Geological Society of America Bulletin

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THOMAS C. MACKINNON

*Geological Society of America Bulletin* 1983;94, no. 8;967-985
doi: 10.1130/0016-7606(1983)94<967:OOTTTA>2.0.CO;2



**Notes**

# Origin of the Torlesse terrane and coeval rocks, South Island, New Zealand

THOMAS C. MACKINNON* *University of Otago, Box 56, Dunedin, New Zealand*

## ABSTRACT

The Carboniferous to Lower Cretaceous Torlesse terrane and Haast Schist derivatives constitute the major part of the complexly deformed facies of the Eastern Province of New Zealand. Strata consist mainly of quartzofeldspathic graywacke and mudstone, intercalated with minor but widely distributed conglomerate, and volcanics with associated chert and limestone. Clastic rocks were deposited largely by sediment gravity-flow mechanisms in a deep-marine environment. Also present are a few highly fossiliferous shallow-marine and terrestrial deposits of limited areal extent, which rest unconformably on or in fault contact with Torlesse flysch. Several periods of deformation are recognized and mélange is present on both local and regional scales. Metamorphism ranges from zeolite to greenschist facies. The bulk of the rocks fall into five areally extensive and mutually exclusive fossil zones of the following ages: Permian (*Atomodesma*), Middle Triassic, early Late Triassic (?) (*Torlessia*), Late Triassic (*Monotis*), and Late Jurassic–Early Cretaceous. Contacts between major fossil zones are mainly tectonic. Petrographic analysis permits subdivision of Torlesse sandstones into five major petrofacies that correspond in age to the five major fossil zones. The sandstone petrofacies (mainly arkosic), together with the composition of conglomerate clasts (mainly indurated Torlesse rocks), indicate that the source terrane was a continental volcano-plutonic arc, probably part of Gondwanaland, coupled with autocannibalistic reworking of older uplifted Torlesse rocks.

In contrast to the quartzofeldspathic nature of the Torlesse, coeval sedimentary rocks of the Eastern Province are volcanogenic. They are thought to represent related forearc-basin (Maitai-Murihiku terranes) and trench-complex (Caples terrane) deposits derived from a volcanic island arc (Brook Street terrane). Three petrofacies are established for Maitai-Murihiku and Caples sandstones. The petrofacies indicate a common, evolving, immature to submature volcanic island arc source for these terranes.

A reconstruction of New Zealand's Eastern and Western Provinces is proposed. In Permian and Triassic times, the Torlesse was deposited in trench, slope, or borderland basins along a trench-transform margin fronting a continental volcano-plutonic arc source (Western Province–Gondwanaland). Deposition was spasmodic but voluminous and was accompanied by concurrent deformation and accretion resulting in parallel belts of Torlesse rock younging outward from the Gondwanaland margin. At the same time, the Brook Street terrane volcanic arc and associated terranes were forming to the west of the Torlesse site, separated from Gondwanaland by a marginal sea. In latest Triassic or Early Jurassic times, the Torlesse was rafted into the volcanic arc system via transform faulting approximately parallel to the Gondwana margin. The collision event resulted in tectonic thickening of Torlesse and Caples rocks at the plate interface and metamorphism to Haast Schist. The source was then dominated by older, partly metamorphosed Torlesse terrane, newly uplifted along the collision front. Closing of the marginal sea behind the Brook Street terrane in Late Jurassic–Early Cretaceous times resulted in juxtapositioning with the Western Province (Gondwanaland) along the Median Tectonic Line.

## INTRODUCTION

The Torlesse terrane is part of the largely Mesozoic, pervasively deformed, circum-Pacific graywacke suite that is commonly inferred to represent accreted subduction complexes. Similar well-studied examples include the Franciscan Complex of California (Blake and Jones, 1974), the Uyak Complex and related Cretaceous strata in Alaska (J. C. Moore, 1972; Connelly, 1978), and the Shimanto terrane in Japan (Imai and others, 1971). The Torlesse has been compared to the Franciscan by many authors (Hatherton, 1969; Dickinson, 1971; Landis and Bishop, 1972; Blake and others, 1974).

The origin of the Torlesse has been the subject of much debate in recent years. The major difficulties center on the source of Torlesse detritus, conflicting interpretations of Torlesse depositional environments, and problems in reconciling the origin of the quartzofeldspathic Torlesse with that of coeval volcanogenic rocks in New Zealand. Lack of consensus has recently led to a spate of conflicting interpretations (compare Howell, 1980; Kamp, 1980; Bradshaw and others, 1980; Crook and Feary, in press).

One cause for confusion is the lack of an up-to-date geologic summary of the Torlesse and related rocks on the South Island, where these rocks are best-exposed. Probably the most thorough previous general summary of the Torlesse is given by Landis and Bishop (1972); however, new data have made many of their conclusions obsolete (compare Landis, *in* Blake and others, 1974). Subsequent summaries of the Torlesse have been brief (Coombs and others, 1976; Carter and others, 1978), although somewhat more detailed summaries of Torlesse structure (Sporli, 1979) and depositional environments (Andrews and others,

*Present address: Chevron Oil Field Research Company, P.O. Box 446, La Habra, California 90631.

Geological Society of America Bulletin, v. 94, p. 967–985, 11 figs., 2 tables, August 1983.

1976; Howell, 1981) have been presented. Sporli (1978) summarized the geology of Torlesse and coeval rocks on the North Island.

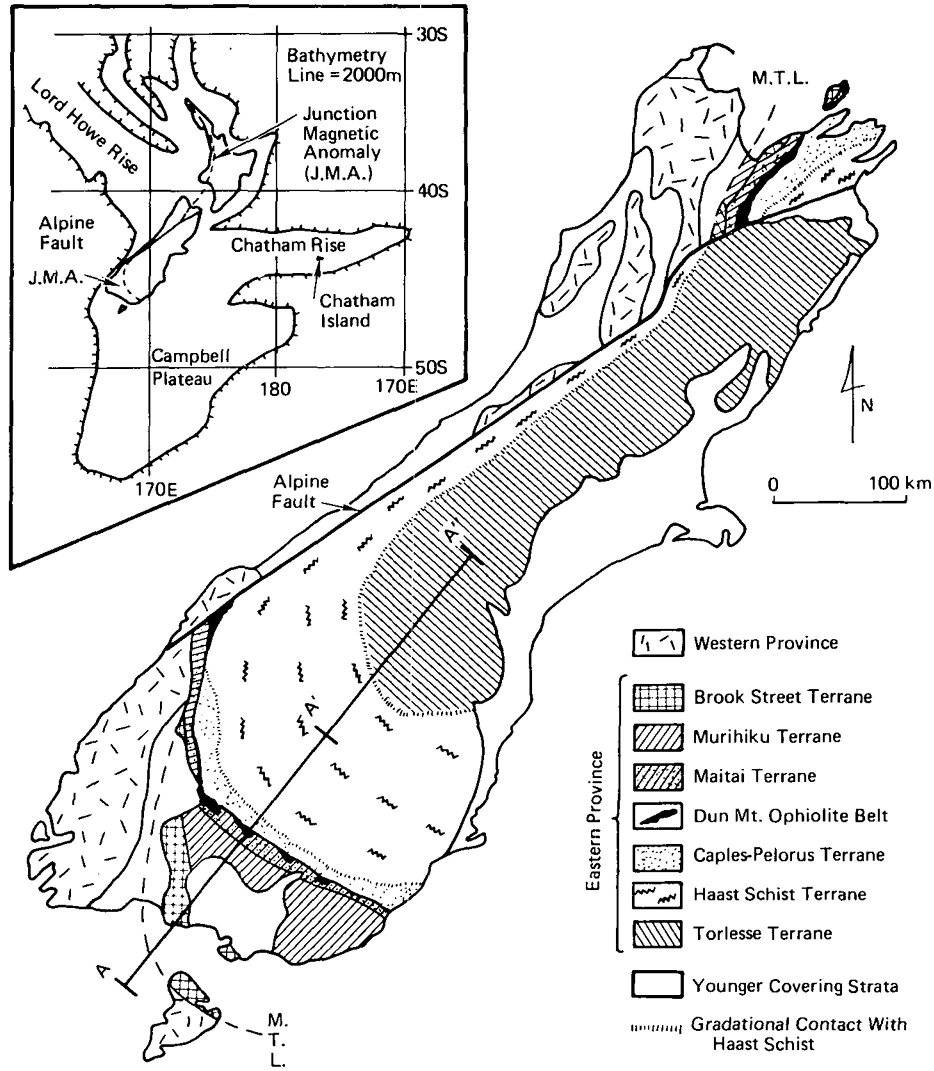
In this paper, I summarize and interpret Torlesse geology on the South Island, briefly describe coeval volcanogenic terranes, and propose a reconstruction of late Paleozoic–Mesozoic New Zealand.

## REGIONAL GEOLOGIC SETTING

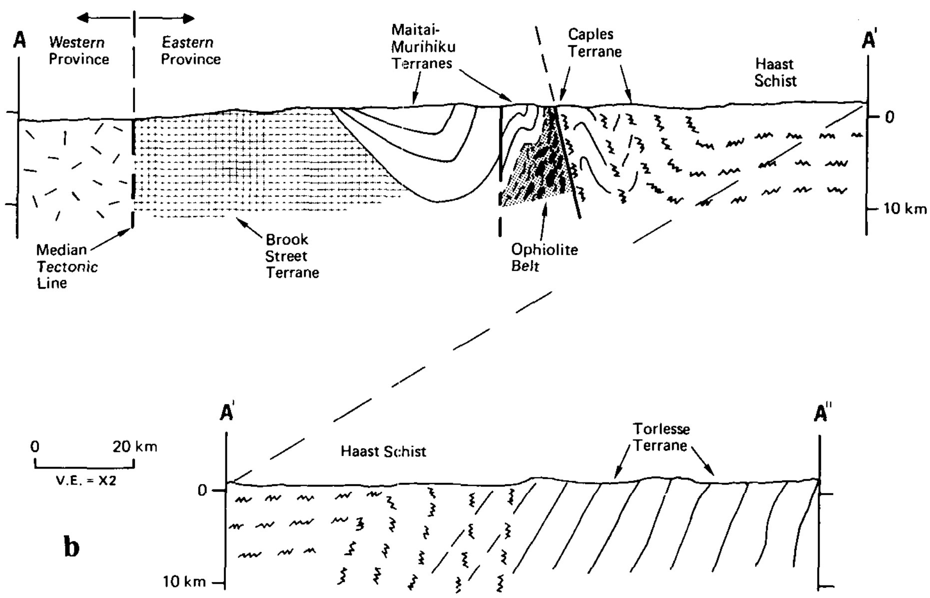
New Zealand is divided into an Eastern and a Western Province (Figs. 1a and 1b) (Landis and Coombs, 1967). The Eastern Province (also known as the New Zealand Geosyncline) includes the Torlesse and coeval terranes and is thought to have been part of an extensive, largely Mesozoic belt of clastic rock deposited along the Austral-Antarctic margin of Gondwanaland (Fleming, 1974). The Western Province, consisting of Paleozoic sedimentary rocks and a variety of crystalline rocks of late Precambrian to Cretaceous age, is thought to have originally formed part of the Gondwana continental block (Cooper, 1975). The two provinces are separated by a tectonically complex zone marked by faulting and intrusions, referred to as the Median Tectonic Line by Landis and Coombs (1967).

In the mid-Cretaceous, the New Zealand segment of Gondwanaland broke away and subsequently drifted via sea-floor spreading to its present position (Molnar and others, 1975). Displacement by the Alpine Fault and probable oroclinal bending have resulted in a recurved arc structure for rocks of the Eastern Province (Fig. 1a, inset).

Following Coombs and others (1976), the Eastern Province is divided into seven lithologic units referred to informally as terranes




a




b

**Figure 1. (a) Geologic map and (b) cross section, South Island, New Zealand, showing the Western Province and the various geologic terranes of the Eastern Province (after Coombs and others, 1976). Inset: New Zealand–Campbell plateau region. Heavy dashed line is the Junction Magnetic Anomaly (Hatherton, 1969), which corresponds to the Dun Mountain Ophiolite Belt.**

(see Carter and others, 1974, 1978, for discussions of alternative stratigraphic nomenclature schemes). From the Pacific side inward these are: the Torlesse, Haast Schist, Caples, Dun Mountain, Maitai, Murihiku, and Brook Street (Figs. 1a and 1b). The terranes are of regional extent and are distinguished by differences in lithology, structure, and metamorphism. Contacts between terranes are commonly faulted, but not always. Note that this differs from the "terrane concept" currently followed by many North American workers (for example, Jones and others, 1981), in which terranes are always fault-bounded entities.

The Torlesse and Caples terranes are composed of highly deformed, sparsely fossiliferous clastic rocks, with minor but widespread spilite and associated chert and limestone. These terranes are considered to be convergent margin deposits (Coombs and others, 1976). The Haast Schist separates the Torlesse and Caples terranes and constitutes their metamorphic equivalents.

The Maitai and Murihiku terranes are made up of a structurally simple succession of clastic rocks without interbedded volcanic flows that are thought to represent forearc basin deposits. These terranes are underlain on one side by the Dun Mountain (ophiolite) terrane, considered to be oceanic crust, and on the other by the Brook Street terrane, thought to represent a volcanic arc (Coombs and others, 1976).

Previous workers (Landis, 1969; Dickinson, 1971; Landis and Bishop, 1972) envisioned a simple tripartite system consisting of arc-trench gap (Maitai, Murihiku terranes), trench complex (Torlesse, Caples, and Haast Schist terranes), and a complex western source (volcanogenic Brook Street terrane plus continental Western Province). Subsequent work has emphasized that Maitai, Murihiku, and Caples rocks were derived from a volcanogenic source, whereas the Torlesse was derived from a quartzofeldspathic continental source, and that these differences cannot be reconciled by a common source terrane (Blake and others, 1974; MacKinnon, 1979, 1980a). The contact between the volcanogenic suite and the Torlesse lies somewhere in the Haast Schist, although its exact location and nature have not been determined.

Most recent workers view the volcanogenic terranes as interrelated oceanic arc (Brook Street terrane), forearc basin (Maitai-Murihiku terranes), and trench complex (Caples terrane) deposits, and the vast quartzofeldspathic Torlesse terrane as having been tectonically juxtaposed outboard of this system (Blake and others, 1974; Coombs and others, 1976; Andrews and others, 1976; Carter and others, 1978; Wood, 1978; Sporli, 1978; Bradshaw and others, 1980; Howell, 1980; Kamp, 1980; Crook and Feary, in press).

## TORLESSE TERRANE

The Torlesse terrane and Haast Schist correlatives form the basement rock of large parts of the North and South Islands (Fig. 1a). A considerable and undeterminable volume of these rocks is probably submerged under the Pacific Ocean to the east. Haast Schist and metagraywacke are known from the Chatham Islands, about 800 km east of South Island, and from a few dredge hauls on the Chatham Rise (Norris, 1964; Cullen, 1965); however, it is uncertain whether these are metamorphosed Caples or Torlesse terrane rocks (personal observations of thin sections of Chatham Island rocks; compare Andrews and others, 1978).

About 99% of the exposed Torlesse is quartzofeldspathic graywacke and gray-to-black mudstone, largely of flysch character. The remaining rocks include intercalated conglomerate, red and green mudstone, and spilitic volcanics with associated limestone and chert.

### Fossil Zones

Fossils are sparsely but widely distributed throughout the Torlesse. Most are isolated occurrences in flyschlike sequences and many have been redeposited. However, local and diverse concentrations are present in a few inferred shallow-marine and terrestrial deposits.

A number of faunal zones have been recognized by previous workers (Campbell and Warren, 1965; Landis and Bishop, 1972; Andrews and others, 1976). The zones range in age from Carboniferous to Lower Cretaceous, although approximately one-half of the international faunal stages during this time span are unrepresented by fossils.

Most of the known fossil occurrences can be grouped into five major zones (Fig. 2): (1) a Permian *Atomodesma* zone, defined largely by scattered and broken prisms of the bivalve *Atomodesma;* (2) a Middle Triassic zone, defined mainly by numerous species of bivalves and brachiopods (notably the bivalve *Daonella*), and also including some diagnostic plant material; (3) a lower Upper Triassic(?) *Torlessia* zone, defined by scattered occurrences of *Torlessia* and *Titahia* (probably annelids); (4) an Upper Triassic *Monotis* zone, defined by scattered and commonly broken shells of the world-wide Norian marker *Monotis,* a bivalve; and (5) an Upper Jurassic–Lower Cretaceous zone defined by numerous fossils, mainly bivalves, and also including two occurrences of terrestrial plant material.

There has been considerable debate over the age of the *Torlessia* zone, which I have assigned to the early Upper Triassic(?). This is because there is no biostratigraphic control of *Torlessia-Titahia* in New Zealand; similar fossils are present in other circum-Pacific deposits ranging in age from Miocene to Permian (Webby, 1967). It has been suggested (Landis and Bishop, 1972; Gregory, 1977) that the areal distribution of the *Torlessia* zone is facies-controlled; however, no consistent lithofacies differences are recognized for *Torlessia*- or *Titahia*-bearing strata as compared to typical Torlesse rocks of other ages.

On the other hand, an early Upper Triassic age is supported by several lines of evidence. For one, the *Torlessia* zone lies between the Upper and Middle Triassic zones, and many fossil localities from these zones lie close to *Torlessia* and *Titahia* occurrences. This contrasts with the fact that the *Torlessia* zone is nowhere adjacent to the Permian or Upper Jurassic–Lower Cretaceous zones. Furthermore, an association of *Torlessia* and late Middle–early Upper Triassic fossils has recently been reported by Campbell and Pringle (1982). These features suggest an early Upper Triassic age (pre-*Monotis*–post-*Daonella*) for *Torlessia*-bearing strata (see also Campbell and Warren, 1965; Andrews and others, 1976; Force and Force, 1978). This conclusion is also supported by the discrete composition of *Torlessia*-zone sandstones, which is transitional between the compositions of sandstones of Middle and Late Triassic age (Table 1).

Although most fossils are part of one of the five major zones, there are a few notable exceptions. Carboniferous conodonts, the oldest known fossils in the Torlesse (Jenkins and Jenkins, 1971), are present in limestone associated with volcanics at one locality within the bounds of the Permian *Atomodesma* zone (Fig. 2). The area is a tectonic mélange with uncertain relationship to the surrounding rocks; it seems likely that the limestone was deposited on a volcanic high, well before significant clastic deposition began (Hitching, 1979). Other notable fossils, all of which are known from but one or a few localities, include: Permian fusulines, found in limestone overlying volcanics

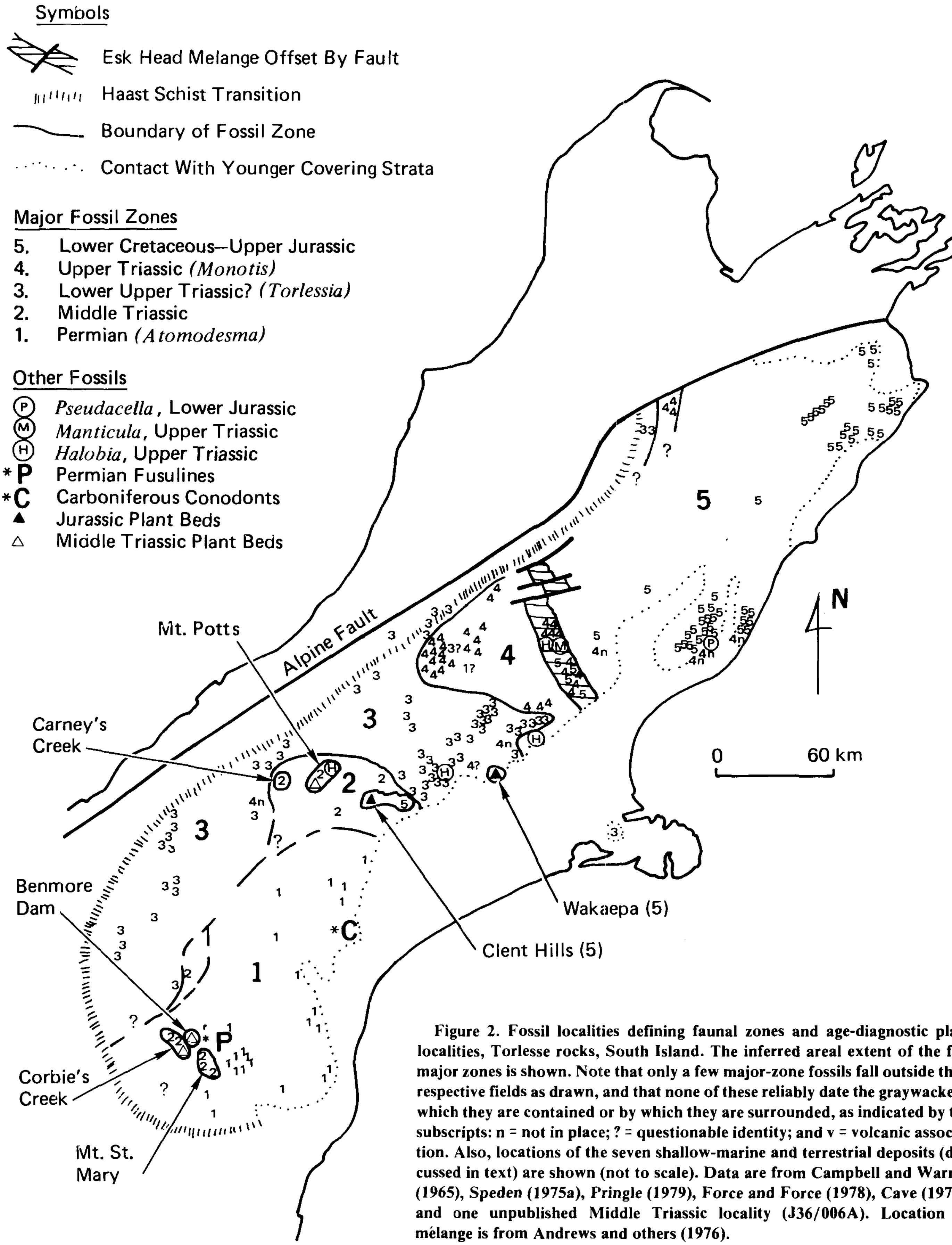



**Figure 2.** Fossil localities defining faunal zones and age-diagnostic plant localities, Torlesse rocks, South Island. The inferred areal extent of the five major zones is shown. Note that only a few major-zone fossils fall outside their respective fields as drawn, and that none of these reliably date the graywacke in which they are contained or by which they are surrounded, as indicated by the subscripts: n = not in place; ? = questionable identity; and v = volcanic association. Also, locations of the seven shallow-marine and terrestrial deposits (discussed in text) are shown (not to scale). Data are from Campbell and Warren (1965), Speden (1975a), Pringle (1979), Force and Force (1978), Cave (1978), and one unpublished Middle Triassic locality (J36/006A). Location of mélange is from Andrews and others (1976).

TABLE 1. COMPOSITION OF TORLESSE SANDSTONES

| Petrofacies | Permian | | Middle Triassic | | lower Upper Triassic | | Upper Triassic | | Upper Jurassic–Lower Cretaceous | |
|---|---|---|---|---|---|---|---|---|---|---|
| No. of samples | 28 | | 17 | | 27 | | 22 | | 25 | |
| | $\bar{x}$ | *range* | $\bar{x}$ | *range* | $\bar{x}$ | *range* | $\bar{x}$ | *range* | $\bar{x}$ | *range* |
| Grain size in mm | 0.26 | (.21–.42) | 0.28 | (.15–.42) | 0.27 | (.15–.42) | 0.29 | (.15–.42) | 0.16 | (.11–.21) |
| % framework | 88 | (84–96) | 89 | (82–94) | 89 | (84–96) | 90 | (85–96) | 89 | (80–95) |
| % matrix (<.03 mm) + cement + alterite | 12 | (4–16) | 11 | (6–18) | 11 | (4–16) | 10 | (4–15) | 11 | (5–20) |
| | $\bar{x}$ | $\sigma$ | $\bar{x}$ | $\sigma$ | $\bar{x}$ | $\sigma$ | $\bar{x}$ | $\sigma$ | $\bar{x}$ | $\sigma$ |
| Q | 24 | (4.4) | 29 | (3.6) | 31 | (4.4) | 35 | (2.9) | 27 | (4.9) |
| F | 50 | (6.0) | 51 | (6.2) | 59 | (6.4) | 42 | (4.4) | 33 | (7.7) |
| L | 26 | (7.1) | 20 | (5.1) | 10 | (3.7) | 23 | (3.4) | 40 | (7.0) |
| P/F | 0.81 | (0.05) | 0.81 | (0.09) | 0.78 | (0.06) | 0.78 | (0.08)* | 0.78 | (0.08) |
| Lv/L | 0.92 | (0.08) | 0.78 | (0.15) | 0.73 | (0.08) | 0.73 | (0.07) | 0.59 | (0.16) |
| %M | 1.6 | (0.9) | 4.4 | (2.2) | 4.7 | (2.2) | 3.5 | (1.5) | 2.5 | (0.9) |

*P/F data from three samples are excluded because some potassium feldspar grains were probably albitized during metamorphism.

*Note:* Point count data for Torlesse sandstones. To ensure age of samples, most were collected at or well within 1 km of an age-diagnostic fossil locality (Fig. 2). $\bar{x}$, mean; $\sigma$, first standard deviation from mean; Q:F:L, framework quartz, feldspar, and lithic fragment content recalcuated to 100%; P/F, plagioclase to total feldspar ratio; Lv/L, volcanic lithic fragment to total lithic fragment ratio; % M, framework percent mica. Alterites are detrital framework grains altered beyond recognition. Point counts were of a minimum of 400 framework grains. Procedures, definitions of parameters, and grain types follow Dickinson (1970), with one minor exception; rare occurrences of phenocrysts within aphanitic rock fragments were counted as rock fragments rather than as the phenocryst mineral itself. All thin sections were selectively stained for plagioclase and potassium feldspar (Norman, 1977; MacKinnon, 1980b).

(Hornibrook and Shu, *in* Campbell and Warren, 1965); isolated shells of the Upper Triassic bivalve *Halobia,* found in flysch and in a limestone block in the Esk Head Mélange (Andrews and others, 1976); the Upper Triassic bivalve *Manticula,* found in a limestone block in the Esk Head Mélange (Speden, 1975b); and the Lower Jurassic bivalve *Pseudaucella,* found in a siltstone float boulder (Speden, 1979). All of the above localities are situated within or adjacent to the major fossil zone to which they are most similar in age.

The stratigraphic relationships and areal distributions of the faunal zones are of key importance in understanding the Torlesse. Each major zone is clearly defined by numerous fossil localities, with very few fossils falling outside their respective zone boundaries. Mapping and reconnaissance studies indicate that contacts between the major zones are mainly tectonic. The interpretation and understanding of such an orderly distribution of fossils, maintained despite pervasive deformation, are of foremost importance in unraveling the origin of the Torlesse.

## Clastic Rocks

**Turbidites and Associated Coarse Clastics.** Most Torlesse strata consist of sparsely fossiliferous alternating sandstone and mudstone. Many sandstone beds are graded, display sole markings, and contain all or parts of the Bouma sequence (Reed, 1957; Webby, 1959; Carter and others, 1978; MacKinnon, 1980a, 1980b; Beggs, 1980; Howell, 1981; MacKinnon and Howell, in press). This evidence indicates deposition by sediment gravity flows in a deep-marine environment and is in accord with interpretations given for other comparable circum-Pacific terranes (for example, Franciscan Complex).

Regardless, there has been considerable debate in New Zealand concerning depositional environments. A shallow-marine origin for the bulk of the Torlesse is favored by Bradshaw (1972), Bradshaw and Andrews (1973), Andrews (1974), and Andrews and others (1976). Their evidence is based mainly on sedimentological studies of two areas (Bradshaw, 1972; Andrews, 1974) that are generally typical of Torlesse strata. However, my observations (MacKinnon, 1980a, 1980b) and those of Howell (1981) indicate that most strata in these areas are middle or upper submarine fan deposits somewhat difficult to interpret because of poor preservation of sedimentary structures. Although there are a few small areas of the Torlesse that are unequivocally of shallow-marine and terrestrial origin (as discussed below), it seems clear that the vast bulk of the Torlesse consists of turbidites and associated coarse clastics (see also Ballance, 1976; Carter and others, 1978).

Torlesse sediment gravity flow deposits are dominated by thick (>60 cm) to very thick (>120 cm) sandstone beds that are massive, or graded starting with the Bouma Ta division. Over-all sandstone; mudstone ratio for the Torlesse averages 2:1 to 3:1. Typical sequences consist of sandstone-dominated intervals as much as several hundred metres thick, alternating with much thinner mudstone-dominated or thin-bedded intervals. Fining- and thinning-upward or coarsening- and thickening-upward sequences are rarely present. Conglomerate is widespread although volumetrically minor (< 1% of total Torlesse exposure) and is usually associated with thick- or very thick-bedded sandstone. Representative sequences, along with Mutti and Ricci Lucchi (1972) facies designations, are shown in Figure 3.

The paucity of thin-bedded and mudstone-dominated intervals relative to sandstone-dominated intervals is one of the most conspicuous features of the Torlesse. In general, thin-bedded and mudstone-dominated intervals are less than 50 m thick, although locally they may be a few hundred metres in thickness. Two notable exceptions to this generalization are as follows: (1) Lower Cretaceous strata are largely thin-bedded with a sandstone:mudstone ratio of approximately 1:1; and (2) the Esk Head Mélange is predominantly disrupted mudstone.

In terms of submarine fan models (terminology follows Normark, 1978), the dominance of thick- and very thick-bedded sandstone suggests major deposition in upper- and middle-fan channels or lobes. Subordinate interstratified thin-bedded and mudstone-dominated sequences are most likely interchannel or interlobe deposits. Thin-bedded or mudstone-dominated depositions thick enough to represent significant deposition in slope, lower-fan, or basin-plain environments are rare.

Evidence summarized below indicates that the Torlesse is an accreted terrane. Deposition was in large part concurrent

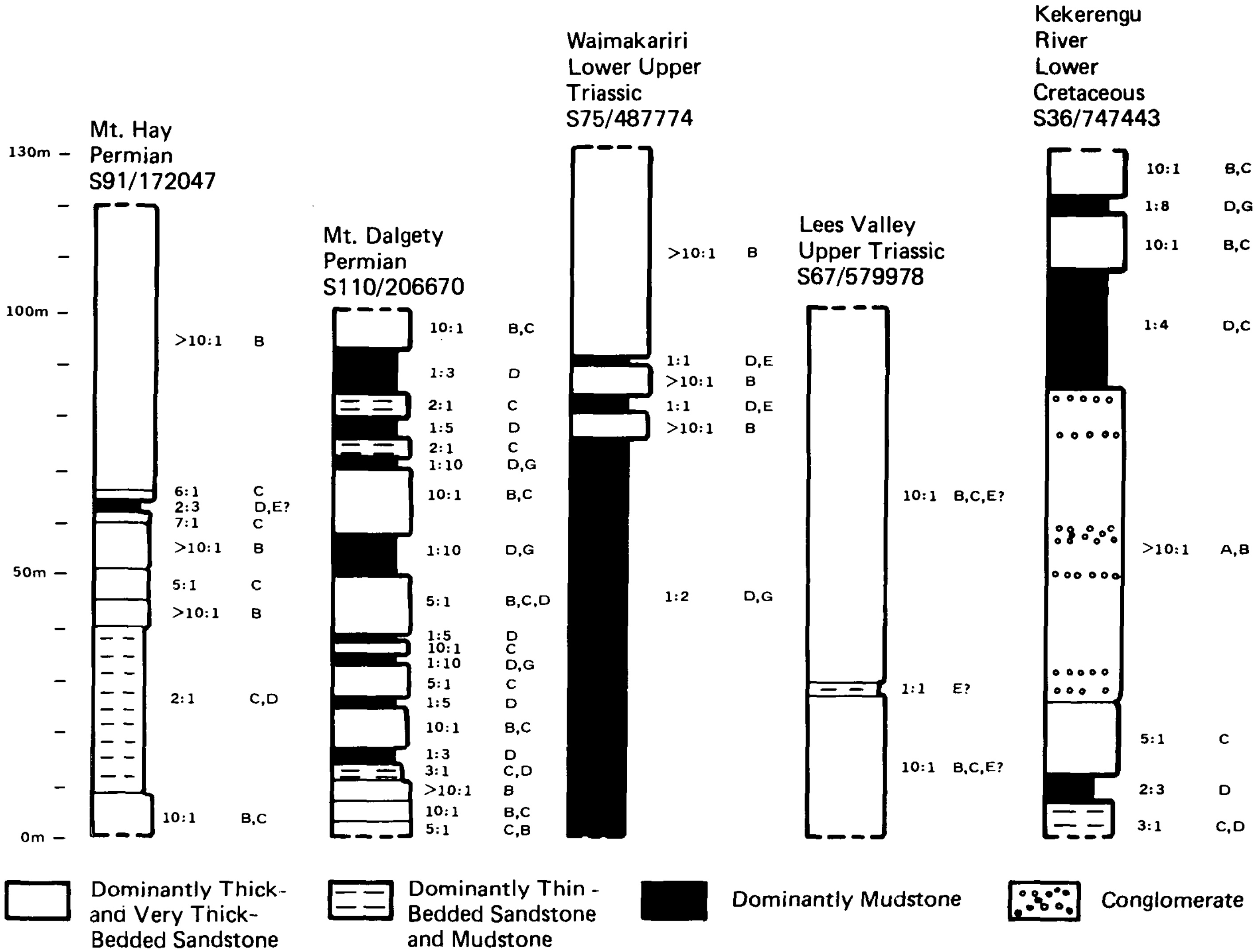



**Figure 3. Measured sections show typical Torlesse strata. Location, age, and grid reference (New Zealand topographic map series 1:63,360) are given at the top of each column. Sand-to-shale ratio and Mutti and Ricci Lucchi (1972) lithofacies (designated by letters and modified to fit Torlesse rocks) are given to the right of each column. Facies A. Conglomerate and pebbly sandstone. Facies B. Mainly thick- to very thick-bedded massive sandstone, amalgamations common. Facies C. Graded sandstone with subequal or subordinate interbedded mudstone, sandstone bed thickness from 0.2 to 2 m, beds begin with Bouma $T_a$. Facies D. Alternating sandstone and mudstone, sandstone:mudstone ratio <1; sandstone beds thinner than facies C and begin with Bouma $T_b$, $T_c$, or $T_d$. Facies E. Alternating sandstone and mudstone, sandstone:mudstone ratio >1, sandstone beds 3 to 20 cm thick, irregular bedding. Facies F. Chaotic deposits including slumps and pebbly mudstone. Facies G. Mudstone, structureless or parallel-laminated.**

with deformation, metamorphism, and recycling of older Torlesse rocks. Thus, the Torlesse was not deposited as one large fan but instead represents a number of smaller deposits that were progressively accreted, uplifted, and eroded through time. Likely depositional sites include trench floor and trench-slope basins.

The high over-all sandstone:mudstone ratio and virtual lack of fan-facies associations other than those reflecting sandy mid- and inner-fan deposits are key elements in any reconstruction. A possible explanation of these features, as developed by MacKinnon and Howell (in press), calls for a voluminous and sandy source terrane supplying detritus from numerous point sources along the basin margins, coupled with possible selective subduction of some mudstone.

**Shallow-Marine and Terrestrial Deposits.** Shallow-marine and terrestrial deposits have been documented in seven small areas of the Torlesse on the South Island. Five of these areas are of Middle Triassic age, and two are of Upper Jurassic age (Fig. 4).

Shallow-marine deposition is indicated for sequences of sandstone, shale, and minor conglomerate at Carney's Creek (Frankham, 1972), Mount St. Mary (Ryburn, 1967), and most of Corbies Creek (*ibid.*) and Mount Potts (Campbell and Force, 1972). Each of these areas contains abundant and diverse marine fossils, primarily brachiopods and bivalves, and specimens commonly have both valves co-joined and are probably in life position. Sedimentary structures indicate deposition mainly by traction currents; previous interpretations of depositional setting include deltaic, shelf, beach, and intertidal environments.

Predominantly terrestrial deposition is indicated for the deposits at Clent Hills

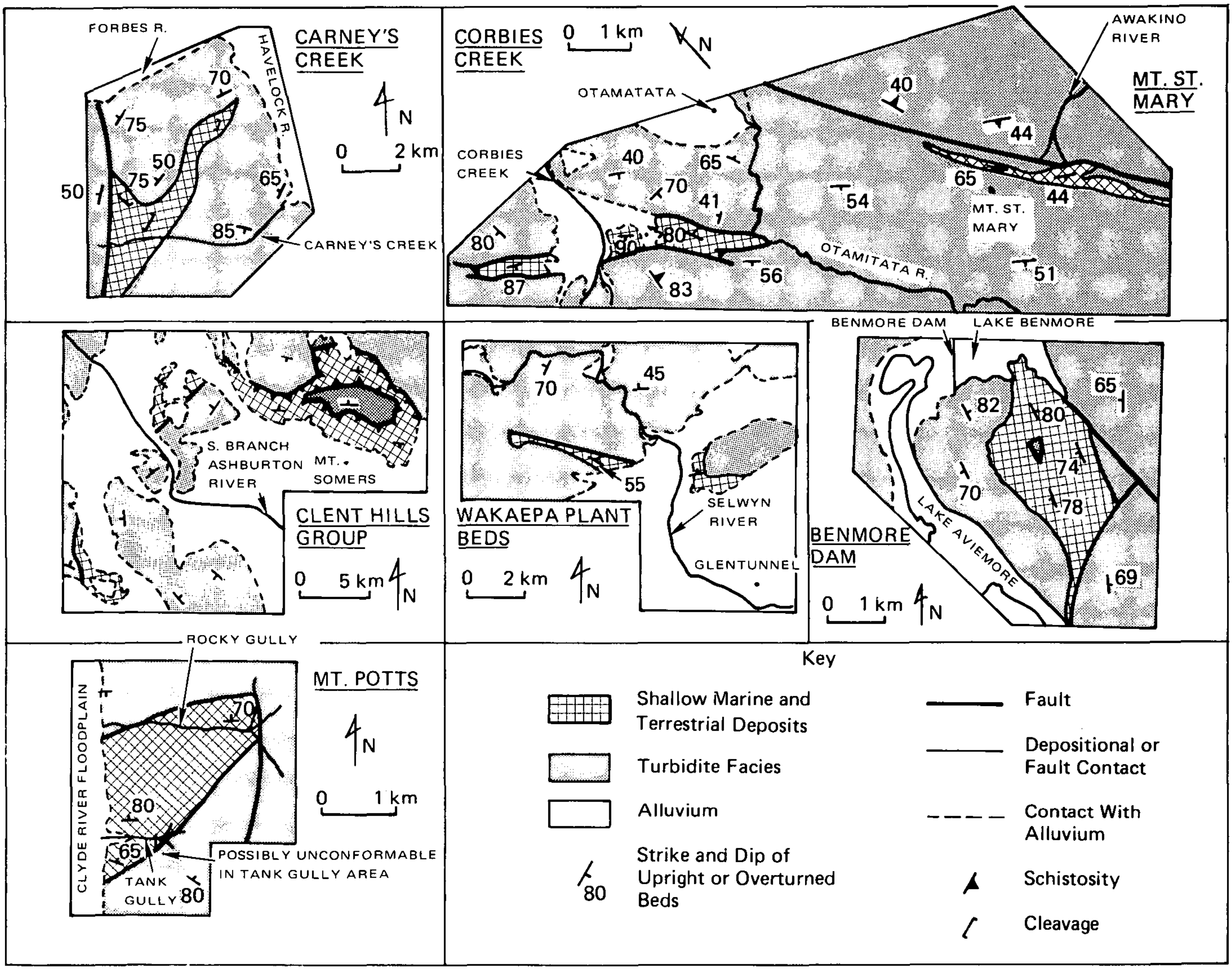



**Figure 4. Geologic sketch maps of the seven shallow-marine and terrestrial deposits discussed in text, showing areal extent, bedding trends, and contacts with surrounding deep-marine Torlesse strata. See Figure 2 for locations. Data from Gregg (1964), Shu (1967), Ryburn (1967), Frankham (1972), Campbell and Force (1972), Retallack (1977, 1979), and Oliver (1979).**

(Oliver, 1977, 1979), Wakaepa (Speight, 1928), and Benmore Dam (Shu, 1967; Retallack, 1977). Strata at these localities are for the most part channelized sandstone and conglomerate that contain abundant traction features and commonly fine upward into plant-rich coal beds (MacKinnon, 1980b). The plant material is abundant and includes many large and delicately preserved fronds (Retallack, 1979). Some plant material is *in situ* (rootlets perpendicular to bedding). Fluvial and associated flood-plain deposition is indicated.

Mapping shows that these shallow-marine and terrestrial deposits are of limited areal extent (Fig. 4), and on the whole can be clearly differentiated from surrounding deep-marine Torlesse rocks on the basis of fossil content and lithology. Contacts with surrounding strata are predominantly faults, but some are mapped as indeterminate and some of these are probably depositional. Most of the deposits cover an area of 5 $km^2$ or less. The Clent Hills deposit is by far the largest, covering approximately 100 $km^2$. Total area covered by the seven deposits is about 150 $km^2$, which is less than 0.5% of total South Island exposure.

## Volcanics

Although volcanics are volumetrically minor components, they are widely distributed and conspicuous. They are mainly spilitic pillow lavas and subordinate hyaloclastites and are commonly associated with varicolored chert (some containing radiolarians) and micritic to shelly limestones (Reed, 1957; Bradshaw, 1972, 1973; Pringle, 1980). Most volcanic occurrences are less than 50 m thick, extend for a few hundred metres to several kilometres along strike, and are usually in fault contact with overlying and underlying flysch. The largest body is about 750 m thick and traceable for approximately 25 km (Bishop, 1976; Pringle, 1980).

Pringle (1980) showed that the volcanics have tholeiitic and alkalic parentage, and that the ratio of flow rocks to fragmental debris is generally 3:1 or less. By comparison with modern volcanism, Pringle concludes that they formed in an oceanic intraplate environment. A similar conclusion was reached by Sporli (1978). No ultramafic rocks or sequences indicative of ophiolites have been recognized (Coombs and others, 1976).

### Structure

Strata are nearly everywhere steeply dipping and have been subjected to multiple premetamorphic and synmetamorphic deformation (Sporli, 1979). The earliest deformation phase probably occurred shortly after deposition, possibly before rocks were completely lithified (Sporli and Bell, 1976; MacKinnon, 1980b). Rehealed crush zones, intense jointing, and disruption of bedding, including boudinage and tectonic lensing of beds, are common features. In addition, isoclinal, recumbent, overturned, refolded, and steeply plunging folds are widely present (Bradshaw, 1972; Sporli and Lillie, 1974; Andrews and others, 1974; Ward and Sporli, 1978; MacKinnon, 1980b).

Most mapping has been on a regional scale (Bradshaw, 1972; Bishop, 1974; Sporli and Lillie, 1974; Sporli and others, 1974; Ward and Sporli, 1978). All areas studied show complex multideformational histories, difficult to relate in detail but broadly similar in outline and style. A generalized structural history that seems applicable to many areas includes early imbrication, folding, and tilting along horizontal fold axes, followed by refolding around steeply plunging axes (Sporli, 1979).

An example of the complexities of structure and its effect on stratigraphy is shown in a detailed study of a 6-km$^2$ area near the crest of the Southern Alps (MacKinnon, 1980b). Here, strata are broken into structurally discrete blocks by steeply dipping premetamorphic and synmetamorphic faults that trend subparallel to bedding. Maximum unbroken stratigraphic thickness is 600 m. Features such as fold axes and bedding cannot be correlated across block boundaries. Strata within blocks are largely intact, although broken formation is present locally, particularly along block boundaries. Reconnaissance observations of other well-exposed areas in the Southern Alps indicate that this pattern of deformation is widespread.

Despite pervasive deformation, mélange consisting of isolated blocks surrounded by sheared mudstone matrix is not common; however, important local and regional occurrences are known (Bradshaw, 1972, 1973; Sporli, 1975, 1978). The most extensive is the Esk Head Mélange, which can be traced for more than 70 km and is 10 to 15 km wide (Fig. 2). A largely tectonic origin is inferred for most Torlesse mélange, in part from internal structural evidence, but more convincingly from the gradational contacts of many of the mélanged areas with surrounding relatively intact rocks. An olistostromal origin prior to tectonism is a possibility for part of the mélange, although this has not been shown. Blocks within mélange are similar to intact Torlesse lithologies. However, the proportions are different: mélange contains more mudstone, volcanic rock, limestone, and chert than does nonmélanged strata.

### Metamorphism

The broad area of nonschistose rocks (that is, Torlesse) are zeolite and prehnite-pumpellyite facies, within which a few fault-bounded outcrops of semischist and schist occur (Landis and Bishop, 1972). Zeolite-facies rocks (mainly laumontite-bearing) are more common in eastern and northern exposures with respect to prehnite-pumpellyite–facies rocks (MacKinnon, 1980a). The pattern suggests a tendency, much complicated by block faulting and possibly other factors, for deeper erosion levels and higher-grade rocks to be exposed as one goes south or west.

The schist-graywacke contact (Fig. 1a) is mapped at the transition from nonschistose to semischistose rock (that is, the transition from textural grade 1 to textural grade 2 as defined by Bishop, 1972). Mineralogically, this approximately corresponds to the transition from prehnite-pumpellyite– to pumpellyite-actinolite–facies rocks (Bishop, 1972). The main body of the schist consists of chlorite- and biotite-zone greenschist-facies rocks composed largely of quartz, albite, chlorite, and mica.

A relatively high P-T gradient of 20 to 25 °C/km was suggested by Landis and Coombs (1967). However, key blueschist-facies minerals (blue amphibole and aragonite) are not known from the Torlesse or clearly correlative schists. Blue amphibole–bearing schists are present in the central and southern part of the main schist belt (Landis and Bishop, 1972), but these may not be from Torlesse protoliths. Of possible significance is the presence of chessboard albite, formed by the metamorphic alteration of potassium feldspar, in many prehnite-pumpellyite and higher-grade Torlesse rocks and associated schists (MacKinnon, 1980a). Although the P-T significance of chessboard albite in graywackes is not clearly established, Moore and Liou (1979) argued that chessboard albite found in Franciscan Complex sedimentary rocks formed during blueschist-facies metamorphism.

Potassium-argon dates indicate that metamorphism, uplift, and cooling to below the argon-retention level (~250 °C) had occurred in some areas by 180 to 200 m.y. ago (Adams, 1979), well before deposition of the Torlesse had ceased. However, uplift and cooling of most of the Haast Schist in Otago occurred much later, mainly between 100 and 140 m.y. ago (Harper and Landis, 1967; Aronson, 1968; Sheppard and others, 1975; Adams, 1979).

### Composition and Provenance of Sandstone and Conglomerate

**Sandstone.** Torlesse sandstones are typically gray, fine to medium grained, poorly to moderately well sorted with subangular grains, and very well indurated. In a general sense, they are aptly referred to as graywackes. Although diagenesis and low-grade metamorphism have obscured the original detrital composition in many sandstones, some are little altered.

The sandstones are predominantly arkosic, with an average quartz-feldspar-lithic fragment ratio (Q:F:L) of 29:47:24. Quartz is generally monocrystalline; chert is rare. Potassium feldspar is largely orthoclase with subordinate but conspicuous microcline. Plagioclase is albite-oligoclase, commonly untwinned and albitized and rarely zoned. The ratio of plagioclase to potassium feldspar is constant at about 5:1. Rock fragments are predominantly silicic volcanics. Other rock fragments include quartzofeldspathic sandstone, mudstone, and schist. Heavy minerals are mainly micas, sphene, epidote-clinozoisite, hornblende, apatite, zircon, and garnet.

Five major sandstone petrofacies are recognized by MacKinnon (1979, 1980a). The term petrofacies is used here to denote sandstones of similar composition (following Dickinson and Rich, 1972) and age. The ages of the five petrofacies correspond with the ages of the five major fossil zones, that is, Permian, Middle Triassic, early Late Triassic(?), Late Triassic, Late Jurassic—Early Cretaceous (Fig. 2).

The petrofacies are clearly distinguished by the ratios Q:F:L and Lv/L (volcanic lithic to total lithic fragments) (Fig. 5 and Table 1). Changing Q:F:L values define a tight arcuate trend in Q:F:L space going from least mature in Permian times (24:50:26), to more arkosic in Middle Triassic (29:51:20) and early Late Triassic(?)

times (31:59:10), to increasingly lithic-rich in the Late Triassic (35:42:23) and Late Jurassic and Early Cretaceous (27:33:40). Lv/L ratio changes gradually from a high of 0.92 in the oldest rocks to a low of 0.59 in the youngest rocks. Another important compositional variation is the presence of detrital pumpellyite in Upper Jurassic–Lower Cretaceous rocks, but not in older rocks.

**Conglomerate.** The predominant clast types in post-Permian conglomerates are well-rounded quartzofeldspathic graywacke and mudstone, believed to have been derived by autocannibalistic reworking of older Torlesse rocks (Andrews and others, 1976; Smale, 1978; MacKinnon, 1980a). Other clast types in post-Permian conglomerates include: volcanics, mainly rhyolites and dacites; metamorphics, mainly quartz-vein types and siliceous metasedimentary varieties; and minor quartz-rich clastic rocks, silicic plutonic clasts, and chert. In Permian conglomerates, a few autocannibalized clasts are recognized, but the predominant clast types are mainly siliceous sedimentary and metamorphic varieties (primarily quartzites and some quartz arenites) and basic to silicic volcanics (MacKinnon, 1980a; Smale, 1980).

Quantitative evidence for reworking is given by MacKinnon (1980a), who studied thin sections of clasts from 17 conglomerates. He showed that most sandstone clasts are indistinguishable from coeval or older Torlesse sandstones. These clasts, together with mudstone clasts of similar composition, compose approximately 10% to 20% of the clasts of Permian and some Middle Triassic conglomerates, and 50% or more of some Middle Triassic and most younger conglomerates. Significantly, many of the clasts from at least Middle Triassic onward contain prehnite, pumpellyite, or quartz veins, whereas the enclosing conglomerate matrix does not. This indicates that these clasts had been metamorphosed prior to uplift and reworking.

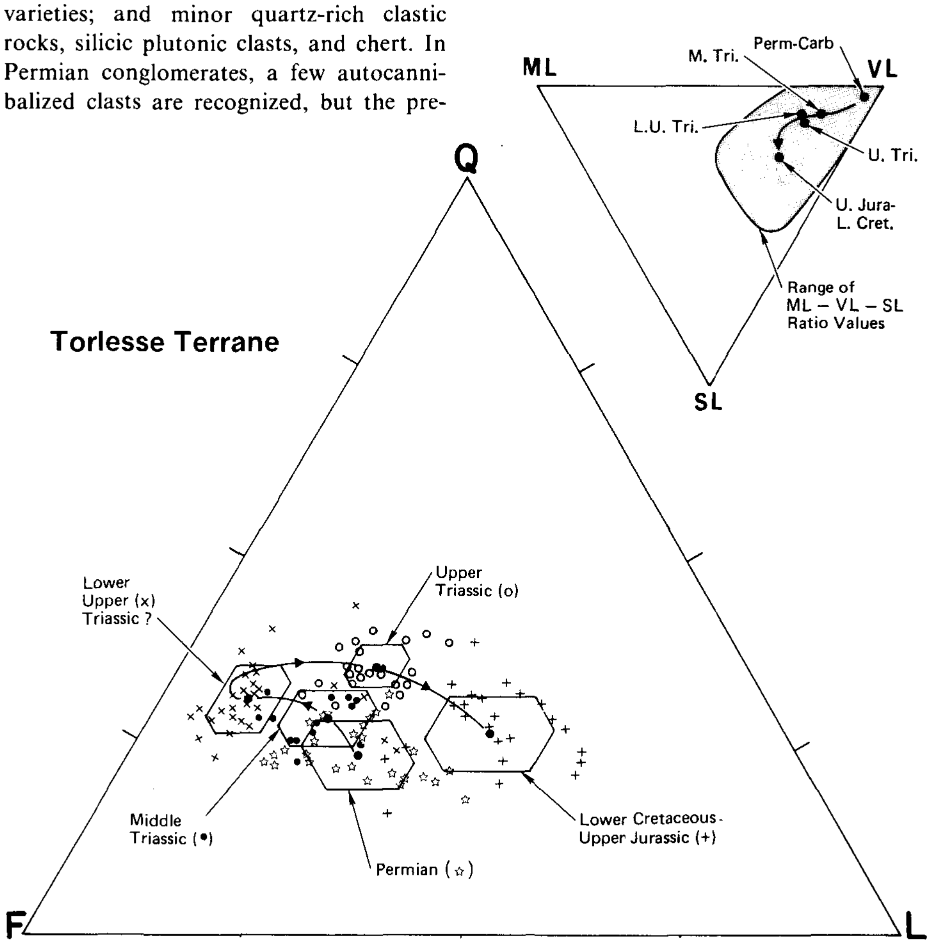



**Figure 5. Large triangle shows Q:F:L values for 119 Torlesse sandstones. Age or petrofacies designation is shown as follows: *, Permian; ·, Middle Triassic; x, lower Upper Triassic; O, Upper Triassic; +, Upper Jurassic–Lower Cretaceous. Also shown are mean values and first standard deviation fields for the five petrofacies. Small triangle shows average ratios for metamorphic lithic (ML), volcanic lithic (VL), and sedimentary lithic (SL) content of sandstones. Arrows in both triangles show trend from oldest to youngest petrofacies.**

**Provenance.** The pre-Jurassic source terrane was predominantly silicic crystalline, with subordinate silicic volcanics as indicated by the arkosic composition, high Lv/L ratio, and heavy mineral content of sandstones. Compositional and textural immaturity of the sandstone and the enormous volume of the Torlesse signify a substantial mountainous continental source. By comparison with previous studies of modern and ancient sandstones (Crook, 1974; Dickinson and Suczek, 1979; Dickinson and Valloni, 1980), the source is interpreted to have been a major, active, continental-margin, volcano-plutonic arc. As a comparison, sands deposited in the Gulf of Alaska area from the Eocene to the present (Galloway, 1974; Hayes, 1973; Stewart, 1976) are closely comparable to Torlesse sandstones.

Reworked clasts in conglomerate require the presence of some older, uplifted, and in part metamorphosed Torlesse rocks in the source area. Reworking was only locally important in pre-Jurassic times, as indicated by the arkosic composition of pre-Jurassic sandstones. In Upper Jurassic–Lower Cretaceous times, older Torlesse rocks may have been the predominant source, as sandstones of this age contain abundant quartzofeldspathic sedimentary and metasedimentary Torlesse detritus, including detrital pumpellyite.

The evolution of the source terrane is reflected by changes in Q:F:L and Lv/L (Fig. 5). Decreasing lithic fragment content from Permian to early Upper Triassic(?) time reflects increasing exposure of plutonic rocks as overlying volcanic cover was stripped away. In younger rocks, increasing lithic content coupled with an increase in the ratio of sedimentary and metasedimentary lithics to volcanic lithics reflects increasing autocannibalistic reworking.

**Source Location.** The Torlesse source terrane was considered by many previous workers to be the Western Province because of its proximity and appropriate composition (Landis and Bishop, 1972). However, the presence of volcanogenic terranes between the Western Province and the Torlesse, long considered a problem (Coombs and others, 1959), has been emphasized in recent years, and most recent workers have considered other sources (Blake and others, 1974).

Most controversial is the proposal of an eastern source by Bradshaw and Andrews (1973) and Andrews and others (1976). Although their proposal has been accepted by some authors (Retallack, 1979; Kamp, 1980), their evidence is not convincing. Their arguments are based mainly on the distribution of conglomerate and on sedimentary-facies distribution. Considering conglomerate distribution first, they lumped all Triassic rocks together (questionable in itself) and claimed that conglomerate occurrences and clast size decrease from east to west, thereby indicating an eastern source. The slight differences in distribution they showed to support this (Andrews and others, 1976, Fig. 2) are minimal and not statistically significant. Furthermore, these differences can be attributed to the greater accessibility of eastern exposures as compared with the essentially roadless high-alpine western outcrops. Their other line of evidence, that of facies distribution, is equally untenable. They argued that shallow-marine and terrestrial deposits are typical of eastern exposures, whereas deep-marine turbidite facies are typical of western exposures. This does not concur with my observations (Fig. 4) nor with those of many other workers (Ballance, 1976; Carter and others, 1978; Howell, 1981) that indicate that shallow-marine and terrestrial deposits are restricted to a few small areas, whereas the bulk of exposures, both east and west, are turbidite facies.

Although sedimentological evidence purporting an eastern source is unfounded, there is little evidence to support transport from other specific directions. For example, there are no recognized areal differences in the proportion of mudstone and sandstone in coeval turbidite facies that would suggest a regional proximal-distal relationship. Also, although paleocurrent data have been reported from several areas (Webby, 1959; Andrews and others, 1974; Sporli and Lillie, 1974; Carter and others, 1978; MacKinnon, 1980a; Beggs, 1980), no consistent regional pattern is apparent, probably because structural complications prevent unambiguous interpretations in most, if not all, areas studied (see Sporli and Lillie, 1974, p. 121; MacKinnon, 1980a, p. 93–94).

There is, however, one slim line of sedimentologic evidence on source direction that warrants consideration. By comparing the distribution of the seven shallow-marine and terrestrial deposits with coeval deep-marine facies, a source direction may be inferred. For Jurassic strata, the two terrestrial deposits of this age (Clent Hills and Wakaepa) lie south of coeval deep-marine facies (Fig. 2). Comparison of Middle Triassic deposits is not as clear-cut, but for the most part, shallow-marine and terrestrial deposits lie south and west of the few known deep-marine strata of this age (see also Beggs, 1980). This evidence, although meager, suggests a source to the south and west.

## ORIGIN OF THE TORLESSE

Deposition of the Torlesse in a tectonically active continental-margin setting is indicated by: metamorphism concurrent with deposition; early premetamorphic or synmetamorphic deformation; autocannibalistic reworking; and deposition of voluminous, fresh, first-cycle, quartzofeldspathic sand in a marine environment.

Active continental margins are bounded by subduction zones or transform regimes, and these may alternate through time as relative plate motions change and triple junctions migrate. Certainly, many features of the Torlesse are comparable with those inferred for deposits associated with subduction complexes, and it seems likely that a subduction zone was present during most of Torlesse depositional times. However, a transform regime, particularly an obliquely convergent transform, may have supplanted subduction during part of this period.

### Accretionary Model

Many features of the Torlesse indicate that accretion, a common feature of subduction complexes, was an important process in the origin of the Torlesse. The most convincing evidence for accretion is the distribution of major fossil zones (Figs. 2 and 6). The mutually exclusive and areally extensive nature of these zones can best be explained by progressive accretion of strata before deposition of the following zone began. The distribution cannot be explained by later deformation of a simple conformable sequence, as this would result in a pattern of thin and structurally intermixed zones, rather than the thick, mutually exclusive zones we now see.

An accretionary origin is further supported by evidence for early deformation, induration, uplift, and erosion of the Torlesse. Uplift and recycling of older Torlesse rocks was apparently well under way by Middle Triassic time, as reworked, in part metamorphosed Torlesse clasts are common in conglomerates of this age. Also, at several localities, shallow-marine and terrestrial deposits of Middle Triassic age lie in probable unconformable contact on older, uplifted, deep-marine Torlesse rocks.

Accretionary complexes commonly show a progression from oldest to youngest strata seaward from a converging margin (Karig and Sharman, 1975). Ancient examples include the "eugeosynclinal" terranes in Japan (Imai and others, 1971), Alaska (Connelly, 1978), and the Franciscan Complex of California (Blake and Jones, 1974).

In the Torlesse, younging trends of fossil zones are readily apparent but are in part contradictory (Figs. 2 and 6). Dismemberment and probable bending along the Alpine Fault have further complicated reconstruction.

On the northern part of the South Island and away from the Alpine Fault, the distribution of the *Torlessia, Monotis,* and Upper Jurassic–Lower Cretaceous zones shows a simple northeast-younging progression. The boundaries between these zones are southeast-trending, as clearly defined by fossil distribution and the trend of the Esk Head Mélange. The pattern is broken only by the presence of two small areas of largely terrestrial Jurassic deposits, faulted against or unconformably overlying older strata, south of the main submarine-fan–dominated Upper Jurassic–Lower Cretaceous outcrop belt. Near the Alpine Fault, these zone boundaries swing to a northeast trend. This is likely a reflection of the effects of rapid uplift, faulting, and possible bending of strata along the Alpine Fault, rather than original distribution pattern.

In the southern part of Torlesse exposures on the South Island, the oldest major zone (*Atomodesma*) lies to the southeast and is flanked progressively by younger *Daonella* and *Torlessia* zones to both the north and west. The northward-younging trend ties into the general northward-younging trends of the younger zones described above.

On the North Island, *Torlessia, Monotis,* and Upper Jurassic–Lower Cretaceous zones show an east-younging pattern. Mélange is present along the *Monotis* and Upper Jurassic–Lower Cretaceous zone boundary as it is on the South Island.

A simple reconstruction of the fossil-zone pattern is proposed, based on the following four inferences:

1. The major Torlesse fossil zones trend roughly east-west or northwest in areas away from the Alpine Fault. On the South Island, this is shown by the trends of the contacts between the *Torlessia* and *Monotis* zones, and between the *Monotis* and the Upper Jurassic–Lower Cretaceous zones (for example, Esk Head Mélange). Predominantly east-west trends can be inferred for contacts between other zones where expo-

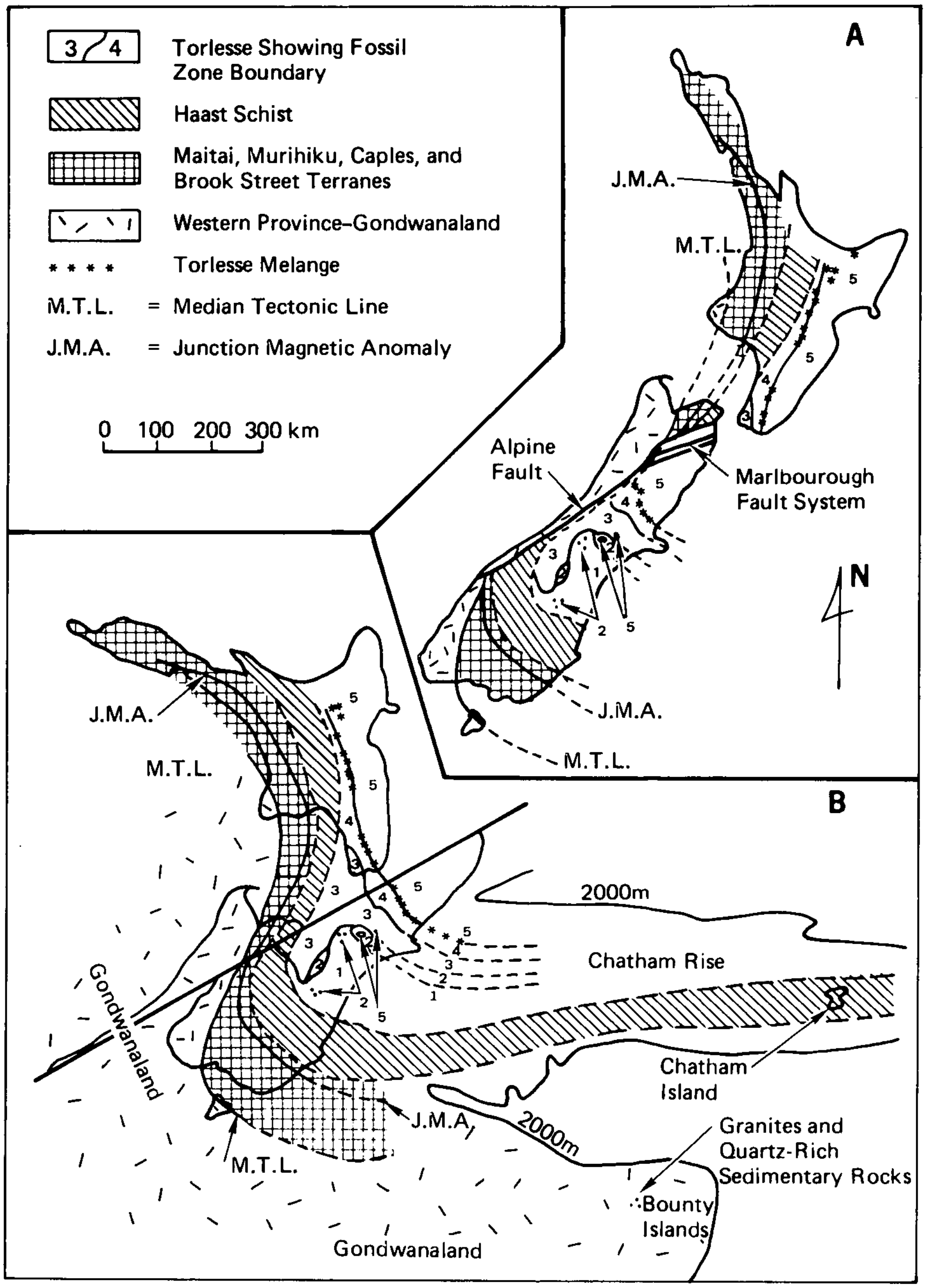



**Figure 6. A. Present pattern of major fossil zones and major occurrences of mélange for Torlesse rocks on the North and South Islands. Sources of South Island fossil zone and mélange data given in Figure 2. North Island fossil-zone boundaries drawn from data given by Speden (1976). North Island mélange localities from Sporli (1978). Numbers refer to fossil zones as follows: 1, Permian-Carboniferous; 2, Middle Triassic; 3, lower Upper Triassic? (*Torlessia*); 4, Upper Triassic; 5, Jurassic–Lower Cretaceous (Lower Jurassic represented by one South Island and three North Island localities only). B. Reconstruction prior to offset by Alpine Fault and associated faults. S-shaped oroclinal bend may be in part a postcollision feature. Fossil zones are shown with inferred continuations to the east. Haast Schist continuation inferred from presence of schist on Chatham Islands and Chatham Rise.**

sure is hidden by alluvium or covered by the Pacific Ocean. In addition, the trend of other Eastern Province terranes on the south part of the South Island, and the presence of Haast Schist on Chatham Island, indicate a regional east-west trend in areas east of the South Island.

2. Strike-slip movement along the Alpine Fault has displaced the three fossil zones and mélange on the North Island from their once connected counterparts on the South Island.

3. Accretion coincided with deposition from Permian time onward.

4. Accretion resulted in belts younging outward from the accretionary margin, in broad accord with other ancient and modern examples cited above.

These inferences lead to the fossil-zone reconstruction shown in Figure 6. The fossil zones are shown as east-west–trending and younging to the north. This suggests accretion onto a continental margin lying to the south.

There are some exceptions to this simple south-to-north progression. Two areas of Upper Jurassic strata lie south of the main Upper Jurassic zone. These are interpreted as forming an older uplifted accreted terrane, inboard of contemporary deeper-water deposition to the north. Possible tectonic settings include a subaerially exposed trench-slope-break high, or uplifted borderland. Shallow-marine and terrestrial deposits of Middle Triassic age may have had a similar origin. Some deep-marine *Torlessia*-bearing lower Upper Triassic(?) strata, and some possibly deep-marine Middle Triassic strata, lie to the west of the Permian zone. This arrangement could be due to extensional basin development inboard of the accretionary front (Landis and Bishop, 1972) or to subsequent tectonic disruption of the original belt pattern along the Alpine Fault.

### A Gondwanaland Source?

The suggestion of accretion to a south-lying margin points to the Western Province as the source terrane (Fig. 6); but most workers reject this on the grounds that the volcanogenic terranes intervene. However, there is no geologic evidence that requires the presence of the volcanogenic terranes in this position during pre-Jurassic times. Thus, a Western Province–Gondwana source should be considered.

In this regard, the Western Province, from all appearances, matches the source-terrane characteristics inferred from Torlesse sandstone composition. Sea-floor magnetic patterns and bathymetry show that the Western Province, including the Campbell plateau region (Fig. 1a), lay adjacent to the Marie Bird Land–Ross Sea area of western Antarctica until middle to Late Cretaceous times (Molnar and others, 1975; Cooper and others, 1982). Although tectonic dismemberment and covering of rock by ice and sea prevent a detailed understanding of this area during Torlesse depositional times, it has been possible to recognize a belt of late Paleozoic to Jurassic igneous activity situated on and parallel to the margin of the reconstructed Western Province–West Antarctica segment of Gondwanaland (Cooper and others, 1982). Thus, as far as is known, the geology of this area is in reasonable accord with a continental-margin, volcano-plutonic arc source, inferred herein from sandstone composition.

As with previous reconstructions, the presence of intervening volcanogenic rocks of the Eastern Province between inferred Torlesse source and depositional site clearly requires an explanation.

## VOLCANOGENIC TERRANES

### General Description

The volcanogenic terranes of the Eastern Province (Figs. 1a, 1b) are commonly inferred to represent various elements of an ancient arc-trench system (Coombs and others, 1976). These include: the Brook Street terrane (volcanic arc); Maitai-Murihiku terranes and Dun Mountain ophiolite terrane (forearc basin and underlying oceanic crust); and Caples terrane (trench complex). The following descriptions are for the south part of the South Island, where the terranes are best-exposed (Fig. 1a).

The *Brook Street terrane* lies on the "inner" or western edge of the Eastern Province and is separated from the adjacent "continental" Western Province by faults and intrusions that mark the Median Tectonic Line. The terrane consists of deeply dissected and discontinuously exposed outcrops of volcanogenic clastics, volcanic flows, and intrusives (Grindley, 1958; Waterhouse, 1964; Mutch, 1972; Mossman, 1973; Challis and Lauder, 1977; Houghton, 1977; Watters, 1978; Williams, 1978). Clastic rocks were deposited largely by sediment gravity flows in a marine environment. Rare, intercalated marine fossils are of Permian age. Interstratified volcanic flows consist primarily of basalt and andesite, with subordinate rhyodacite. In some areas, clastic rocks and flows lie in thick, apparently conformably sequences, which in one place measures 14 km (Houghton, 1981). In other areas, intrusives are predominant. These are largely granitic to gabbroic and include some ultramafics. Radiometric dates range from Permian to Early Cretaceous (≈250 to 112 m.y. ago), although the younger dates in this range are somewhat questionable (Aronson, 1968; Devereux and others, 1968; Houghton, 1977; Williams and Harper, 1978).

The Brook Street terrane is bounded on the north and east by a regional synclinorium formed by thick clastic sequences of the Maitai-Murihiku terranes. The contact is commonly faulted, but in places the Brook Street terrane is depositionally overlain by either an Upper Permian shallow-marine limestone facies of the Maitai terrane, known as the Productus Creek Group, or by Lower to Middle Triassic terrigenous clastics of the Murihiku terrane (Waterhouse, 1964; Houghton, 1977).

The northern limb of the synclinorium is underlain by the *Dun Mountain Ophiolite terrane* (Coombs and others, 1976), which consists of discontinuous exposures of ultramafic and associated rocks traceable continuously through the length of New Zealand by its associated magnetic anomaly (Junction Magnetic Anomaly of Hatherton, 1969). Although most outcrops are internally disrupted and tectonic mélange is common, where intact sequences are present, partial to complete ophiolite sequences are recognized.

Conformably overlying the ophiolite terrane are rocks of the *Maitai terrane*, here consisting of a 4- to 5-km-thick conformable sequence of mainly volcanogenic clastic rocks with subordinate tuff, limestone, and quartzofeldspathic sandstone, all of Upper Permian age (Wood, 1956; Grindley, 1958; Waterhouse, 1964; Carter and others, 1978; Landis, 1974a, 1980). Formations are recognized locally, some of which can be correlated with strata displaced by the Alpine Fault in the northern part of the South Island. Deposition was mainly by pelagic and sediment gravity flow mechanisms, probably in a deep-marine environment. Metamorphic grade is largely zeolite facies with locally occurring lawsonite-albite-chlorite facies.

The bulk and core of the synclinorium are composed of the *Murihiku terrane*. The contact between the Upper Permian Maitai and basal Lower Triassic Murihiku rocks is generally not exposed but is faulted where visible. *Murihiku strata* consist of up to 10 km of volcanogenic sedimentary rocks, of which about 80% to 90% are composed of subequal amounts of sandstone and mudstone, the remainder consisting of tuff and conglomerate (Boles and Coombs, 1977). Lithologically based formations are recognized locally (Speden, 1971; Boles, 1974), but lateral facies changes appear to prevent their recognition on a regional scale. Sub marine-fan, slope, shelf, and terrestrial de posits have been recognized (Carter an others, 1978). The sequence is moderatel fossiliferous and except for probably mino or local breaks in the record, a continuous conformable sequence from Lower Triassic to Middle Jurassic is present (Campbell and Coombs, 1966; Speden, 1971; Boles, 1974). Younger strata of Upper Jurassic age are present in a small, fault-bounded sliver near the Alpine Fault (McKellar and others, 1962). Metamorphism to the zeolite facies occurs throughout (Coombs, 1954; Boles and Coombs, 1977).

The *Caples terrane* consists of a belt of highly deformed volcanogenic rocks, separated from the Dun Mountain Ophiolite Belt to the south by the Livingstone-MacPherson fault, and to the north passing with increasing metamorphic grade into the Haast Schist. On the north part of the South Island, correlative rocks are known as the Pelorus terrane. Lithologies include graywacke and argillite, with subordinate spilite, limestone, and chert. Clastic rocks are predominantly flyschlike and were deposited in a deep-marine environment (Carter and others, 1978; Castle, 1978; Turnbull, 1979a). Rare fossil localities indicate a Permian and possibly Triassic age (Campbell and Campbell, 1970; Turnbull, 1979a). Structure is similar to Torlesse structure: multiple deformation, overturned sequences, recumbent and isoclinal folds, and broken formation–mélange are all recognized (Bishop and others, 1976; Turnbull, 1979a). Despite structural complexities, formations have been mapped in some areas. Near the Alpine Fault, an apparently conformable sequence 7,000 m thick is recognized and divided into seven formations (Kawachi, 1974; Bishop and others, 1976). Farther to the southwest, similar formations are recognized, but whether they are truly laterally continuous counterparts is difficult to assess (compare Turnbull, 1979a). Metamorphism is to prehnite-pumpellyite to greenschist facies, with lawsonite known from several localities (Landis and Coombs, 1967; Kawachi, 1974; Bishop and others, 1976).

### Sandstone Composition

Most Maitai, Murihiku, and Caples sandstones are poorly to moderately well-sorted, have angular to subangular grains, and are composed largely of volcanic lithic fragments and plagioclase (Dickinson, 1971; Speden, 1971; Boles, 1974; Landis,

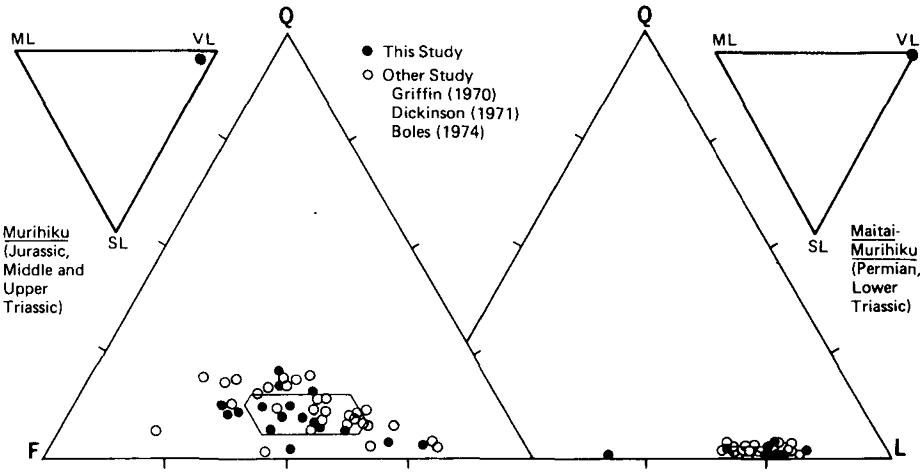



**Figure 7. Q:F:L data and first standard deviation fields for the two Maitai-Murihiku petrofacies.**

1974a; Turnbull, 1979a; MacKinnon, 1979, 1980a). Quartz content (% Q) is usually less than 15%. Volcanic lithic fragment composition varies from basalt to rhyolite. Rare nonvolcanic rock fragments include hornfels and volcanogenic sedimentary rocks. Feldspar is largely volcanic-derived plagioclase. Heavy minerals include mica, hornblende, pyroxene, epidote, sphene, garnet, tourmaline, zircon, and apatite. Metamorphism has extensively altered most Maitai sandstones, although largely intact samples can be found with care. Murihiku sandstones are generally of a lower metamorphic grade and thus are better preserved.

Two major petrofacies are recognized for Maitai-Murihiku sandstone by MacKinnon (1980a), who combined new data with those of previous workers (Griffin, 1970; Dickinson, 1971; Boles, 1974). These are a Permian through Lower Triassic Maitai-Murihiku petrofacies, and a Middle Triassic through Jurassic Murihiku petrofacies. In addition, plagioclase arenites (for example, Q:F:L = 20:79:1; P/F = 0.88) are known from a thin horizon of the Maitai [Tramway (Annear) Formation, Landis, 1974b, 1980] and from a few Jurassic Murihiku beds (MacKinnon, 1980a).

Permian and Lower Triassic Maitai-Murihiku petrofacies sandstones form a narrowly defined range of compositions with average Q:F:L values of 2:26:72 (Fig. 7 and Table 2). In no sample is % Q greater than 5%. Lithic fragments are nearly all volcanic (Lv/L = 0.97) and most are basic to intermediate in composition. Feldspar is virtually all plagioclase (P/F = 0.99), and mica content (% M = 0.1) is consistently low.

Middle Triassic and Jurassic Murihiku petrofacies sandstones show a wider variation in composition than do the older sandstones from these terranes. Most have considerably higher quartz and feldspar contents; average Q:F:L values are 11:40:49 (Fig. 7 and Table 2). Also higher are the mica content (% M = 1.0), ratio of plagioclase to total feldspar (P/F = 0.85), and ratio of volcanic to nonvolcanic lithic fragments (Lv/L = 0.90). Boles (1974) and Boles and Coombs (1977) showed that volcanic lithic fragments are predominantly rhyolite and dacite in most Middle Triassic and some Upper Triassic sandstones, whereas andesite fragments dominate in most younger sandstones.

Examination of 17 relatively unaltered Caples sandstone samples shows that their compositions are similar to the other two major petrofacies combined (Figs. 8 and 9; Table 2). Average Q:F:L composition is 7:26:67. Lithic fragments are almost all volcanic (Lv/L = 0.94) and range in composition from rhyolite to basalt. Feldspar is largely plagioclase (P/F = 0.93) and mica content is low (% M = 0.3). A detailed petrofacies analysis of Caples sandstones has been presented by Turnbull (1979b). However, his data are not incorporated with my work because in my view (MacKinnon, 1980a), quartz content has been significantly overestimated, and his samples are too highly altered to give data of adequate comparable reliability.

TABLE 2. COMPOSITION OF MAITAI, MURIHIKU, AND CAPLES SANDSTONES

| Petrofacies | Maitai-Murihiku (Permian–Lower Triassic) | | Murihiku (Middle Triassic through Jurassic) | | Caples (Permian-Triassic?) | |
|---|---|---|---|---|---|---|
| No. of samples | 21 | | 50 | | 17 | |
| | $\bar{x}$ | *range* | $\bar{x}$ | *range* | $\bar{x}$ | *range* |
| Grain size in mm | 0.38 | (.25–.59) | 0.38 | (0.15–0.9) | 0.35 | (.21–.59) |
| % framework | 80 | (73–88) | 78 | (72–97) | 87 | (78–92) |
| % matrix (< .03 mm) + cement + alterite | 20 | (12–27) | 12 | (3–28) | 13 | (8–22) |
| | $\bar{x}$ | $\sigma$ | $\bar{x}$ | $\sigma$ | $\bar{x}$ | $\sigma$ |
| Q | 2 | (1.0) | 11 | (5.0) | 7 | (5.7) |
| F | 26 | (8.5) | 40 | (11.3) | 26 | (8.1) |
| L | 72 | (8.4) | 49 | (13.8) | 67 | (12.1) |
| P/F | 0.99 | (0.02)* | 0.85 | (0.11) | 0.93 | (0.6)* |
| Lv/L | 0.97 | (0.04) | 0.90 | (0.12)** | 0.94 | (0.5) |
| %M | 0.1 | (0.1) | 1 | (1.1) | 0.3 | (0.5) |

*Does not include data from two Maitai and seven Caples samples, because potassium feldspar grains were probably albitized during metamorphism.

**Does not include data from 22 samplesreported in Griffin (1970), because his rock-fragment identifications are considered inaccurate.

*Note:* Point count data for Maitai, Murihiku, and Caples sandstones. Data for Maitai and Murihiku sandstones are from Griffin (1970), Dickinson (1971), Boles (1974), and MacKinnon (1980a), as compiled by MacKinnon (1980a). Data for Caples sandstones are from MacKinnon (1980a). Procedures and definitions of parameters used for MacKinnon's point counts are as outlined in the footnote for Table 1. Explanations for symbols are same as for Table 1. All thin sections of samples from other workers, except Dickinson's (1971), were examined to ensure the reliability of the reported point counts.

## Discussion

Key factors supporting the interpretation that the volcanogenic terranes represent an arc-trench system include: (1) the spatial relationships anoeval nature of the terranes; (2) compatibility of the arc-derived volcanogenic sandstones of the Maitai, Murihiku, and Caples terranes with derivation from the Brook Street terrane volcanic arc; (3) depositional relationships of the Brook Street terrane and onlapping Maitai-Murihiku strata; and (4) the simple structure, generally low-grade burial metamorphism, and underlying ophiolite of the Maitai-Murihiku terranes (forearc basin deposits) as contrasted with the complex structure, relatively high P:T ratio metamorphism, and intercalated limestone-chert-volcanic association of the Caples terrane (trench complex deposit).

Although this simple forearc-trench interpretation is attractive, several variations

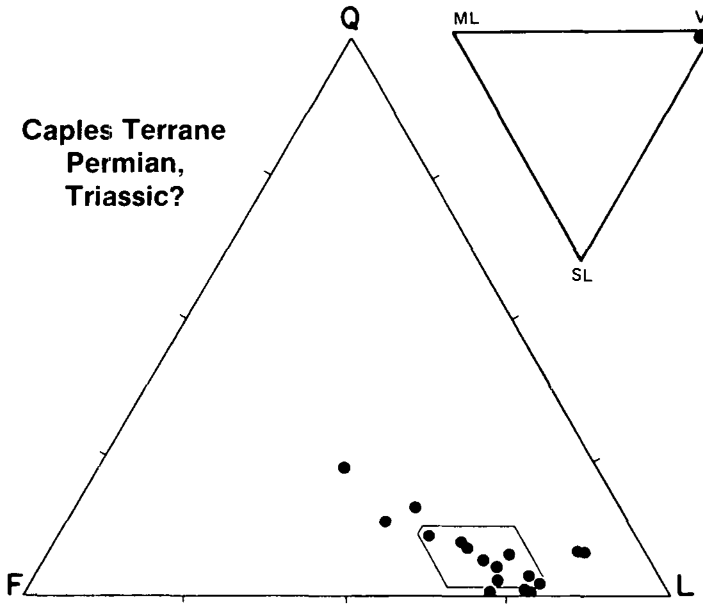



Figure 8. Q:F:L data and first standard deviation field for Caples terrane sandstones.

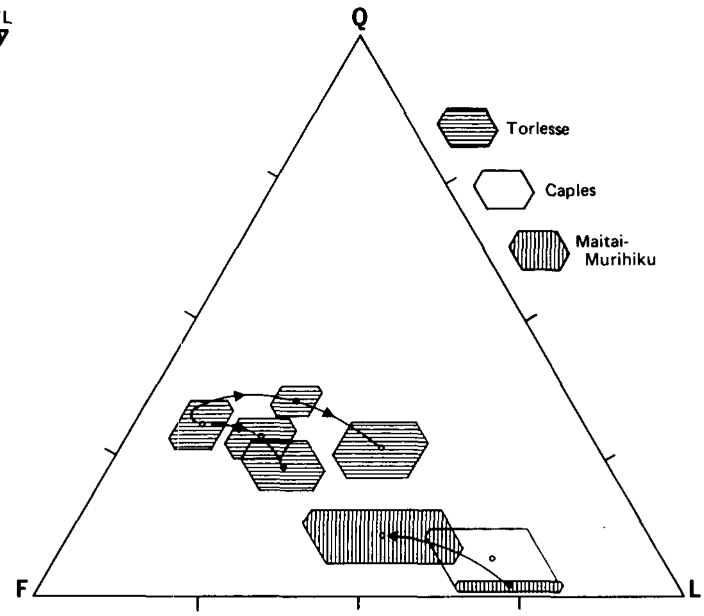



Figure 9. Comparison of Q:F:L first standard deviation fields for sandstones from the Torlesse, Maitai-Murihiku, and Caples terranes.

have also been considered. Coombs and others (1976) discussed the possibility that the Dun Mountain Ophiolite Belt originated in a back-arc basin (that is, northeast-directed subduction west of the Brook Street terrane), with subsequent reversal in subduction polarity in the Permian. Williams and Smith (1979) have presented evidence that the Brook Street terrane near the Alpine Fault may be composed of two separate arcs that later were tectonically juxtaposed.

Howell (1980) proposed that the Caples terrane was allochthonous with respect to the other volcanogenic terranes, having been juxtaposed from a distant, unknown location after Caples deposition was complete. Such a scenario cannot be ruled out because Caples and Maitai-Murihiku strata are separated everywhere by a fault. However, substantial evidence indicates otherwise.

Similar detrital composition of Caples and Maitai terrane rocks is the most compelling evidence for a common source for these terranes. Q:F:L, Lv/L and other compositional parameters for the Maitai-Murihiku versus Caples terranes are all closely comparable (Figs. 7, 8, and 9; Table 2). In addition, they have similar non-opaque heavy-mineral assemblages, dominated by hornblende, pyroxene, and epidote, and also including zircon, sphene, apatite, garnet, and tourmaline. Although it can be argued that these similarities are the result of derivation of Maitai-Murihiku and Caples detritus from separate volcanic arcs of similar composition, this is unlikely. Volcanic arc-derived sands, although grossly similar in composition, show substantial variation in detail. For example, modern sands shed from various Pacific volcanic arcs are easily distinguished by their compositional differences (Harrold and Moore, 1975; Kulm and Fowler, 1974; Stewart, 1978).

An interrelationship between Permian Maitai and Caples terrane rocks is also suggested by stratigraphic features. It may be significant that these are the only rocks in the Eastern Province in which formations are recognized that can be traced laterally for long distances. Stratigraphic and lithologic similarities were noted previously by Landis (1969) and Kawachi (1974). Further comparative study of the Maitai and Caples terranes may offer the best prospect of establishing a firm linkage between these terranes.

The nature of the Brook Street terrane volcanic arc is a key factor in any reconstruction. Considerable evidence shows that it was an *island* arc and not a continental volcanic arc, as proposed by Force (1974) and implied in Bradshaw and others' (1980) reconstruction. This is indicated by Brook Street terrane rock types, including: the dominance of fragmental material over flow rocks; presence of intercalated marine fossils; and absence of continental-type deposits as roof pendants or country rock.

Furthermore, the compositions of Maitai, Murihiku, and Caples sandstones strongly indicate an island-arc source. Modern island arc–derived sandstones consistently have a Q:F:L quartz content of less than 20% (Dickinson and Valloni, 1980). This is compatible with the New Zealand sandstones, which average about 12%. In contrast, marine sands deposited offshore of modern continental volcanic arcs (for example, the Cascade Range of the northwest United States) have a considerably higher % Q (20% to 50%) and considerably lower Lv/L and P/F ratios (Kulm and Fowler, 1974; Dickinson and Valloni, 1980) than do the New Zealand sandstones, because of dilution by nonvolcanic sources before reaching the sea.

Island arcs range in character from immature intrapacific types (such as the Marianas) to mature arcs with substantial sialic components (such as Japan). Compositions of sands derived from various Pacific island arcs, given by Okada (1973), Harrold and Moore (1975), and Stewart (1978), show that relative arc maturity is reflected by variations in quartz content (% Q) and in ratios of volcanic lithics to total lithics (Lv/L) and plagioclase to total feldspar (P/F). Immature arcs have a lower % Q and higher Lv/L and P/F ratios than do mature arcs. Considering the New Zealand sandstones, most Permian and Lower Triassic Maitai-Murihiku sandstones and some Caples sandstones have very high Lv/L and P/F ratios (≈0.98) and low % Q content (≈3%); these correspond well with modern immature to submature arc-derived sands. Most Middle Triassic through Jurassic Murihiku sandstones and some Caples sandstones have a relatively higher % Q (≈11%) and lower Lv/L (≈0.90) and P/F (≈0.85) ratios, indicative of derivation from a submature arc. Of the studied Pacific arcs, the Aleutian chain sheds sands that are most similar to the New Zealand sandstones (compare Stewart, 1978).

## RELATIONSHIPS OF THE TORLESSE AND VOLCANOGENIC TERRANES

The Torlesse and the volcanogenic terranes of the Eastern Province are clearly distinguished by differences in detrital composition and provenance. Whereas the quartzofeldspathic Torlesse was derived from a tectonically active continental-margin source, the Caples, Maitai, and Murihiku were derived from a volcanic island arc. Comparisons of sandstone composition of the major petrofacies (Fig. 9) show that there is no overlap in Q:F:L first standard deviation fields between the two compositional suites. The two depositional sites with respective source terranes must have been largely or entirely separated throughout their depositional histories.

Despite this, there is evidence to suggest that the origins of the Torlesse and the volcanogenic terranes were not entirely unrelated. For one, they were deposited during the same time span. In addition, their faunas are strikingly similar (although with some rare exceptions; Campbell, 1974), indicating that both were deposited in the same faunal province (Andrews and others, 1976). Furthermore, Landis and Bishop (1972) pointed out an apparent sympathetic relationship in depositional rates between the Torlesse and the Murihiku: periods of rapid sedimentation of Murihiku strata correspond to periods of little or no recognized sedimentation in the Torlesse and vice versa. Finally, the inferred polarity of subduction associated with both the Torlesse and volcanogenic terranes is the same.

Obviously, none of the above similarities constitutes a conclusive link between the Torlesse and the volcanogenic terranes. However, when taken together, it is unlikely that all of these similarities are the result of mere coincidence. Rather, they suggest some sort of interrelated although spatially separate origin.

The earliest firm geologic connection between the two belts is the concurrent metamorphism of Caples and Torlesse strata to Haast Schist. The oldest K-Ar cooling dates from the schist range back to 200 m.y. ago (latest Triassic–Early Jurassic) (D. G. Bishop, 1980, personal commun.) and may indicate that the belts were juxtaposed at this time, although still with largely separate sources. However, these older dates are from pumpellyite-actinolite–facies rocks, and it is possible, although unlikely, that they reflect metamorphism at geographically separate localities prior to collision. Regardless, juxtaposing was complete before 140 m.y. ago, as by this time, uplift and cooling of the bulk of the Haast Schist (greenschist facies) was under way (Adams, 1979).

## RECONSTRUCTION

I have proposed that the Torlesse was accreted in north-younging, east-west–trending belts (with respect to present-day geography) outboard of a continental source to the south, probably Gondwanaland (Fig. 6). In contrast, the volcanogenic terranes were deposited in an island arc-trench setting. Furthermore, the contrasting suites are coeval, have similar faunal elements, show a sympathetic relationship in depositional rates, and have similar associated subduction polarities. The following reconstruction incorporates these points with a "collision" model similar to the reconstructions initially put forth by Blake and others (1974) and Coombs and others (1976).

In Permian and Triassic time, the Torlesse was deposited in trench-slope or borderland basins along a trench–transform margin fronting Gondwanaland (Fig. 10). The main source terrane was an active volcano-plutonic arc of high relief running parallel to the Gondwana coastline. Deposition was spasmodic, but voluminous, and was accompanied by concurrent deformation and accretion, resulting in parallel belts of Torlesse rocks younging outward from the Gondwanaland margin. Indurated and partially metamorphosed Torlesse rocks were locally exposed to erosion in trench-slope-break or borderland settings, with deposition of shallow-marine and terrestrial deposits in these areas during the Middle Triassic (for example, Corbies Creek, Mount Potts). The single occurrence of limestone containing Permian fusulines (which have a lower latitude–Tethyan affinity than is generally ascribed to most Torlesse fossils) probably formed as a capping on a submarine volcanic high that subsequently was carried south to higher latitudes via sea-floor spreading and incorporated into the Torlesse during subduction. Carboniferous conodont-bearing limestone and associated volcanics probably had a similar origin.

While the Torlesse was being deposited, the Brook Street volcanic arc and associated terranes were forming to the west of the Torlesse site. Maitai-Murihiku strata were deposited in a forearc basin, whereas Caples rocks were deposited in trench-slope and trench basins. Given that the Brook Street terrane was an island arc, there must have been oceanic crust behind the arc from Permian through Early Jurassic time. This is shown as a marginal sea (Fig. 10).

Both the Caples trench and the Torlesse trench-transform system are shown as laterally separate parts of a convergent margin of the same two plates. Initial formation of both source terranes may have occurred simultaneously in Permo-Carboniferous times, in response to initiation of convergent motion during a major realignment of plate motion. Deposition at both sites continued through Triassic-Jurassic times, albeit sporadically in the Torlesse, in response to continuing convergence of the same plates.

Such a scenario explains why the Torlesse and volcanogenic terranes are coeval, and why their associated subduction polarities are similar. In addition, similarities in fauna are explained because both depositional sites, although laterally separate, were situated at approximately the same latitude. Furthermore, the observed sympthetic variations in depositional rates might result because any shifts in rate or direction of plate motion would simultaneously affect both source terranes, possibly changing their rates of uplift, magmatic intensity, or both, and thereby influence rates of deposition.

In latest Triassic or Early Jurassic time (190–200 m.y. ago), the Torlesse was rafted into the volcanic-arc system, in part via transform faulting approximately parallel to the Gondwanaland margin, but with some element of obliqueness at least during the collision event itself (compare Force, 1974; Ward and Sporli, 1978). The collision resulted in tectonic thickening of Torlesse and Caples rocks at the plate interface and

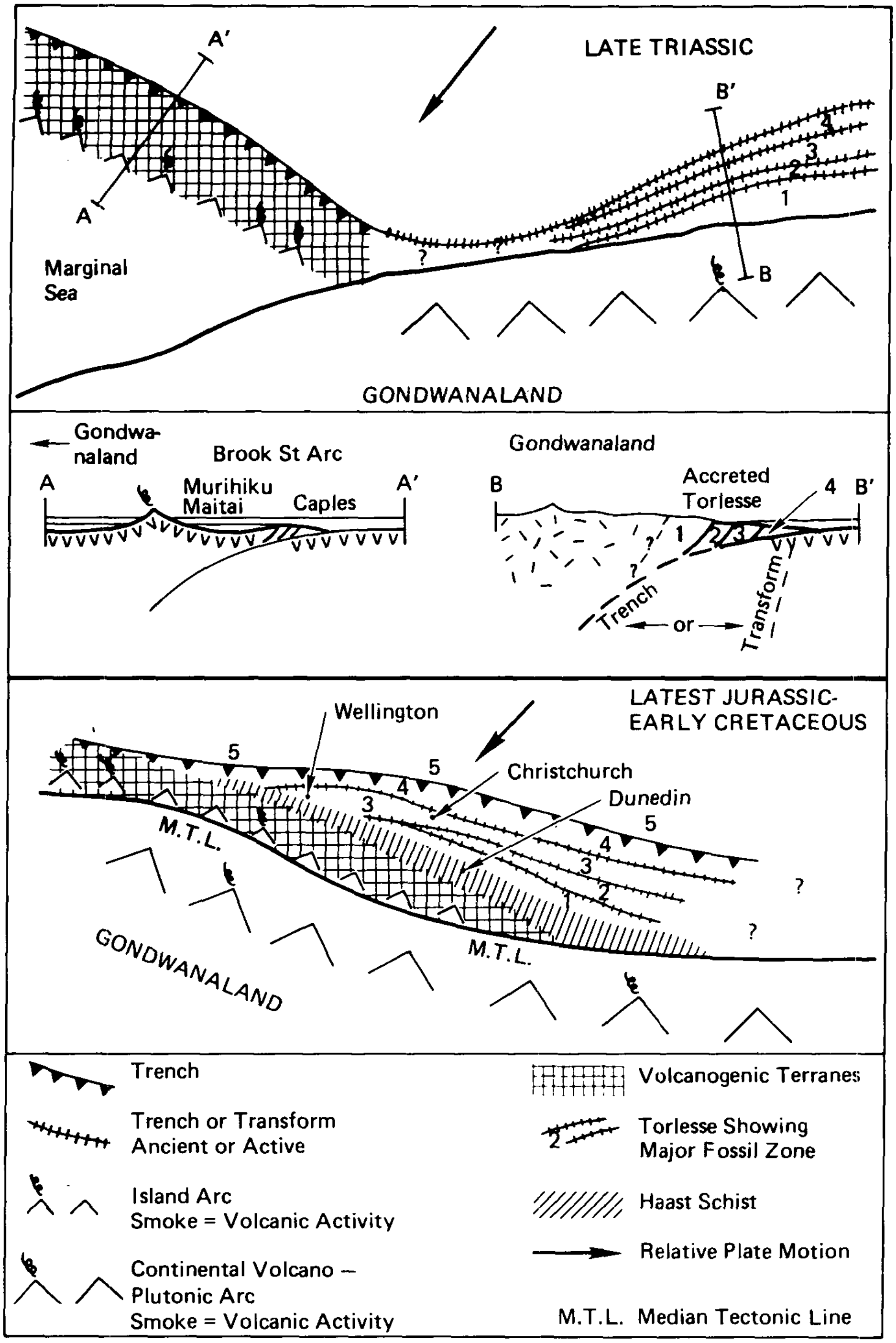



**Figure 10. Top and middle: reconstruction in Late Triassic times showing Torlesse accumulating in trench-transform settings off Gondwanaland, as the volcanogenic terranes form in an island-arc–trench setting to the west. Older trench-transform margins are shown in the Torlesse as separating major fossil zones; however, these margins may have also been active within zone boundaries.**

**Bottom: latest Jurassic–Early Cretaceous reconstruction following closing of the marginal sea behind the volcanic arc, and collision of the Torlesse with the volcanogenic terranes following strike-slip movement of the Torlesse roughly parallel to the Gondwanaland margin.**

metamorphism to Haast Schist. Metamorphic climax occurred during the Jurassic (140–195 m.y. ago).

Juxtaposition of the Brook Street terrane with Gondwanaland (Western Province) was accomplished by closure of the marginal sea by subduction or by strike-slip (transform) movement. The suture is represented by the Median Tectonic Line (Landis and Coombs, 1967). Timing of closure and cessation of volcanism is uncertain and probably varied significantly along the length of the arc. On the south part of the South Island, voluminous volcanogenic detritus, including tuffs, was deposited through Early Jurassic time (to ≈ 160 m.y. ago). The only record of Upper Jurassic arc-derived detritus in this area is from one small fault-bounded sliver near the Alpine Fault (McKellar and others, 1962). Intrusive relations along the Median Tectonic Line in the Eglinton area indicate that juxtapositioning of the Brook Street terrane and Western Province was complete by latest Jurassic–Early Cretaceous time (≈ 140 m.y. ago) (Williams and Harper, 1978). Thus, closure of the marginal sea and cessation of major Brook Street terrane volcanism in the south part of South Island occurred some time in the Late Jurassic (140–160 m.y. ago). On the North Island, a thick succession of Upper Jurassic volcanogenic strata (that is, Murihiku) is present (Stevens and Speden, 1978). Thus, closure and cessation of arc volcanism in this area may have occurred at a relatively later date (≈ 140 m.y. ago).

Deposition of the Torlesse may have ceased or slowed during the Early Jurassic, as a response to the Torlesse-Caples collision event. A new subduction regime may have formed during that time or at the beginning of the Late Jurassic. The initial location of the subduction zone is marked by the Esk Head Mélange.

Voluminous deposition resumed in the Late Jurassic and continued into the Cretaceous. During that time, the source was dominated by older, in-part metamorphosed Torlesse terrane, newly uplifted along the collision front. Some Upper Jurassic shallow-marine and terrestrial sediments were deposited on this newly uplifted terrane (for example, Clent Hills). Some sediment also may have been derived from a Gondwana source to the southeast or possibly from across the schist belt from the then-sutured volcanogenic terranes and Gondwanaland (Fig. 10).

It is possible to envision a much earlier Torlesse-Caples collision event, possibly in the Early Triassic, followed by lateral feed and accretion of the Torlesse in the trench associated with the Brook Street terrane arc (compare Sporli, 1978). However, several problems are inherent in this model. First, there are no apparent proximal-distal facies changes recognized in Torlesse rocks, as would be expected in such a model; rather, strata are consistently dominated by thick- and very thick-bedded sandstone and apparently were deposited close to their source. Second, tuffs are common in the volcanogenic terranes, particularly in Triassic time, and their rarity in the Torlesse is difficult to explain if the volcanogenic terranes formed close by. Third, such a model becomes complex if some Caples rocks are of Triassic age, as seems likely; this would necessitate an unlikely forearc basin site for these complexly deformed "eugeosynclinal" strata, whereas coeval Torlesse sediment was accreted in a subduction complex outboard of this.

The Gulf of Alaska (Fig. 11) is a modern situation in which analogues of all the essential elements of the Eastern and Western Provinces of New Zealand are present in an arrangement similar to that envisioned prior to collision (Fig. 10). A continental volcano-plutonic arc (Alaska, St. Elias Ranges; compare Western Province, Gondwanaland) and older uplifted flysch deposits in coastal ranges (Chugach Mountains; compare reworked Torlesse source) have been supplying Torlesse-like quartzofeldspathic sands to the Gulf of Alaska area during Tertiary and Quaternary time (Hayes, 1973). Also, quartzofeldspathic sands on the Aleutian Abyssal Plain, probably derived from trench-transform margins along the northwest coast of North America, are now being rafted into the east-central part of the Aleutian trench (Stewart, 1976). At the same time, the Aleutian arc (compare Brook Street terrane) has been shedding volcanogenic sands (Stewart, 1978), similar to the volcanogenic sandstones of New Zealand, to forearc basin (compare Maitai-Murihiku) and trench and trench-slope basin (compare Caples) sites.

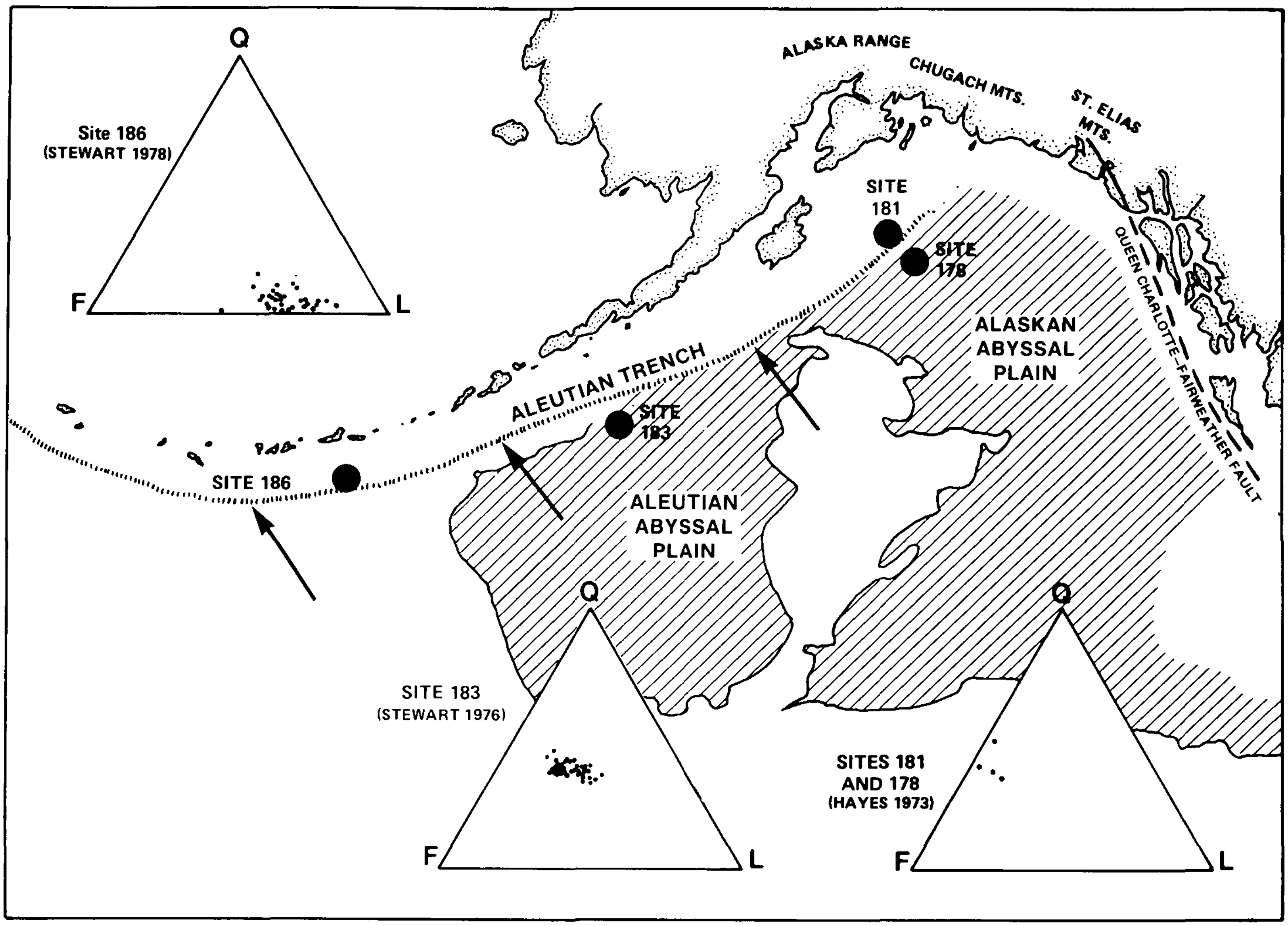



**Figure 11. Geologic setting and composition of sands from the Gulf of Alaska area. Arrows show relative motion between Pacific and American plates.**

Like the New Zealand situation, the volcanogenic and quartzofeldspathic sources and depositional sites are discrete, but both deposits will contain similar faunal elements; furthermore, both deposits are coeval, as their origins are in large part the result of relative movement between the same two plates (Pacific and North American). Subsequent changes in sea-floor spreading patterns, including large-scale strike-slip (transform) faulting, can be envisioned that would further juxtapose the two suites in a manner similar to the present arrangement of Eastern Province terranes in New Zealand.

## ACKNOWLEDGMENTS

I thank C. A. Landis for continuous help and encouragement during my nearly four-year stay at the University of Otago, New Zealand. Thanks also to J. D. Campbell, R. M. Carter, and D. S. Coombs for support, encouragement, and discussions, and to many others on the faculty and staff of the Geology Department, University of Otago. This paper was significantly improved through reviews by M. C. Blake, Jr., D. S. Coombs, D. G. Howell, C. A. Landis, and T. H. Nilsen. Research grants from the University of Otago covered field expenses. Chevron Oil Field Research Company provided technical assistance in preparing the paper.

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Manuscript Received by the Society December 28, 1981
Revised Manuscript Received August 2, 1982
Manuscript Accepted August 4, 1982