sideritic carbonate which may also occur in the matrix. In analysed rocks, pumpellyite has been detected only where CaO whole-rock contents are in excess of c. 0.6%. Its presence has not been confirmed south of Bull Creek. The most southerly occurrence of stilpnomelane found in the present study is c. 600 m north of Bull Creek, although Kisch (1981) recorded it in pelite at Chrystalls Beach. It commonly occurs as sprays of thin flakes

Table 2 Representative point count analyses of psammites, Chrystalls Beach Complex.

	Southern unit		Northern unit		
OU number	43140	43141	69048	69056	61853
Grid reference, H45	880432	892447	910465	918477	924515
Locality	800 m SSW of Bull Ck	1.1 km NE of Bull Ck	S of Quoin Point	1.2 km NE of Quoin Pt	N wall, Akatore estuary
Lithology	med sst	med sst	med sst	med sst	med sst
Quartz	11	15	18	14	13
Plagioclase	3	4	5	3	4
Potassic feldspar	<1	6	6	5	6
Fine-grained lithics	56	45	40	24	41
[1]Matrix and indeterminate	29	30	30	54	35
Heavy minerals, biotite	1	–	1	–	1
[2]Granitoids, granophyre	1	3	4	3	3

[1]Includes: true matrix; indeterminate material that may be recrystallised matrix or deformed and recrystallised lithic clasts; and other newly crystalline material, such as occupies strain shadows, but avoiding crosscutting veinlets.
[2]Component minerals are included in the analyses as given above.

in the matrix and in clasts of potassic feldspar. In some rocks, it occurs preferentially in granitoid clasts, partially replacing potassic feldspar. New-formed epidote is common from c. 1 km north of Quoin Point. At Akatore Creek, reconstitution has led to quartz - albite - phengite - stilpnomelane - pumpellyite - epidote - actinolite semischist with clasts of perthite well preserved in some rocks. In others, alkali feldspar has been completely replaced by aggregates of albite and stilpnomelane. Lawsonite is known from a single occurrence in a late quartz-carbonate vein 3 km south of Taieri Mouth (grid ref. I45/632945) (M. Moss pers. comm. 1991; D.S.C. pers. obs.).

Intense penetrative deformation and metamorphic recrystallisation progressively destroy primary sedimentary features towards the north. Near Brighton, psammites are fully reconstituted laminated schists of textural zones IIIB and IV. Approximate positions of isotects according to Mortimer (1993b) and Bishop & Turnbull (1996), and the pumpellyite-out and biotite-in isograds, are shown in Fig. 2.

GEOCHEMISTRY

SiO_2 and Al_2O_3

Mortimer & Roser (1992) applied the terms greywacke and psammitic schist to Otago schists of Torlesse Terrane affinity where SiO_2 exceeds 68% by weight normalised to 100% (LOI-free), and argillite and pelitic schist where SiO_2 is <68%. Where relict textural features are preserved in Chrystalls Beach–Brighton metasediments, those with <68% SiO_2 (Tables 3, 4) are indeed very fine sandstones, siltstones, or mudstones in line with this definition. Many rocks with a little more or less than 68% SiO_2 are best described as semipelitic. Normalised SiO_2 contents of a psammite-semipelite pair from Watsons Beach are 77.33 and 67.13%, respectively (Mortimer & Roser 1992). This gives additional justification for a 68% normalised SiO_2 cutting line as an indicator of original grain size in the Chrystalls Beach–Brighton block. Psammites with substantial andesitic, dioritic, or basaltic content (as in many Caples Group rocks), however, have relatively low SiO_2, and for these, SiO_2 cannot be used as an indicator of premetamorphic grain size. There is a strong negative correlation between SiO_2 and Al_2O_3 in the Chrystalls Beach–Brighton suite, but a highly calcareous rock (OU68566, Table 3) plots off the trend (Fig. 4).

K_2O, Na_2O, and SiO_2

In spite of much overlap, Chrystalls Beach–Brighton psammites, like those of the Caples, are on average substantially more sodic and less potassic (Table 5) than South Island Torlesse Terrane sandstones of comparable Permian to Late Triassic age (Roser et al. 1995) and inferred Torlesse derivatives in Otago Schist (Palmer et al. 1991). The range of grain sizes, sedimentary facies, and metamorphic facies is so similar, that it is difficult to escape the conclusion that this is an intrinsic feature distinguishing Chrystalls Beach–Brighton psammites from Torlesse sandstones.

Chrystalls Beach–Brighton psammites, like Torlesse sandstones and their metamorphic derivatives, are here arbitrarily distinguished from pelites by having SiO_2 >68%. They average 71.9% SiO_2 (Table 5), which is indistinguishable from the SiO_2 content of the Rakaia Subterrane of the Torlesse Terrane, and much higher than the average of 64.3% SiO_2 for 42 texturally defined type-area Caples Group sandstones (Roser et al. 1993). Amongst the latter is a small minority of high-silica sandstones, five having >70% SiO_2, and being comparable in this respect to Chrystalls Beach–Brighton psammites. Three of these come from Mt Campbell Formation.

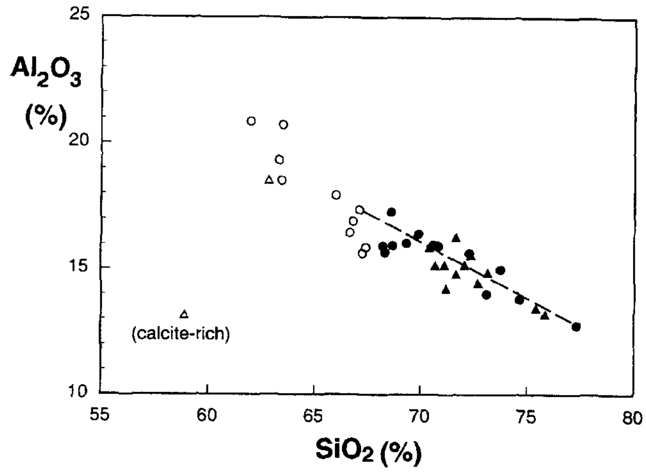


Fig. 4 Al_2O_3 versus SiO_2 in the Chrystalls Beach–Brighton block, southeast Otago, normalised to 100%, LOI-free. Filled symbols = SiO_2 >68%. Open symbols = SiO_2 <68%. Triangles = Chrystalls Beach to near Watsons Beach (southern unit). Circles = Watsons Beach to Brighton, including northern unit and more highly metamorphosed rocks. Dashed line joins a psammite-pelite pair (Mortimer & Roser 1992).

In a plot of K_2O/Na_2O versus SiO_2 (Fig. 5A), most points for the Chrystalls Beach–Brighton block fall in a field labelled ACM by Roser & Korsch (1986) to indicate sediments derived from active continental margins. This field is here relabelled Mature ARC, ACM to indicate derivatives of mature volcanic arcs generating relatively felsic eruptives, as well as active continental margins. A few of the sediments spread marginally into the field labelled ARC by Roser & Korsch (1986), here relabelled ARC, Maf-Int to include the possibility of a mafic volcanic provenance unrelated to arc volcanism as well as derivatives of arcs generating mafic to mafic-intermediate volcanics. Sandstones and argillites of the Rakaia Subterrane (Roser et al. 1995) and inferred Torlesse Terrane derivatives in the Otago Schist (Mortimer & Roser 1992) plot overwhelmingly in the Mature ARC, ACM field (Fig. 5B). Type Caples Group sediments (Fig. 5C) plot mostly in the field of arc derivatives, although they overlap into the Mature ARC, ACM field.

The differences in SiO_2 content between the Chrystalls Beach–Brighton suite and the Caples Group do not appear to be a grain-size or sorting effect. We conclude that, in terms of the parameters plotted, the Chrystalls Beach–Brighton suite is more Torlesse-like than Caples-like, although a minority of type Caples Group rocks, especially in the Mt Campbell Formation, plot in a field of overlap. The Chrystalls Beach–Brighton suite is also more sodic, with lower average K_2O/Na_2O than Torlesse Terrane psammites. In this respect it is more Caples-like than Torlesse-like.

Analyses attributed to the Waipapa Terrane as currently understood, including Hunua and Morrinsville facies, Taupo Volcanic Zone basement, Tongariro Power Development Project, and a few from eastern Marlborough Sounds, are plotted in Fig. 5D. Four high-silica sandstones from

Table 3 Major- and minor-element XRF analyses of metasediments from the Chrystalls Beach–Brighton block[1].

OU number	68557	68558	68559	68560	68561	68562	68563	68564	68565	68566	68567	68568	68569	68570	68571	68572	68573
[2]Other ref. no.	CB-3	CB-9	CB-12	CB-13	CB-14	CB-15	CB-20	BC-5	BC-11	BC-12	BC-13	WB-1	WB-3	WB-10	TM-2	TM-3	TM-7
Sheet	H45	H45	H45	H45	H45	H45	H45	H45	H45	H45	H45	H45	H45	I45	I45	I45	I45
Grid ref.	867423	875428	878430	880432	877429	882436	883438	885439	889444	891447	892448	896453	898454	909465	933553	934554	933558
[3]Lithology	sst	sst	sst	sst	sst	sst	sst	sst	sst	calc. sst	sst	sst	sst	sst	siltst	siltst	siltst
SiO_2	74.40	74.02	69.76	68.28	70.41	68.94	71.46	68.69	70.45	52.38	68.88	71.89	72.14	72.24	65.79	64.60	66.15
TiO_2	0.57	0.60	0.52	0.72	0.62	0.80	0.49	0.58	0.52	0.50	0.52	0.54	0.43	0.38	0.67	0.75	0.83
Al_2O_3	12.98	13.23	15.86	14.63	15.15	14.52	14.23	15.49	14.42	11.70	13.81	14.61	14.66	13.85	15.28	15.94	15.57
Fe_2O_3(total)	3.02	2.42	3.14	4.40	2.92	3.85	3.63	3.60	3.42	6.82	3.61	2.45	2.46	2.97	4.67	4.95	4.83
MnO	0.09	0.22	0.03	0.05	0.04	0.09	0.03	0.02	0.05	0.39	0.04	0.03	0.03	0.05	0.07	0.11	0.08
MgO	0.73	0.35	0.82	0.99	0.59	0.83	1.00	1.19	1.15	1.35	0.86	0.82	0.69	0.79	1.75	1.85	2.06
CaO	0.25	0.43	0.30	0.77	0.58	0.48	0.64	0.45	1.12	9.11	1.51	0.48	0.33	1.03	2.34	1.77	1.42
Na_2O	4.78	6.22	4.05	5.36	5.04	4.87	4.66	4.86	5.17	3.50	4.48	5.43	4.50	4.55	4.50	4.64	5.16
K_2O	1.20	0.63	2.75	1.30	1.80	1.16	2.09	2.57	1.90	2.79	2.96	1.93	2.50	2.92	2.56	2.16	1.87
P_2O_5	0.08	0.07	0.10	0.09	0.14	0.11	0.08	0.08	0.07	0.38	0.10	0.07	0.07	0.07	0.14	0.14	0.13
LOI	2.11	1.87	2.71	2.56	3.57	4.04	1.81	2.14	1.46	10.97	3.24	1.98	2.00	1.31	2.49	2.61	2.22
Total	100.21	100.06	100.04	99.15	100.86	99.69	100.12	99.67	99.73	99.89	100.01	100.23	99.81	100.16	100.26	99.52	100.32
[4]SiO_2(norm)	75.84	75.38	71.67	70.69	72.37	72.08	72.69	70.43	71.69	58.91	71.18	73.17	73.76	73.08	67.29	66.66	67.43
ppm																	
Ga	12	12	18	15	16	15	12	19	19	19	18	15	15	18	19	19	18
Rb	41	21	106	58	52	43	72	88	65	97	104	68	87	97	77	68	64
Sr	121	210	153	189	199	189	155	128	189	191	114	123	120	182	190	243	138
Y	17	21	21	24	27	23	19	18	23	41	29	22	22	24	21	23	18
Zr	155	192	195	164	179	197	160	200	169	157	183	170	180	157	157	174	190
Pb	11	20	19	17	13	14	12	24	17	20	17	15	17	20	16	19	17
Th	6	8	11	6	6	7	10	11	11	13	11	12	12	12	9	8	10
U	1	3	2	2	1	2	3	3	2	6	3	3	3	9	2	2	2
Ni	13	12	13	10	13	13	13	13	11	17	11	10	10	10	18	21	15
Cu	10	4	8	9	7	43	12	7	7	7	9	8	6	5	13	14	9
Zn	53	67	66	62	74	65	59	53	55	69	59	37	50	57	86	79	72
Nb	5	6	7	5	6	6	6	6	7	6	7	5	5	6	5	5	6
Sc	9	8	9	10	11	14	7	10	8	12	9	9	7	6	11	12	11
V	65	50	57	56	81	81	63	77	67	80	69	67	52	45	90	110	100
Cr	21	12	21	13	25	26	20	24	20	20	21	19	17	13	25	28	27
Ba	162	108	451	321	221	256	318	356	319	394	339	253	475	475	493	442	332
La	9	21	16	19	19	16	13	14	19	31	28	22	22	19	13	15	14
Ce	27	45	38	46	43	34	32	35	43	70	62	40	52	39	32	36	31
Pr	3	3	3	5	6	4	4	3	3	10	7	2	5	6	7	4	3
Nd	7	17	14	18	18	15	14	13	7	35	24	15	18	16	16	19	14
As																	

OU number	60992	60993	60994	60995	60996	60998	60997	60999
[2]Other ref. no.	P50663	P50664	P50665	P50674	P50677	P50678	P50679	P50728
Sheet	H45	H45	H45	I45	I45	I45	I45	I44
Grid ref.	785452	897454	897454	943589	983654	028695	033698	064755
[3]Lithology	sst	sst	siltst	sst	sst	sst	sst	sst
SiO_2	69.79	75.27	65.23	73.66	66.19	68.73	66.79	70.43
TiO_2	0.62	0.40	0.71	0.60	0.63	0.63	0.68	0.53
Al_2O_3	14.90	12.42	16.86	13.63	15.30	15.55	15.59	15.24
Fe_2O_3(total)	4.36	1.87	5.45	2.48	3.71	4.18	5.15	3.20
MnO	0.07	0.03	0.06	0.04	0.07	0.04	0.07	0.04
MgO	1.68	0.81	1.85	0.88	1.22	1.42	2.00	1.28
CaO	0.32	1.15	0.39	0.50	1.09	0.90	1.21	0.20
Na_2O	5.21	2.88	2.75	5.07	5.19	3.01	5.14	4.36
K_2O	1.08	2.40	3.74	1.76	1.95	2.69	1.09	2.06
P_2O_5	0.09	0.10	0.13	0.10	0.11	0.19	0.15	0.07
LOI	2.04	2.58	3.12	1.64	4.22	2.61	2.10	2.75
Total	100.16	99.91	100.29	100.36	99.68	99.95	99.97	100.16
[4]SiO_2(norm)	71.13	77.33	67.13	74.62	69.34	70.61	68.24	72.30
ppm								
Ga	18	14	22	14	16	17	16	15
Rb	41	91	148	58	63	106	42	68
Sr	230	151	81	119	67	192	302	56
Y	23	17	30	14	14	15	13	16
Zr	188	201	173	287	468	175	162	173
Pb	15	15	19	13	9	10	14	18
Th	9.9	12	12.8	11	9	13.5	10.4	9.6
U	2.7	2	3.2	2.1	1.7	1.6	1.2	0.8
Ni	13	5	18	4	5	7	16	6
Cu	13	9	24	6	15	13	8	7
Zn	63	30	108	48	54	77	72	60
Nb	6	6	10	7	8	10	6	14
Sc	11	6	14	8	9	10	11	7
V	91	39	109	60	67	109	111	62
Cr	38	17	45	17	16	46	33	17
Ba	226	370	610	296	402	597	368	485
La	15	14	27	14	11	11	13	21
Ce	40	35	65	38	28	29	35	48
Pr								
Nd								
As	7	9	10	3	5	8	2	5

[1]OU68557–68568 and OU60992 = southern unit; OU68569–68573 and OU60993–60999 = northern unit and Taieri Mouth to Brighton; each group in order, SW to NE.
[2]Hada et al. (1988, fig. 1) locality letters and number (new analyses) and GNS (P) numbers, analyses from Palmer et al. (1991).
[3]*Premetamorphic lithology inferred from relict sedimentary textural features and normalised* SiO_2 *content (see text); sst = sandstone, calc = calcareous, siltst = siltstone.*
[4]SiO_2 normalised for LOI-free, 100% total.

McDougalls Quarry, Taupo Volcanic Zone, are indicated separately, as confident terrane correlation in this area is made difficult by lack of continuity of outcrop. The pelite member of a turbidite pair from Marlborough (Mortimer 1993a) has higher SiO_2 than the associated sandstone. This is the opposite of what is normal for more siliceous sandstones, but is not unusual for mafic to low-silica intermediate volcaniclastic sediments. In terms of the parameters plotted, the Waipapa dataset, including the eastern Marlborough Sounds examples, is Caples-like.

Sandstones and siltstones from the Kaihikuan Stage of late Middle to early Late Triassic age (Crampton et al. 1995) in the Murihiku Terrane, Southland, plot in a field (Fig. 5E) within that of the approximately coeval Chrystalls Beach–Brighton suite.

Major element discriminants

In a major-element discriminant diagram (Fig. 6A), the majority of Chrystalls Beach–Brighton metasediments plot in the field P3 of Roser & Korsch (1988) spreading into P2. The P3 field is indicative of felsic plutonic and volcanic provenance, and P2, of intermediate volcanic provenance. Average rhyodacite of Le Maitre (1976) plots in the Chrystalls Beach–Brighton cluster; average dacite and andesite plot in field P2. Sediments of the Torlesse Terrane (Fig. 6B) also plot mostly in P3, spreading marginally into P2. Analyses for the Caples Group from the type area (Fig. 6C) are centred in P2, but four of the five analysed high-SiO_2 examples and a few others spread into P3, and other specimens plot in P1, which is characterised by mafic volcanic detritus. The Waipapa Terrane analyses (Fig. 6D)

Table 4 Major-element XRF analyses of pelites and semipelites from the Chrystalls Beach–Brighton block[1] (Li et al. 2000).

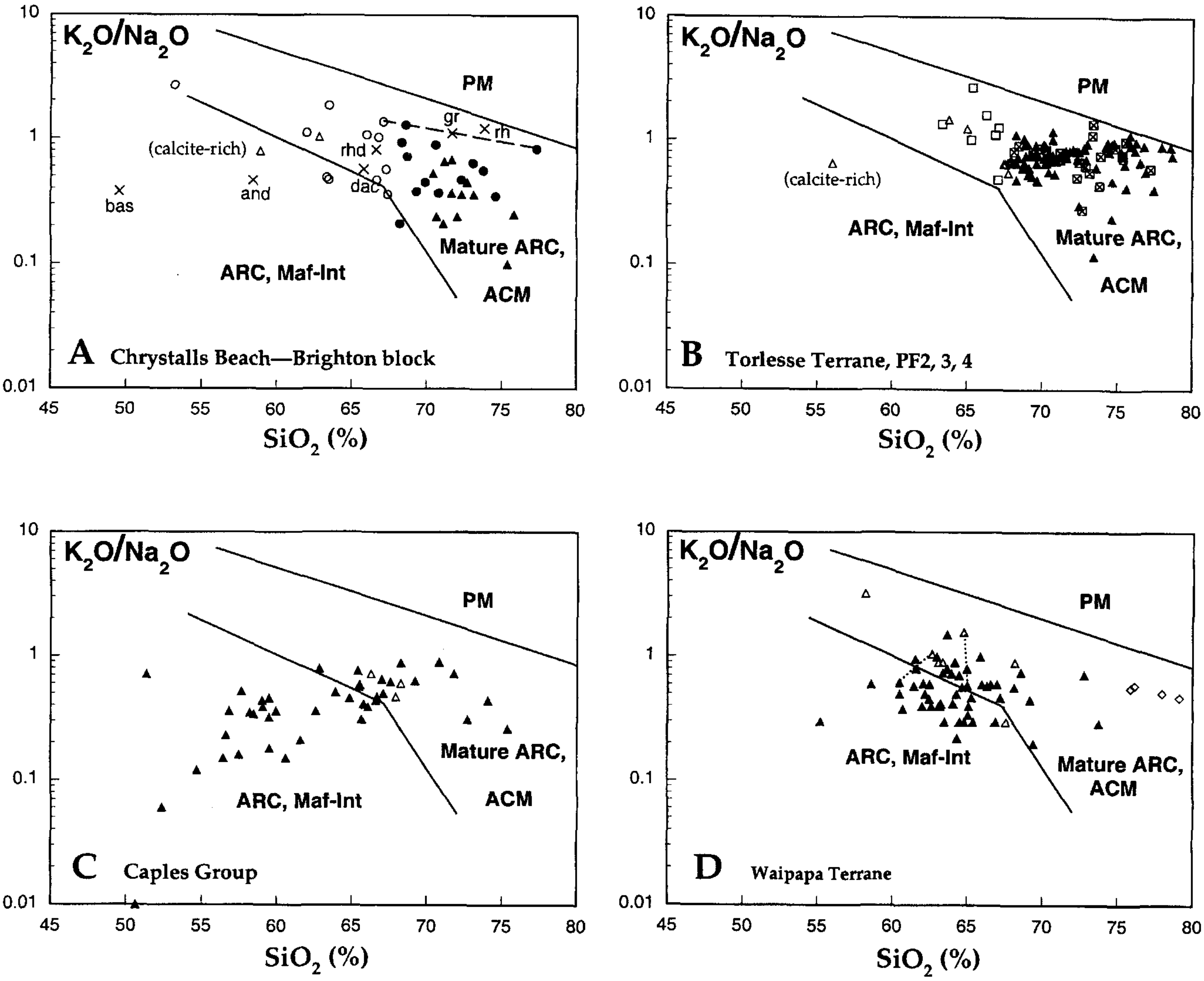
OU number	68554	68556	68546	68553	68545	68548	68544	68551	68552	68550	68543	68549
Li et al. #	D47	D77	D8.2	D42.2	D6	D18.4	D3	D36	D37	D33	D2	D32
Sheet	H45	H45	I45	I45	I45	I45	I45	I45	I45	I45	I45	I45
Grid ref.	884436	834456	918516	933533	942584	955612	987657	970636	971637	997674	997675	034699
[2]Lithology	siltst	siltst/fsst	siltst/fsst	siltst	sandy siltst	siltst?	sandy siltst?					
SiO_2	60.51	65.87	63.57	66.09	66.52	64.75	67.39	58.69	60.39	68.49	60.92	60.97
TiO_2	0.81	0.60	0.76	0.60	0.64	0.68	0.75	0.83	0.94	0.61	0.85	0.61
Al_2O_3	17.85	15.10	17.26	16.63	15.43	16.38	15.81	19.73	19.70	15.42	18.58	17.79
Fe_2O_3(total)	6.02	6.81	4.11	3.68	4.78	4.32	2.91	4.13	3.41	2.86	4.59	5.33
MnO	0.09	0.14	0.06	0.19	0.08	0.07	0.07	0.07	0.07	0.08	0.12	0.10
MgO	2.04	2.22	1.61	1.69	1.59	1.52	1.02	1.82	1.66	1.19	1.69	2.03
CaO	1.17	0.34	1.57	0.36	1.01	1.07	0.84	1.44	0.23	0.77	1.13	1.52
Na_2O	3.57	2.70	3.49	3.05	3.86	3.98	5.19	3.66	3.02	5.23	5.48	5.17
K_2O	3.69	2.50	3.72	3.91	2.79	4.04	2.31	4.06	5.54	1.95	2.71	2.45
P_2O_5	0.53	0.11	0.14	0.12	0.12	0.11	0.12	0.21	0.12	0.11	0.12	0.10
LOI	2.83	3.12	2.64	2.90	2.20	2.44	2.31	5.12	3.78	1.92	2.26	3.33
Total	99.11	99.51	98.93	99.22	99.02	99.36	98.72	99.76	98.86	98.63	98.45	99.40
[3]SiO_2(norm)	62.85	68.34	66.02	68.62	68.70	66.81	69.90	62.01	63.51	70.82	63.33	63.46

[1]Arranged in order, SW to NE; OU68554 and ?OU68556 = southern unit; remainder northern unit and Taieri Mouth to Brighton.
[2]Premetamorphic lithology inferred from relict sedimentary textural features, where preserved; fsst = fine sandstone.
[3]SiO_2 normalised for LOI-free, 100% total.

Table 5 Average major-element chemistry of psammites and semipelites (SiO_2 > 68%) from the Chrystalls Beach–Brighton block (Tables 3 and 4) compared with Permian to Late Triassic petrofacies PF1–PF4, South Island Torlesse Terrane sandstones (Roser et al. 1995); inferred Torlesse Terrane psammites in Otago Schist (Palmer et al. 1991); all type-area Caples Group sandstones (Roser et al. 1993); the three most SiO_2-rich sandstones of Roser et al. (1993) in the Mt Campbell Formation, Caples Group; sandstones attributed to the Waipapa Terrane as for Fig. 5D omitting McDougalls Quarry; and Kaihikuan (Middle Triassic) sandstones of the Southland Syncline, Murihiku Terrane, as for Fig. 5E. All analyses normalised to 100%, LOI-free.

	Chrystalls Beach–Brighton	South I. Torlesse (Perm, Tr) PF1–4	Otago Schist Torlesse Terrane	Caples Group	Most Si-rich in Mt Campbell Formation	Waipapa Terrane	Southland Syncline Murihiku Kaihikuan
n[1]	24[2]	93	24	42	3	49	10
SiO2	71.91	71.87	72.25	64.32	71.78	64.37	70.33
TiO2	0.60	0.50	0.52	0.88	0.58	0.85	0.60
Al2O3	15.12	14.32	14.78	16.17	14.27	16.62	14.93
Fe2O3*	3.47	3.52	3.48	6.76	5.30	6.66	3.49
MnO	0.07	0.06	0.05	0.11	0.08	0.12	0.06
MgO	1.09	1.28	1.21	2.63	1.57	2.40	1.03
CaO	0.72	1.84	1.56	3.07	1.04	2.51	1.60
Na2O	4.80	3.78	3.49	4.05	3.28	4.08	4.55
K2O	2.13	2.72	2.55	1.84	1.99	2.17	3.30
P2O5	0.10	0.11	0.11	0.16	0.12	0.22	0.11
K2O/Na2O	0.44	0.72	0.73	0.45	0.61	0.53	0.73

[1]Number of analyses averaged.
[2]Average omits 68556 (interlaminated siltstone and sandstone).



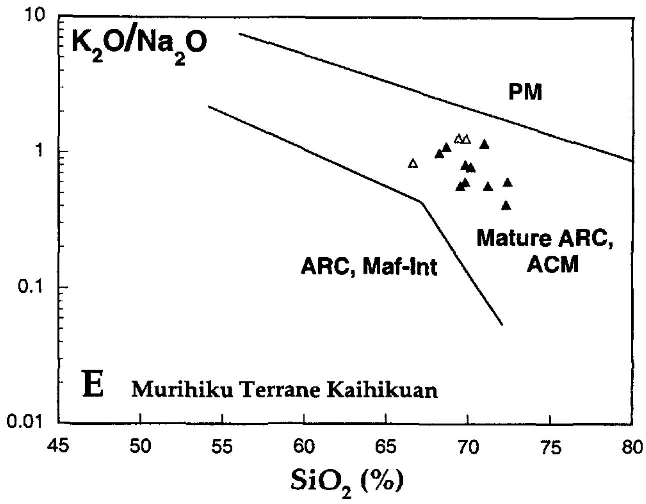
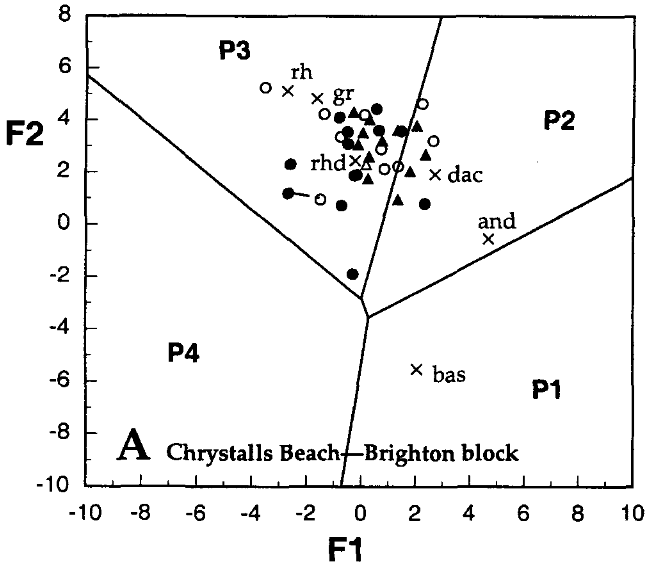
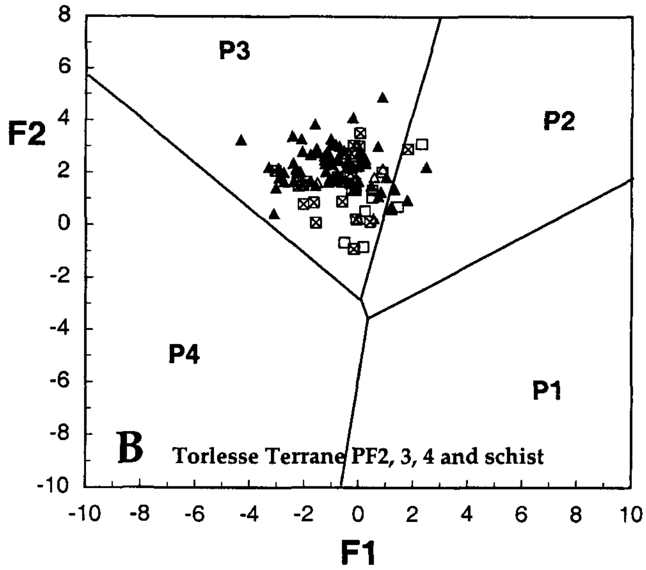
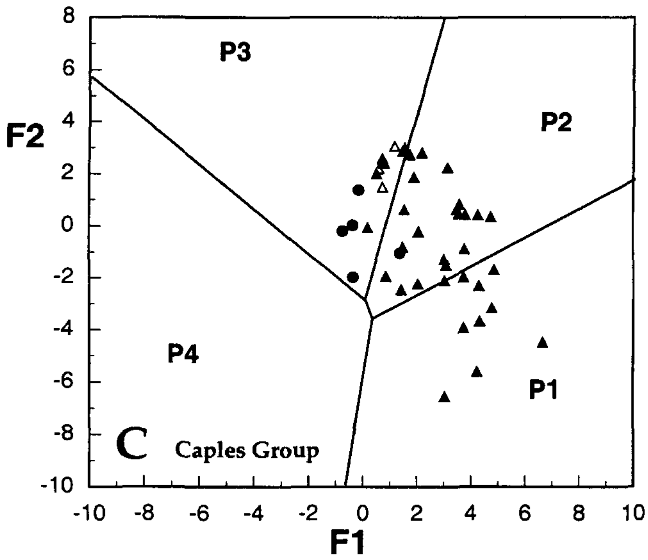


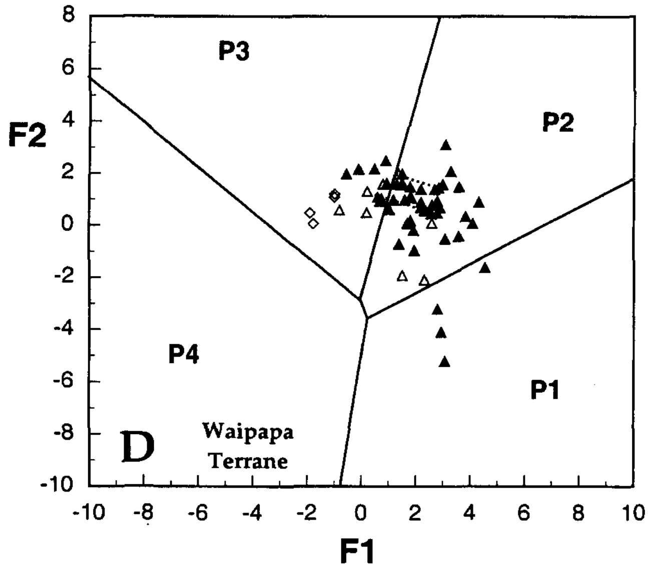
Fig. 5 K_2O/Na_2O wt% versus SiO_2 wt%, normalised to 100%, LOI-free. **A**, Chrystalls Beach–Brighton block, terrigenous metasediments (Tables 1, 2) (Palmer et al. 1991). Crosses = average basalt, andesite, dacite, rhyodacite, rhyolite, granite of Le Maitre (1976); other symbols as in Fig. 4. **B**, Torlesse Terrane terrigenous sediments, South Island, of inferred Middle and Late Triassic age (petrofacies PF2, 3, 4) (Roser et al. 1995) (triangles), and inferred Torlesse derivatives in Otago Schist (Mortimer & Roser 1992) (squares). Filled symbols and squares with crosses = SiO_2 >68%; open triangles and squares = SiO_2 <68%. **C**, Caples Group type-area sandstones (filled triangles) and argillites (open triangles) (Roser et al. 1993). **D**, Waipapa Terrane sandstones (filled triangles) and argillites (open triangles): Whangarei, Hunua facies (Elliot 1967); Morrinsville facies localities (Reid 1982); Whangarei and Kawau Island, Hunua facies (Roser 1983); Whakapapa, Tongariro Power Development projects (Beetham & Watters 1985; Graham 1985); Marlborough Sounds (two psammite-argillite pairs) (Mortimer 1993); Manaia Hill Group and Taupo Volcanic Zone (Palmer et al. 1995). Diamonds = high-SiO_2 sandstones, McDougalls Quarry, TVZ (Palmer et al. 1995). **E**, Murihiku Terrane Kaihikuan (late Middle to early Late Triassic), Southland Syncline non-tuffaceous sandstones (filled triangles) and siltstones (open triangles) (B. P. Roser & D. S. Coombs unpubl.).

Fields for sandstone-mudstone suites reflecting provenance and tectonic setting according to Roser & Korsch (1986) are relabelled as follows: PM = passive continental margins; Mature ARC, ACM = mature volcanic arcs and active continental margins; ARC, Maf-Int = immature volcanic arcs and other mafic to intermediate volcanics.









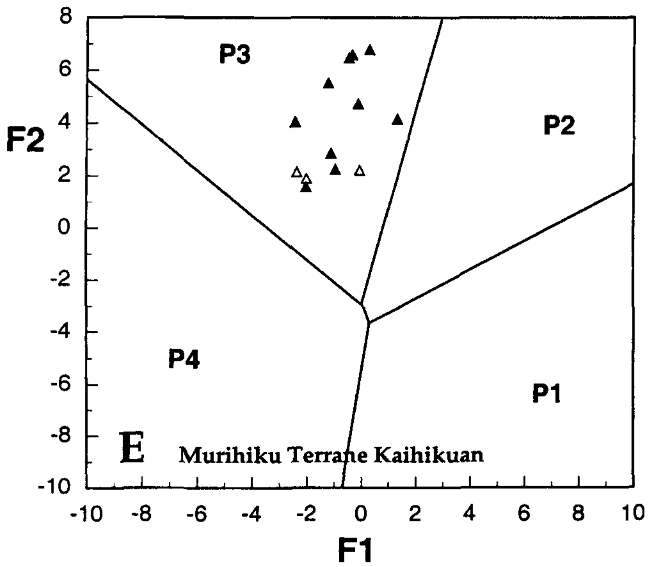


Fig. 6 Major-element discriminant diagram of Roser & Korsch (1988). **A–E**, Data sources and symbols as for Fig. 5 except for filled circles in Fig. 6C for Caples Group sandstones with SiO_2 >70%. $F1 = -1.773TiO_2 + 0.607Al_2O_3 + 0.760Fe_2O_3T - 1.500MgO + 0.616CaO + 0.509Na_2O - 1.224K_2O - 9.09$, and $F2 = 0.445TiO_2 + 0.070Al_2O_3 - 0.250Fe_2O_3T - 1.142MgO + 0.438CaO + 1.475Na_2O + 1.426K_2O - 6.861$. For fields P1, P2, P3, P4, see text.

occupy a field virtually indistinguishable from the Caples, with the high-SiO_2 McDougalls Quarry specimens spreading furthest into P3.

In terms of the discriminants portrayed, the Chrystalls Beach–Brighton suite is clearly more Torlesse-like than Caples-like. However, the Chrystalls Beach–Brighton suite, both psammitic and pelitic, extends to higher F2 values than Torlesse Terrane rocks. This results from the tendency for higher Na_2O, in spite of, on average, lower CaO and K_2O, and suggests the presence of relatively sodic granitoids, rhyodacites, or rhyolites in the Chrystalls Beach–Brighton source area. Other major element contents of the average Chrystalls Beach–Brighton and Torlesse derivatives are closely comparable (Table 5).

The corresponding plot for Kaihikuan Stage rocks of the Murihiku Terrane (Fig. 6E) is similar to that for the Chrystalls Beach–Brighton suite, although with a tendency to even higher F2 values.

Minor element discriminants

Mortimer & Roser (1992) and Roser et al. (1993) developed minor-element ratio diagrams that sharply discriminate between previously recognised Torlesse Terrane and Caples Terrane rocks. For example, of 73 points for Caples Terrane rocks in a plot of Ce/V versus La/Y, only four fell on the "Torlesse" side of the line separating most Caples and Torlesse analyses, and of 224 plotted for the Torlesse Terrane, only six plotted on the "Caples" side (Mortimer & Roser 1992). In contrast, in corresponding diagrams (Fig. 7), data points for the Chrystalls Beach–Brighton suite spread right across these boundaries, although centred on the "Torlesse" side. It can be shown that for each of the three diagrams, points representing two of the most SiO_2-rich, "Torlesse"-like, Mt Campbell sandstones plot in the Caples Terrane field and one in the field of Caples/Torlesse overlap. The Torlesse-like features of the Chrystalls Beach–Brighton suite in Fig. 7 thus cannot be ascribed to the characteristics of Mt Campbell or other known Caples Group formations. The Chrystalls Beach–Brighton data points occupy scatter fields of their own, intermediate in position to those of the "Torlesse" and "Caples" Terranes, and overlapping both.

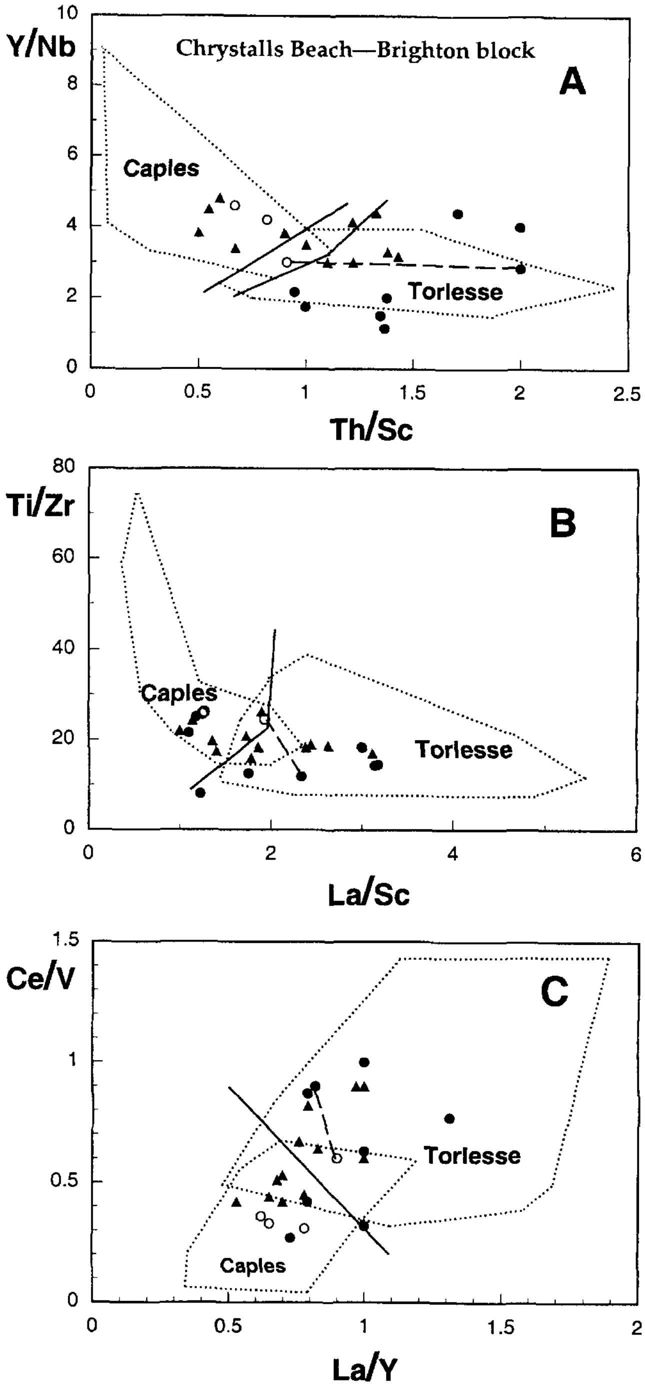


Fig. 7 Minor- and trace-element ratio diagrams, Chrystalls Beach–Brighton block. Data from Tables 1 and 2, and Palmer et al. (1991); symbols as in Fig. 4. Fields of Caples Terrane and Torlesse Terrane rocks (dotted boundaries) with discriminant lines (full lines) separating most data points after Roser & Cooper (1990), Mortimer & Roser (1992), and Roser et al. (1993) (see text). Symbols as in Fig. 4; dashed lines join psammite-pelite pairs.

DISCUSSION

Area of problematic affinity

The Chrystalls Beach–Brighton block (Fig. 1) provides a well-exposed section through the wedge-shaped area of problematic affinity postulated by Mortimer & Roser (1992). They suggested that this may represent either a slice of allochthonous Torlesse Terrane or an autochthonous Torlesse-like sedimentary facies within the Caples Terrane. They favoured the latter in view of: (1) the lack of known melanges on the fringes of the wedge, where they might be expected for an allochthonous hypothesis; (2) essential parallelism between the (inferred) Torlesse/Caples Terrane boundary, dominant schistosity, and a position between the IIIA-IIIB and IIIB-IV isotects throughout 380 km of outcrop; and (3) a possible eastwards increase in abundance of Gondwana-derived quartzose sandstones in the Caples Terrane. Mortimer & Roser (1992) sketched other poorly defined areas of uncertain affinity near the inferred Torlesse/Caples Terrane boundary.

Petrography and geochemistry in relation to Torlesse and Caples Terranes

Angularity of sand grains and abundance of lithic fragments show that the Chrystalls Beach–Brighton psammites, like those of the Caples Group in its type area, are not recycled. Recycling was also limited in the Torlesse Terrane

(MacKinnon 1983), but the Chrystalls Beach–Brighton and type Caples Group rocks are rich in volcanic lithics in contrast to those of the Torlesse Terrane, which are feldsarenites.

We agree with Mortimer & Roser (1992) that the sedimentary geochemistry of the Chrystalls Beach–Brighton suite is diagnostic of neither Caples nor Torlesse Terranes in terms of proposed discriminants. The suite is characterised by psammites that are different both petrographically and geochemically from the psammites of mafic to intermediate arc-volcanic provenance that predominate in the type area of the Caples Group; they are substantially higher in SiO_2 and contain much felsic volcanic detritus. In their silica-rich nature, they show greater similarity to Torlesse Terrane rocks, but they tend to have higher values of the F2 discriminant, reflecting higher Na_2O. In plots of minor-element ratios, the Chrystalls Beach–Brighton suite occupies fields intermediate in position to those of the Torlesse Terrane and of the Caples Terrane as hitherto understood, but straddling both.

Aspiring lithologic association

Relatively abundant manganiferous and other cherts, metabasites, and phyllites in the Chrystalls Beach–Brighton block invite comparison with the Aspiring lithologic association, although all these lithologies occur locally in the Torlesse and Caples Terranes. Psammites of the Aspiring lithologic association have typical Torlesse geochemical characteristics (Mortimer & Roser 1992). With one exception, analyses of 16 psammites and 9 pelites ascribed to the Aspiring lithologic association by Palmer et al. (1991) plot within or very close to the fields for accepted Torlesse rocks as shown in Fig. 4–6, and projection points do not spread across the Torlesse/Caples discriminant boundaries in Fig. 7. There is thus no case for correlating the Chrystalls Beach–Brighton block with the Aspiring lithologic association on grounds of metasediment geochemistry.

The Lower Clutha section

Psammites in the Lower Clutha River section (Becker 1973) on the south and west side of the "anomalous" wedge are shown by Roser et al. (1993) to be geochemically indistinguishable from those of the Caples Group 100 km farther west. Insofar as this section is concerned, there is thus no indication of an eastwards increase in quartz content as suggested by Mortimer & Roser (1992). As in Caples sediments other than the most SiO_2-rich in the type area, the Lower Clutha psammites commonly contain detrital augite, which is unknown in the Chrystalls Beach Complex. There are no reported occurrences in the Lower Clutha section of the melange and volcanic lithologies that are a feature of the Chrystalls Beach Complex. We agree that the Lower Clutha and Chrystalls Beach suites are distinct, and that the former can be regarded as part of the Caples Terrane.

Nature of source region in relation to those of Torlesse and Caples Terranes

From the petrographic and geochemical evidence, we conclude that the Chrystalls Beach–Brighton psammites were derived from a region of felsic volcanism. Relatively fine grained, shallow-level, I-type granitoids were also exposed and provided a subordinate but variable contribution to the detritus. The psammites appear to contain a higher proportion of felsic volcanic detritus than those of the Torlesse Terrane, and Na_2O/K_2O ratios are higher. In contrast, volcanism in the source area for the Caples Group was largely mafic to intermediate, although it extended into the felsic siliceous range. Granitoid clasts are rare in Caples Group formations in their type area (Turnbull 1979b).

Faunal considerations

The new radiolarian data (Ito et al. 2000) establish a Middle Triassic age for pelagic sediments in the less-metamorphosed part of the Chrystalls Beach Complex. Tube fossils occur in turbidites, *Torlessia* sp. in the southern unit, and *Titahia corrugata* Webby in the northern unit. These forms are widespread in the Torlesse Terrane, especially *Torlessia* sp., which occurs in beds of late Middle to early Late Triassic age. They are unknown in the Caples Group, which contains generally similar sedimentary facies but in which the only well-dated fossils appear to be reworked and of Permian age. The tube fossils do not appear to have been reported from the Waipapa Terrane.

Middle Triassic radiolarians of non-Tethyan, suspected high-latitude affinities, including the genus *Glomeropyle* Aita & Bragin, occur in the southern unit of the Chrystalls Beach Complex together with species well known from Tethyan regions. A similar fauna occurs at the Mahinepua peninsula, east of Wangamoa, Northland, in the Waipapa Terrane (Aita & Bragin 1999), but the suspected high-latitude forms are unknown, so far, in the northern unit of the Chrystalls Beach Complex.

$^{87}Sr/^{86}Sr$

Adams & Graham (1997) found that Otago schists from north of Dunedin have $^{87}Sr/^{86}Sr$ ratios at the date of metamorphism, 0.7064–0.7092, similar to those of the Rakaia Subterrane of the Torlesse. They attributed this to a granitoid source dominated by I-types, although MacKinnon (1983) reported siliceous volcanics among lithic clasts in Torlesse Terrane sandstones of Triassic age; siliceous volcanism with a continental basement may thus have been a major control of Torlesse geochemistry. Adams & Graham (1997) also showed that strontium isotopes for six localities extending from Bull Creek to Brighton and Fairfield, together with another locality near the western extremity of the wedge-shaped problematical area in Fig. 1, gave initial $^{87}Sr/^{86}Sr$ = 0.7052–0.7064. On a diagram of strontium isotope ratio versus metamorphic age, the data plotted with a linear trend in a distinctive field separate from that of Torlesse Terrane rocks. The ratios for two suites of intermediate arc-volcanic provenance from near Balclutha regarded as characteristic of Caples rocks are still lower, in the range 0.7035–0.7044 (Graham & Mortimer 1992). Adams & Graham (1997) suggested that the differences between accepted Caples-type sediments and those of problematic affinity could result from sedimentation in a basin receiving both mafic to intermediate and silicic to intermediate volcaniclastic materials, separated in space or in time.

Relationship to the Waipapa Terrane

Adams et al. (1999) showed that certain rocks from the younger Torlesse Terrane (Pahau Subterrane) of Wellington, the Kaimanawa Ranges, eastern Marlborough schists, and rocks of the central North Island attributed by them to the Waipapa Terrane, plot on the strontium isotope ratio versus metamorphic age diagram in a band of fields having a generally similar trend and overlapping that of the "uncertain" southeast Otago rocks. They suggested the possibility of a Waipapa Terrane correlation for the Otago Schist of uncertain affinity.

As shown above, average major element geochemistry of rocks attributed to the Waipapa Terrane, mostly of the Hunua and Morrinsville facies (e.g., Spörli 1978), is similar to that of the Caples Terrane as known in its type area. Both suites are characterised by mafic to intermediate volcanic detritus, and SiO_2 contents are much lower than those of psammites in the Chrystalls Beach–Brighton block. Both the Caples and the Waipapa suites include a small minority of sandstones with higher SiO_2 contents comparable to those of the Chrystalls Beach–Brighton suite, although not necessarily conforming in alkali-element and minor-element ratios. Correlation of the Chrystalls Beach–Brighton block with the Waipapa Terrane as usually understood, or with the Caples Terrane as known in its type area, is rejected on geochemical and petrographic grounds. It is outside the scope of the present contribution to explore the status of areas of high-silica sandstones that have been attributed to a composite Waipapa Terrane and which might be affiliated with the Chrystalls Beach–Brighton block. Black (1994) has concluded that the names Caples, Older Torlesse (Rakaia Subterrane), and Younger Torlesse (Pahau Subterrane) should be used for rocks attributed to Waipapa Terrane.

Coherence within the Chrystalls Beach–Brighton block

Petrographic and geochemical coherence for psammitic and pelitic sediments throughout the Chrystalls Beach–Brighton block is shown by the modal analyses, averaged chemical analyses, and a similar scatter of points (Fig. 3–6) for the southern and northern units and for localities north and south of Taieri Mouth. Variations are no more than is to be expected within different formations in any terrane. This conclusion is strongly reinforced by the strontium isotope pattern. We detect no geochemical evidence for a terrane boundary within the block.

Relationship to Middle Triassic of the Murihiku Terrane

The Early to early Middle Triassic North Range Group of the Murihiku Terrane in the Southland Syncline (Fig. 1) consists of detritus of essentially basaltic andesite composition (Boles 1974; Frost & Coombs 1989). In contrast, the Middle Triassic to Late Triassic Taringatura Group is dominated by felsic volcanic detritus, although with variable andesitic input. Murihiku Terrane rocks of the Kaihikuan Stage of late Middle to early Late Triassic age are of approximately the same age as turbidites in the southern part of the Chrystalls Beach Complex, but are of shallower water facies.

Available data for the Murihiku Kaihikuan plot in similar fields to the Chrystalls Beach–Brighton suite on K_2O/Na_2O versus SiO_2 and major-element discriminant diagrams (Fig. 5, 6), although with higher average K_2O (Table 5), K_2O/Na_2O, and F2 values. Minor-element ratio diagrams (Fig. 8) are similar to those for the Chrystalls Beach–Brighton block, data points straddling beyond the field of Torlesse Terrane, but with less scatter, an effect that may result from the smaller dataset.

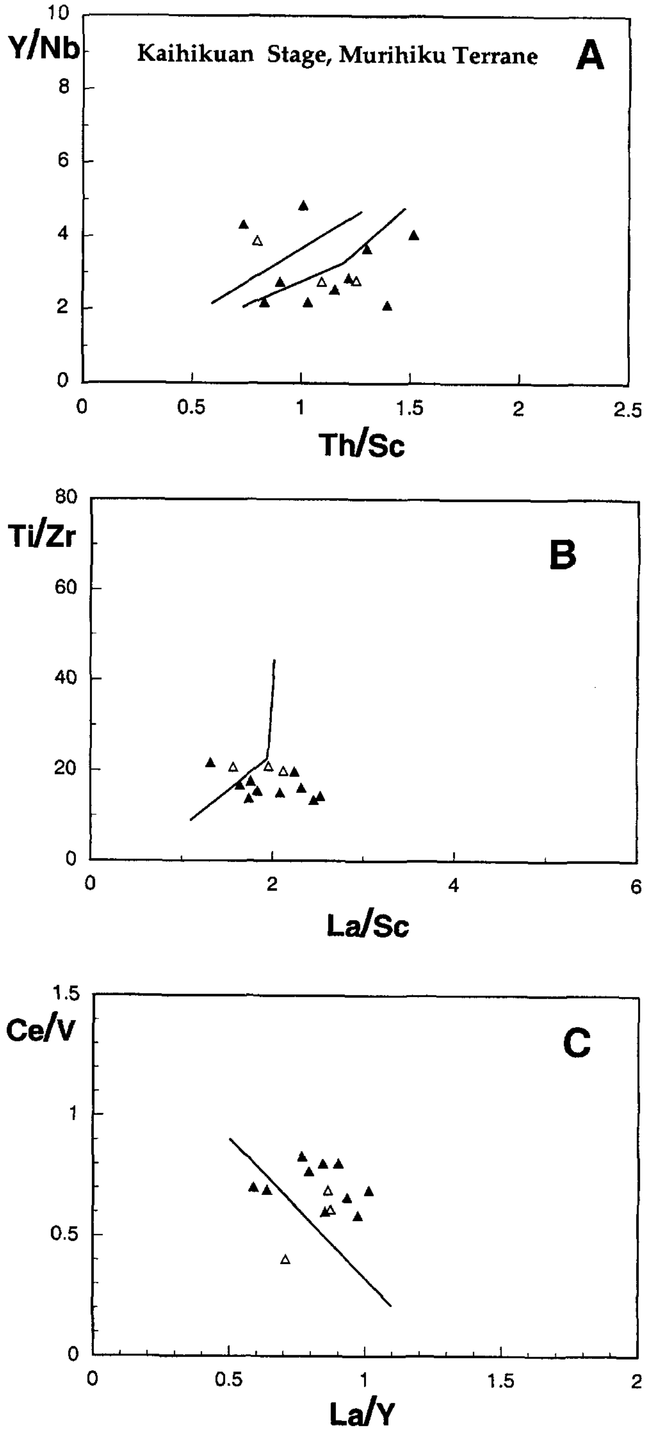


Fig. 8 Minor- and trace-element ratio diagrams for the Kaihikuan Stage, Murihiku Terrane, Southland Syncline (B. P. Roser & D. S. Coombs unpubl. data). Caples–Torlesse discriminant lines as in Fig. 7.

Both the Chrystalls Beach–Brighton suite and the Murihiku Terrane Kaihikuan Stage sediments are derived from source regions of felsic volcanism. Comparison of Fig. 8 with Fig. 7 suggests their closer similarity to each other than to Torlesse sandstones. The Murihiku Kaihikuan is of relatively shallow water facies deposited proximal to a volcanic arc with continental basement, and the Chrystalls

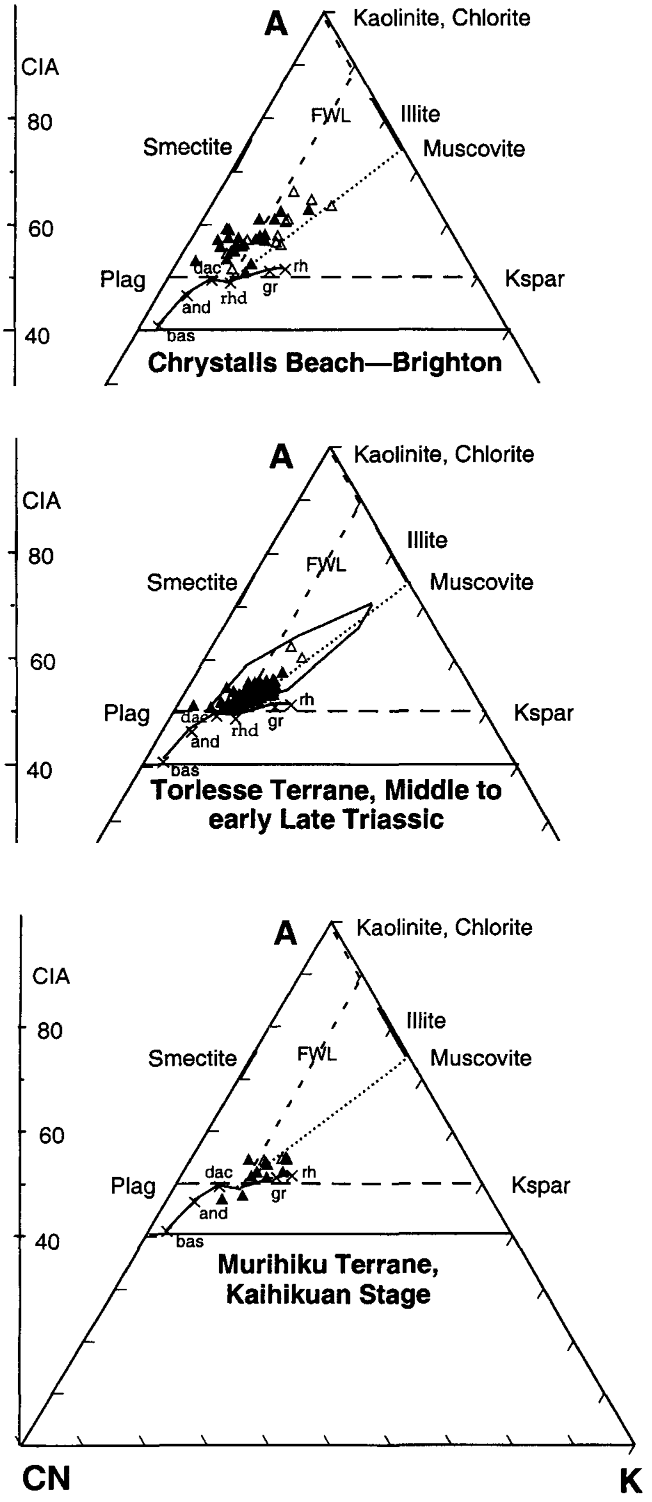


Fig. 9 A-CN-K diagrams (molecular proportions) where A = Al_2O_3, CN = (silicate CaO + Na_2O; CaO corrected for P_2O_5 as apatite, but not for carbonates), K = K_2O. *Top*: Chrystalls Beach–Brighton psammites and pelites. *Middle*: Torlesse Terrane petrofacies PF2 and 3 (Middle to early Late Triassic, data of Roser et. al 1995) with envelope that encompasses all Rakaia Subterrane Torlesse data from South Island and Wellington, including argillites but excluding four outliers. *Bottom*: Murihiku Terrane, Kaihikuan Stage. Filled symbols = psammites; open symbols = pelites. Average igneous rock types according to Le Maitre (1976). CIA = chemical index of alteration; FWL = feldspar weathering line (Nesbitt & Young 1984). The dotted line links a hypothetical rhyodacite source material to muscovite (see text).

Beach–Brighton suite is interpreted as being of trench slope or trench floor deposition. Could they be derived from the same arc source?

Relationships are further examined using A-CN-K plots (Fig. 9). Two Murihiku Kaihikuan rocks that plot below the plagioclase–potassium feldspar join contain minor introduced calcite cement. A predicted feldspar weathering line, FWL (Nesbitt & Young 1984), is drawn parallel to the A-CN join through average rhyodacite, which is taken to approximate an average sediment source composition. Sorting of clay minerals from residual feldspar at any point on such a line would result in clay-rich compositions approaching apex A and sand compositions approaching the feldspar join. A dotted line joins the rhyodacite point and muscovite, which is a likely end-product, following illite, of syn- and post-sedimentation K-metasomatism of clay minerals (Fedo et al. 1995). Some of the spread of points could result from weathering of source materials of variable composition, such as is to be expected in limited catchments in regions of active volcanism. Evidence for this in the Kaihikuan Stage of the Murihiku Terrane is provided by the presence of andesitic as well as felsic tuffs (Coombs et al. 1976a). Not only do Middle to early Late Triassic Torlesse Terrane sediments of the South Island plot very close to the rhyodacite–muscovite join (Fig. 9), so do all Permian–Jurassic Rakaia Subterrane sandstones and argillites of both North and South Islands (Roser & Korsch 1999). These extend well towards the muscovite projection point and exhibit marked fractionation between sand and mud.

In Fig. 9, the Chrystalls Beach–Brighton suite plots to the left of coeval Torlesse Terrane and Murihiku Terrane suites, reflecting higher Na_2O/K_2O ratios. The highest chemical index of alteration (CIA) (Nesbitt & Young 1984; Fedo et al. 1995) for Chrystalls Beach–Brighton psammites is 63. This is well within the range for modern sands derived from the Sierra Nevada batholith (Nesbitt et al. 1997), as are the Torlesse and Murihiku suites.

In spite of being on average more potassic, some of the Murihiku Kaihikuan sandstones contain both albitised plagioclase clasts and authigenic albite cement, the cement suggesting redistribution of Na_2O. Mobility of Na, K, and Ca in Murihiku sediments can be extreme, especially in tuffaceous rocks which have not been plotted in the present study (B.P.R. & D.S.C. unpubl. data). In contrast, average Chrystalls Beach–Brighton metasediments from north of Taieri Mouth, where all original potassic feldspar has disappeared through metamorphism, are not significantly different in K_2O or Na_2O from those south of Taieri Mouth in which potassic feldspar is preserved. The possibility of Na and/or K metasomatism in the various suites remains a problem, but it seems likely that the different scatter patterns for the three suites in Fig. 9 reflect differences in the sources—that of the Chrystalls Beach–Brighton suite possibly having an intrinsically higher Na_2O/K_2O ratio and a larger amount of less-felsic material.

The Chrystalls Beach–Brighton pattern is relatively diffuse. It falls towards the left in the A-CN-K triangle and shows a lack of fractionation between sands and silts as shown by the similar spread of sand and silt symbols. This pattern contrasts with a tightly constrained trend toward muscovite with marked sand-mud fractionation for the Rakaia Torlesse Subterrane, a trend shown both by the data points plotted for specimens coeval with the Chrystalls Beach Complex and by an envelope that encompasses the full range, Permian–Jurassic. This provides further evidence against a Torlesse affiliation for the Chrystalls Beach–Brighton block.

CONCLUSIONS

1. The Chrystalls Beach Complex psammites are of different petrofacies from those hitherto described from Torlesse, Caples, and Murihiku Terranes.
2. On the basis of age, petrographic content, and geochemical data, the Chrystalls Beach–Brighton metasediments cannot be correlated with known formations of the Caples Group as developed in the type area. However, the Caples Terrane as preserved in the type area for the Caples Group can be no more than a faulted fragment of a former larger entity. The Chrystalls Beach–Brighton block could be part of a former greater Caples Terrane that included beds younger than type Caples Group rocks, not now represented in the type Caples area. With advancing maturity in Middle Triassic times, volcanism in the arc that is believed to have been the source region for Caples Terrane sediments may have proceeded to a more consistently siliceous, dacitic to rhyolitic composition. Alternatively, a separate volcanic source may have become involved. This would account for observed geochemical features, including initial $^{87}Sr/^{86}Sr$, which is higher than that of type Caples Group rocks, yet lower than that of Torlesse rocks.
3. Permian rocks have been attributed to "Waipapa" Terrane in northern Northland (Black 1994), but most recognised Waipapa Terrane is of Jurassic age, much younger than the apparent age of Caples Group as known in its type area. Psammites of both are closely similar in major element geochemistry. This is consistent with, but does not prove, the possibility that they are parts of the same terrane. Geochemical and petrographic data show that psammites of the Chrystalls Beach–Brighton block are far more felsic than those of the main areas of Waipapa Terrane as usually understood. The suggestion that the Chrystalls Beach–Brighton area of uncertain terrane affinity may correlate with the Waipapa Terrane of the central North Island requires further study of the terrane affinity of the North Island rocks concerned as well as of Caples–Waipapa relationships in general.
4. The Chrystalls Beach Complex is of the same age as parts of the Torlesse Terrane and shares with it the presence of *Torlessia* and *Titahia* tube fossils. It shows greater geochemical and petrographic similarity to Torlesse than to known Caples Terrane rocks, but it also shows significant and consistent differences. The case for linking the block with the Torlesse Terrane, or with the Aspiring lithological association, is further weakened by its greater geochemical similarities to isochronous Murihiku Terrane arc-derived sediments. The suggestion that the Chrystalls Beach–Brighton block may be a tectonically introduced and atypical part of the Torlesse Terrane is unlikely to be correct.
5. The Chrystalls Beach–Brighton block may be a separate terrane fragment, tectonically bounded, and with a different history from both the Caples and the Torlesse Terranes. The lack of a recognised tectonic boundary could be ascribed to lack of exposure and metamorphic overprint.
6. Sedimentation of the Chrystalls Beach Complex took place in deep water in a trench slope basin or trench floor in Middle to early Late Triassic time. The psammites are derived from a region of felsic volcanism in which shallow-level I-type granitoids were also exposed. Coeval Murihiku sedimentation took place in much shallower water, proximal to a volcanic arc which was built on continental basement and was dominated at the time by active felsic volcanism. Source regions for the two suites are conceivably segments of the same arc at greater or less distance from the present sites, as a result of strike-slip movements, or they may be segments of separate arcs festooning the Triassic Gondwana border. Long-distance axial transport of turbidites may also have been involved. Available geochemical and petrographic data tend not to support identical source regions, but are equivocal in interpretation.
7. In the absence of more definitive evidence, the Chrystalls Beach–Brighton block and the remainder of the "anomalous" area of which it is a part may continue to be regarded as part of an extended Caples Terrane, having a wider range of age and other characteristics than previously accepted. However, the alternative possibility that it is a separate terrane fragment cannot be dismissed on present evidence.

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