© *Journal of the Royal Society of New Zealand, Volume 13, Number 3, 1983, pp. 107-127*

Middle Triassic estuarine deposits near Benmore Dam, southern Canterbury and northern Otago, New Zealand

G. J. Retallack*

The hills around Benmore Dam are formed of complexly-deformed, meta-sediments of the Torlesse Supergroup. These include a narrow, 130-m-thick sliver of schists and meta-siltstone of Permian age, called the Akatarawa Formation (new name). This formation includes a marker bed of fossiliferous limestone, limestone breccia and ferruginized volcanics, deposited in a quiet, open marine shelf environment, and in warm temperate to tropical water termperatures.

The remaining thick (> 2 km) sequence of Torlesse rocks are of Middle Triassic age (Ladinian international or Kaihikuan local stage), and are here called the Otematata Group. The basal formation of this group is the Black Jacks Conglomerate (new name), which was deposited in braided streams of a deep, narrow valley in a mountainous landscape of indurated quartzofeldspathic sandstones. Interbedded shaly units are most common near the top of the Black Jacks Conglomerate, where they contain abundant fossil plants of Middle Triassic age (Late Anisian to Ladinian). Low-diversity assemblages of fossil plants and possible ice-disrupted palaeosols are evidence of a cool temperate or subantarctic palaeoclimate and palaeolatitude. Fossil marine algae and likely mangal vegetation found near the top of the formation may have lived in an estuary or fiord where braided streams debouched into the sea. The Black Jacks Conglomerate is conformably overlain by the Spillway Formation (new name), which forms the upper part of the Otematata Group. The Spillway Formation includes thick beds of sandstone, which are occasionally conglomeratic, as well as units of rhythmically bedded siltsone and shale. It was deposited in beaches, offshore bars and other shallow marine environments. Marine fossils are rare and poorly preserved in the Spillway Formation, but are of Ladinian age (Kaihikuan local stage).

All of these units have been isoclinally folded during latest Triassic to Cretaceous orogenic activity. The main mass of Black Jacks Conglomerate is folded into the Desolation Syncline (new name), and partly overthrust within the Glen Begg Shear Zone (new name) onto and into the overlying Spillway Formation. Isoclinal folds and the shear zone are disrupted by numerous, near-vertical faults of late Tertiary and Quaternary age, such as the Nettle, Briar, Acaena, and Bugloss Faults (all newly named). The last-mentioned two faults completely enclose the Akatarawa Formation, thus obscuring any former stratigraphic relationship with the Otematata Group.

INTRODUCTION

In the hills southeast of Benmore Dam (southern Canterbury) and northwest of the nearby town of Otematata (northern Otago) a complexly-deformed sequence of Ladinian (Kaihikuan local stage) rocks is exposed. Like rocks of comparable age in Tank Gully, near Mt Taylor (Oliver, 1979; Oliver *et al.*, 1982), and near Lake Benmore (Force and Force, 1978) in Canterbury, and southwest of Otematata, in northern Otago (Retallack and Ryburn, 1982), these sediments were evidently deposited in shallow marine and terrestrial environments. They are additional evidence of a Middle Triassic shoreline in the predominantly deep-marine (Hicks, 1981; Howell, 1981) Torlesse rocks, which form much of the spectacular alpine scenery of the South Island of New Zealand. Although these various Middle Triassic coastal deposits of Torlesse rocks are broadly similar, each has distinctive features, produced in specific local palaeoenvironments.

* Department of Geology, University of Oregon, Eugene, Oregon 97403, U.S.A.

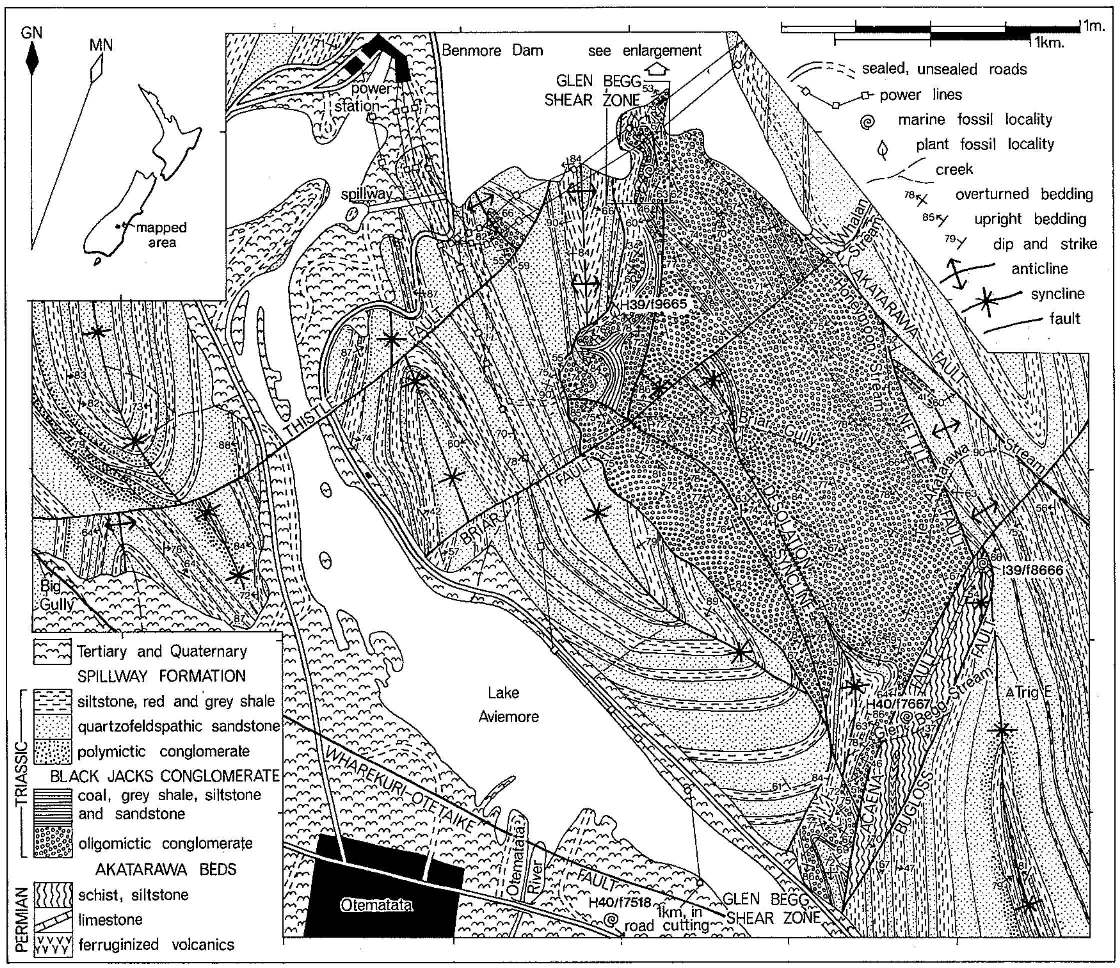


Fig. 1—Geological map of the area around Benmore Dam, near Otematata, southern Canterbury and northern Otago, New Zealand. Grid ticks are after N.Z.M.S. map S117.

(Note added in press: For Akatarawa Beds, please read Akatarawa Formation.)

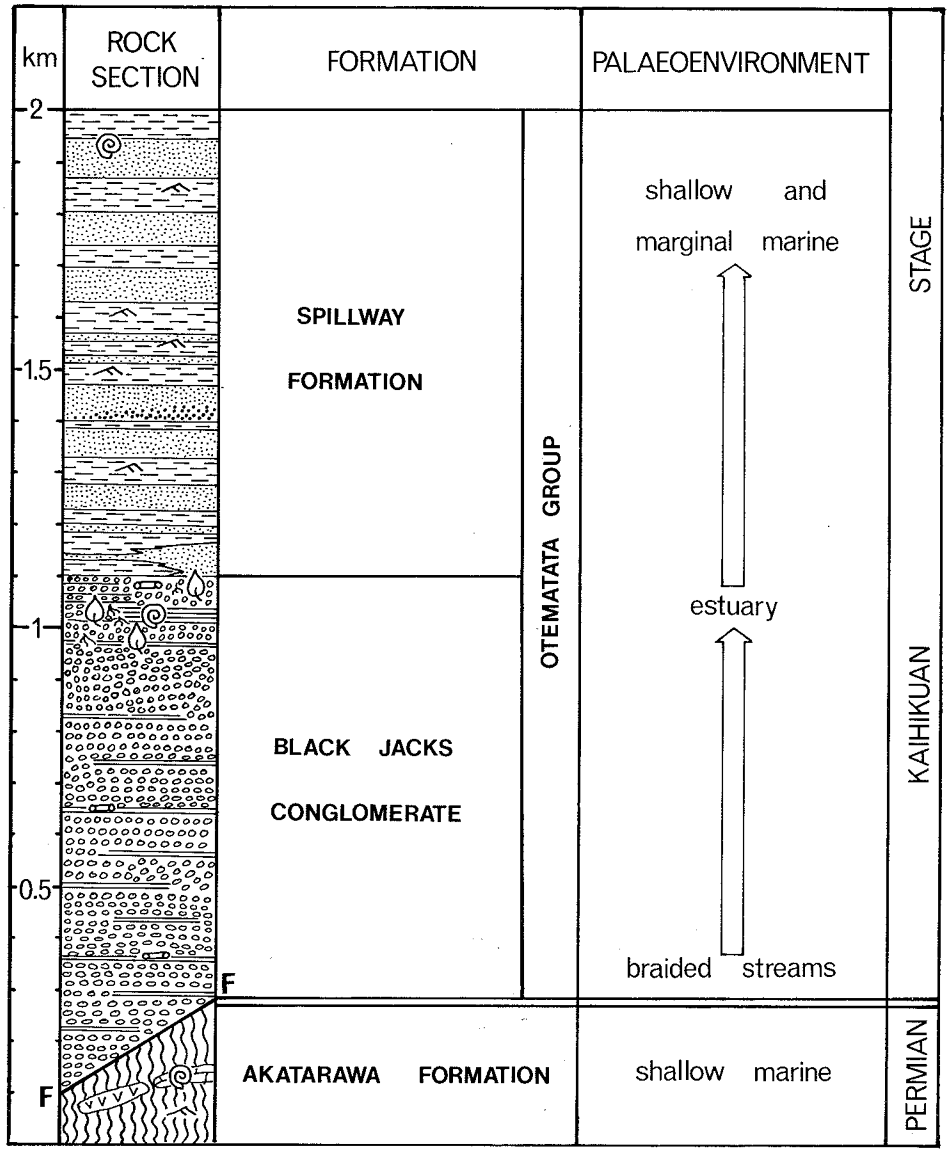
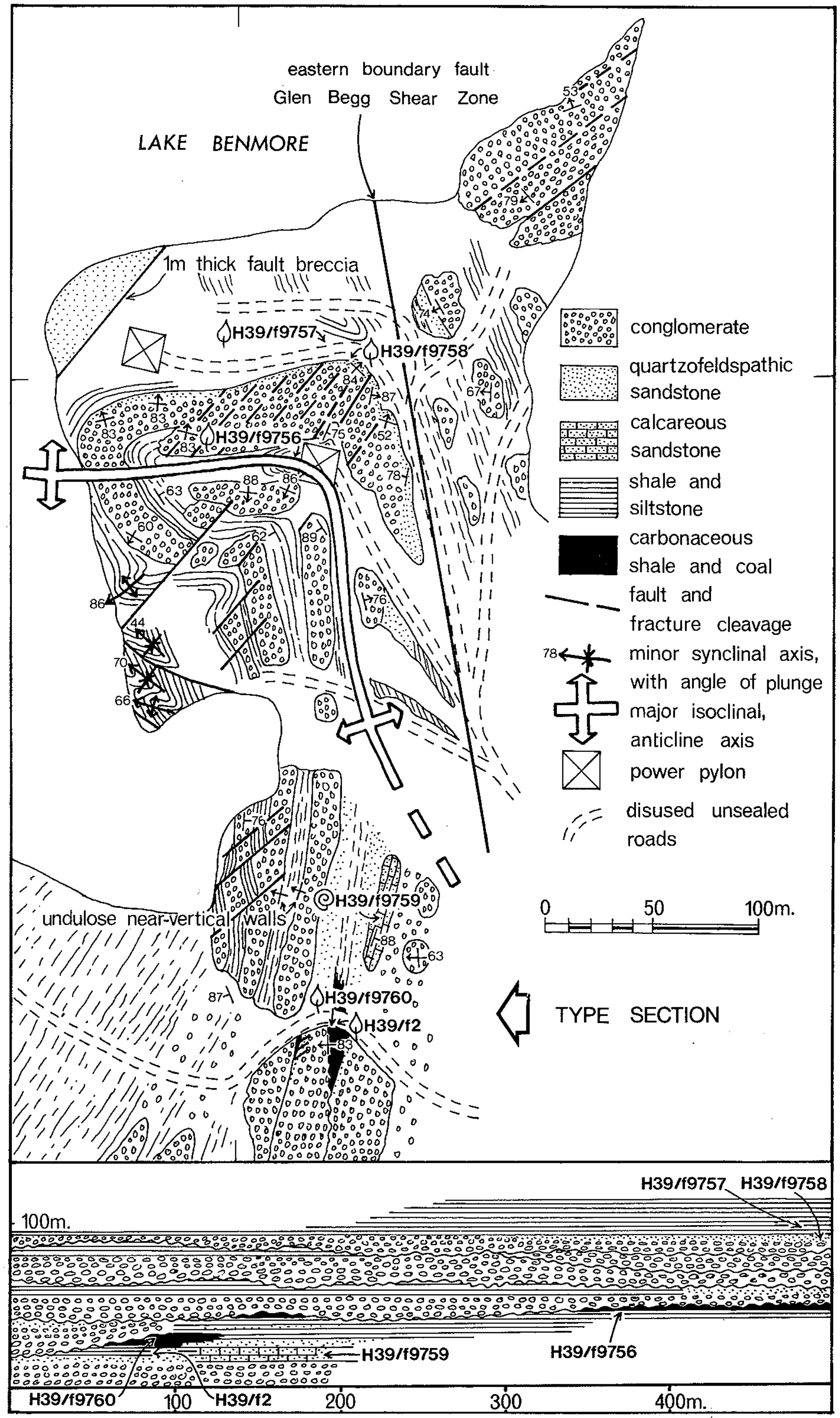


Fig. 2—Stratigraphy and relationships of formations of Otematata Group and adjacent Akatarawa Formation. Lithological key as for Fig. 1, other symbols after Fig. 7.

This paper is an attempt to reconstruct in detail the former environments and biota of the Middle Triassic meta-sedimentary rocks near Benmore Dam.

Fossil plants from what was at that time the future site of Benmore Dam were first described by Shona Bell in a publication which includes geological notes by H. J. Harrington and I. C. McKellar (Bell *et al.*, 1956). Additional palaeontological discoveries from an unpublished regional mapping project (Shu, 1964) were later incorporated into Campbell and Warren's (1965) discussion and listing of fossil localities in Torlesse rocks. Smale (1980a,b) made a detailed study of a distinctive conglomerate near Te Akatarawa homestead. He thought that this conglomerate was of Permian age, but it is here mapped as part of the Middle Triassic sequence.


eastern boundary fault
Glen Begg Shear Zone
LAKE BENMORE
1m thick fault breccia
H39/f9757
H39/f9758
H39/f9756
H39/f9759
H39/f9760
H39/f2
undulose near-vertical walls
conglomerate
quartzofeldspathic sandstone
calcareous sandstone
shale and siltstone
carbonaceous shale and coal
fault and fracture cleavage
minor synclinal axis, with angle of plunge
major isoclinal, anticline axis
power pylon
disused unsealed roads
0 50 100m.
TYPE SECTION
100m.
100
200
300
400m.

The interpretations reported here resulted from my own field work in 1975, mapping in as much detail as possible the small peninsula (Fig. 3) closest to Bell's and Shu's fossil localities, which are now under the water of Benmore Dam. During the summers of 1976 and 1977, this mapping was extended to include a larger area (Fig. 1) in an effort to understand the relationships of the plant-bearing unit with surrounding rocks, especially with nearby Permian limestones (Fig. 2), as well as with the Middle Triassic Corbies Creek Group, only 5 km to the southwest (Retallack and Ryburn, 1982) and with Middle Triassic rocks of the Mt St Mary Range, at the closest point some 10 km to the southeast (Speden, 1960; Campbell and Warren, 1965). Unfortunately the relationships of all these units remain unclear, because all are separated by complex and major structural features.

Grid references cited in this paper are from the New Zealand 1:50,000 maps H39, H40, and I39. Localities of the New Zealand Fossil Record File, now based on this new metric map series, are prefixed by "f" and also cited by map number in the 1:50,000 series. Also cited are catalogue numbers of petrographic thin sections of fossils (prefixed B-), rocks (prefixes P-), and of coal analyses (prefixed WD-), in the files and collections of the Geological Survey of New Zealand; and fossils (prefixed OU-) in the collections of the Geology Department, Otago University.

GENERAL GEOLOGICAL STRUCTURE AND SEQUENCE

Only three pre-Tertiary, meta-sedimentary rock formations were recognized in the hills around Benmore Dam. All three are part of the (metamorphic) Torlesse Zone, Alpine Assemblage, Rangitata Orogen (as defined by Carter *et al.,* 1974) and of the (tectonic) Torlesse Terrane, Alpine Domain, Rangitata Orogen and (petrographic) Canterbury Suite, Rangitata Sequence (of Andrews *et al.,* 1977). These formations are also stratigraphic subdivisions of the Torlesse Supergroup, as that term is used by Suggate (1978) and Stevens and Speden (1978). The Permian Akatarawa Formation crops out poorly, in a thin, fault-bounded sliver between Glen Begg and Te Akatarawa Streams, on the northern crest of the large plateau east across Lake Aviemore from Otematata. The remaining exposures of bedrock are mapped as Otematata Group, of Middle Triassic age. The Otematata Group includes the terrestrial and marginal-marine Black Jacks Conglomerate and the marine Spillway Formation (Fig. 2). All three formations show lateral changes in thickness and rock type important for understanding their geological history and environments of deposition, which are difficult to unravel without first considering their presently complex structure.

The Glen Begg Shear Zone (new name, modified from "Glen Begg Fault" of Smale, 1980b) is a tract of plastically deformed rock which can be traced from the mouth of Glen Begg Stream to within a kilometre of Benmore Dam wall, and then 2 km north (off the area mapped in Fig. 1), where it intersects the peninsula out to Black Jacks Point. This zone of deformation is confined to the shaly upper Black Jacks Conglomerate and lower Spillway Formation. The wedge-like block of conglomerate in the central portion of the shear zone, and its irregular southern edge, are evidence of thrusting of the Black Jacks Conglomerate over the Spillway Formation. Isoclinal folds of conglomerate in other portions of the shear zone may be (in part) drag folds produced by dextral transcurrent movement along the shear zone.

The new name, Desolation Syncline, was inspired by the poorly vegetated wilderness of spurs, rocky monoliths and screes of conglomerate in the headwaters of Briar Stream. This isoclinal fold is clearly visible in the outcrops of shales of the lower Spillway Formation (at H39/g.r. 88932162 and at H40/g.r. 89691997), and can also be interpolated between areas in which the upward-fining beds of conglomerate provide evidence of opposed stratigraphic facing (Fig. 1).

Fig. 3 (opposite) — Reconstructed section (below) and outcrop map (above) of the Upper Black Jacks Conglomerate and lower Spillway Formation, 1 km east of Benmore Dam. Grid ticks are after N.Z.M.S. map S117.

The whole of the mapped area is cut into irregular blocks by a grid of faults, trending northwest and northeast. Judging from their more or less straight courses over very hilly terrain, and their small lateral displacements, they appear to be near-vertical faults of mainly vertical movement. The small but consistent offset of older isoclinal folds is an indication of limited sinistral shear on the northeast trending faults.

The Akatarawa Fault was recognized by Harrington and McKellar (in Bell *et al.*, 1956), Shu (1964) and Smale (1980b), largely from alignment of Honeymoon and Te Akatarawa Streams. The Nettle Fault (new name) truncates an outlying, overturned anticline of Black Jacks Conglomerate. There are excellent exposures of crushed and fractured rock at its southern end near the col between Te Akatarawa and Glen Begg Streams (I39, g.r. 90162086). The Bugloss Fault, named from the blue-flowered weed *Echium vulgare,* may be an offset continuation of the Nettle Fault. The Acaena Fault has also been named after another troublesome introduced weed. It separates Permian from Triassic rocks. The Briar Fault (new name) partly controls the course of Briar and Whalan Streams and truncates the Desolation Syncline and other folds. The Thistle Fault (new name) also truncates several isoclinal folds. Fault breccias and mylonites of this fault can be seen near the top of the hill, north of Big Gully (H39/g.r. 86192090), and above the southern end of the spillway of Benmore Dam (H39/g.r. 87432258).

This area appears to have had a similar history of deformation to other areas of Torlesse rocks studied by Bishop (1974), Spörli and Barter (1973), Sheppard *et al.* (1974), Oliver (1979), Adams (1979), and Spörli (1979). In summary, phase I of this history included soft-sediment deformation during the Triassic and Jurassic, usually discernible only from minor irregularities in the orientation of bedding. Phase II consists of post-depositional to early metamorphic, isoclinal folds formed during a latest Triassic to early Cretaceous period of deformation, commonly called the "Rangitata Orogeny". This was a time of regional metamorphism of quartzofeldspathic sandstones and conglomerates to prehnite-pympellyite facies, and local alteration of vitric tuffs to zeolite facies (laumontite; Bishop, 1976; Kisch, 1981). Phase III includes warping and refolding of these isoclinal folds on steeply plunging axes, perhaps in part during a later phase of the "Rangitata Orogeny". Postmetamorphic subhorizontal folding of phase IV probably occurred during the Cretaceous or early Tertiary. Phase V of uplift, block faulting and concentric folding occurred mainly during the late Tertiary, and is commonly called the "Kaikoura Orogeny". Of these generally recognized phases of deformation, only phase I was not seen in the Otematata Group near Benmore Dam.

Within this chronology of deformation, the isoclinal folding of the Spillway Formation, the overthrusting and translocation of the Black Jacks Conglomerate within the Glen Begg Shear Zone, and the formation of the Desolation Syncline probably represent deformation of phases II and III, or the "Rangitata Orogeny". Some lateral warping of isoclinal fold axes may represent phase III. Block faulting clearly post-dates folding, and probably represents phases IV and V, or the "Kaikoura Orogeny". The mirror image of mapped shale and sandstone of the lowermost Spillway Formation at either end of the Desolation Syncline could be explained by a broad, subhorizontal fold of phase IV. The sinistral movement on the block faults (Fig. 1) and sinistral refolding of small folds in the Glen Begg Zone (Fig. 3) are compatible with the present regime of tectonic stress (Spörli, 1979).

STRATIGRAPHY

Akatarawa Formation (new name)

Definition: The Akatarawa Formation is Permian in age and consists largely of green meta-siltstone and schist. It also includes a thin marker horizon of limestone, limestone breccia and ferruginized volcanic rocks.

Name: This unit has been called the "Akatarewa Beds", following a former incorrect spelling of Te Akatarawa Stream (Bell *et al.,* 1956; Shu, 1964; Hornibrook and Shu, 1965; Campbell and Warren, 1965). Smale (1980b) included these rocks within his "Akatarawa Conglomerate". The conglomerates he described are here mapped as Spillway

Formation, and are separated from the Akatarawa Formation by the Bugloss Fault. Because both these prior names were either inappropriate or informal, the Akatarawa Formation can be considered a new name.

Type section: Only a 60 cm thick limestone marker horizon and several 0.1 to 0.3 m thick beds of green meta-siltstone crop out in the type section above the col between Te Akatarawa and Glen Begg Streams (map I39, g.r. 90182070 to 90342060). The long intervals covered by grass and soil are presumably underlain by schist and by mylonite associated with boundary faults of the formation.

Thickness: Judging from its observed dip and the mapped position of the faults, and assuming a minimal development of associated fault breccia and mylonite, the Akatarawa Formation is about 130 m thick in the type section.

Description: Unlike surrounding rocks of the Otematata Group, the Akatarawa Formation crops out poorly, except for a marker horizon of limestone, limestone breccia and ferruginized volcanic rock, which can be traced around the nose of an isoclinal fold and along its western flank for about 1.5 km south of the type section. The limestone in the type section appears micritic and massive in hand specimen. It contains scattered, well-worn fragments of brachiopods and crinoids, and thin (up to 5 mm) partings of siltstone and schist. In petrographic thin section (P43165A,B), the micritic matrix is extensively recrystallized to a finely granular fabric, and well-rounded crinoidal fragments down to medium-sand-size are much more abundant than apparent from hand specimens. Narrow (about 1 mm wide) zones of deformation are marked by coarsely recrystallized calcite and irregular patches of chert, as well as by microfaulting of thin, shaly interbeds. This limestone is best classified as a sparse biomicrite (in the classification of Folk, 1962) or a wackestone (of Dunham, 1962).

South of the headwaters of Glen Begg Stream (and south of H40/g.r. 89921958), the limestone marker horizon becomes discontinuous lenses of limestone breccia. The clasts of limestone appear identical in hand specimen to those of the type section, and are subangular to subrounded and up to 10 cm in diameter. Their matrix is a dark red silty claystone, which in places shows randomly oriented, lath-shaped light-coloured patches of clay. This enigmatic rock is interpreted as a ferruginized volcanic rock.

The bulk of the Akatarawa Formation consists of green meta-siltstone and schist. Fresh fragments of schist found in the upper reaches of the stream bed of Glen Begg Stream were green and displayed a prominent crenulation cleavage not seen in rocks of the Otematata Group. The meta-siltstones are light greyish-green and less sheared than the schist. Ripple-drift cross-lamination is preserved in several places. A particularly good set in the type section was used to determine stratigraphic facing. Silty interbeds in the limestone at the type section included mainly grains of feldspar, with lesser amounts of quartz and minor amounts of rock fragments.

No sandstone or roundstone conglomerate was found in the Akatarawa Formation.

Relationships: The Akatarawa Formation is a narrow sliver of rock separated by faults from the surrounding Otematata Group. Within this fault-sliver, it is folded into a syncline. This is only slightly dislocated from a syncline extending southward into the Otematata Group, but unrelated to structures in the Otematata Group to the north. Thus the stratigraphic relationships between the Akatarawa Formation and the Otematata Group are not known.

Palaeontology: Verbeekinid or neoschwagerinid fusulinacean foraminifera, ahermatypic polycoeliid rugosan corals, brachiopod fragments and crinoid columnals in limestone of the Akatarawa Formation have been taken to indicate a Permian age (at localities S117/f666 and f667 of Hornibrook and Shu, 1965, now I39/f8666 at g.r. 91072058 and H40/f7667 at g.r. 89991965). The foraminifera were re-identified as schwagerinid fusulinaceans by Gobbett (1973) who regarded them as Late Permian in age.

Depositional environment: The light grey biomicrite accumulated in an open, well oxygenated, marine environment, little influenced by currents. Rounded brachiopod and crinoid fragments, and abraded outer walls of the large formanifera, are indications that this quiet area was adjacent to a more agitated and biologically productive shallow

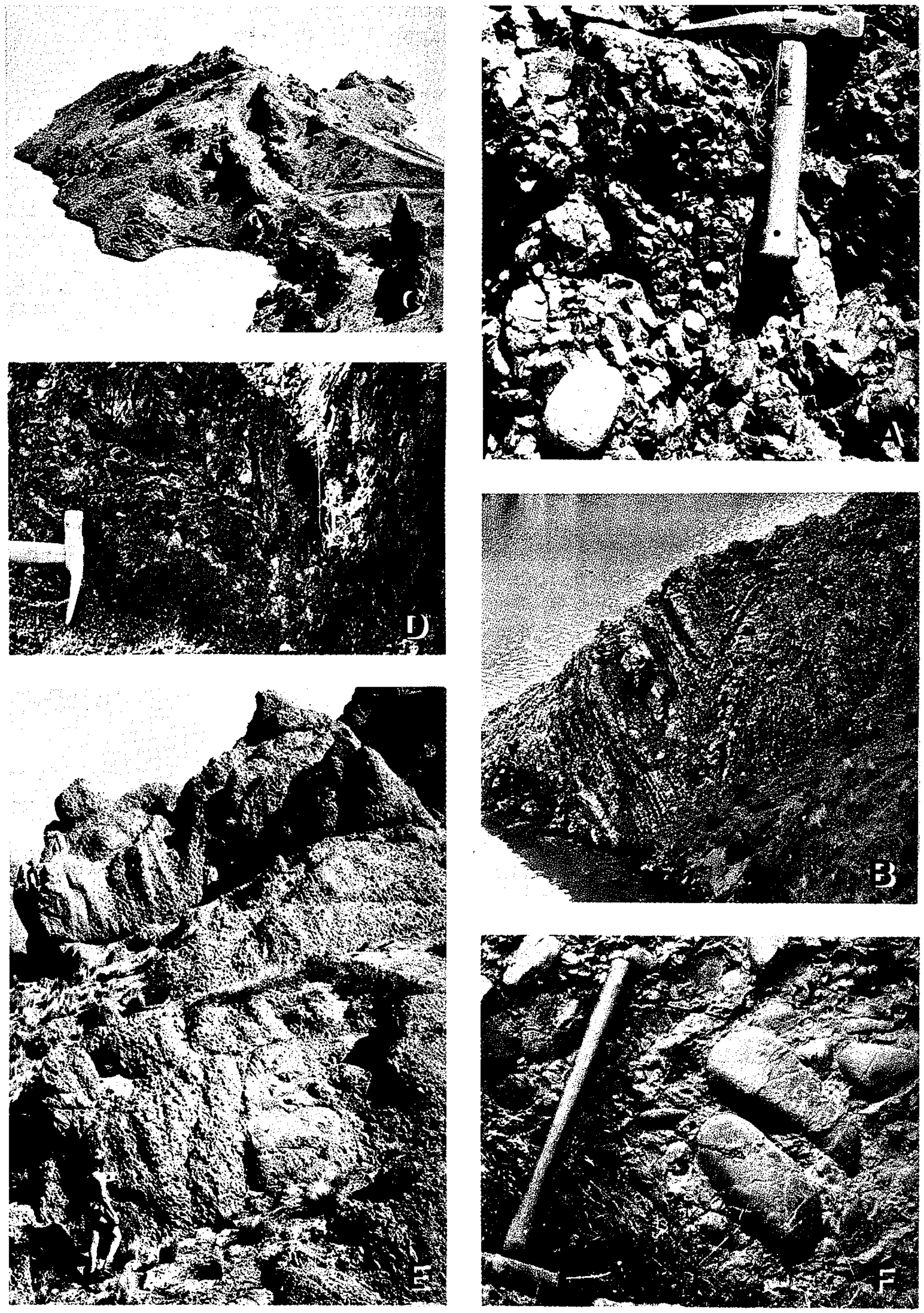


Fig. 4—Rock types near Benmore Dam. A,B, Spillway Formation; A, polymictic conglomerate, with conspicuous pink granitic pebbles, on hill northwest of Big Gully (H39/g.r. 85782107); B, drag fold in interbedded sandstone and shale, southwest corner of peninsula, 1 km east of Benmore Dam (Fig. 3; H39/g.r. 88412284). C-F, Black Jacks Conglomerate; C, walls of folded conglomerate in Glen Begg Shear Zone, 1 km east of Benmore Dam wall (Figs. 1,3; north from H39/g.r. 88322232); D, possible frost-heave disturbance of vertically-dipping leaf coal, between hammer head and deeply weathered coaly band to right (lower palaeosol profile of Fig. 7), 1 km east of Benmore Dam wall (H39/g.r. 88582261); E, conglomerate on ridge between head of Honeymoon Stream and Trig. E (H39/g.r. 89892109); F, large blocky boulders in western wall of conglomerate north of creek, on peninsula 1 km east of Benmore Dam (H39/g.r. 88522284).

marine environment. Like modern large foraminifera, schwagerinid fusulinaceans were probably benthonic foraminifera, of tropical to warm temperate seas. They probably lived within the upper photic zone (up to 9 m deep) and contained symbiotic algae (Ross, 1963, 1979a, 1979b).

Associated meta-siltstones contain ripple marks indicating moderate current activity, but lack any characteristic features of intertidal mudflats or deep-oceanic turbidites. A volcanic provenance is clear from the abundance of plagioclase, but no volcanic shards or other evidence of explosive volcanism were seen. These meta-siltstone, schists and limestones were probably deposited on the outer shelf of a volcanic island or continental margin.

Otematata Group (new name)

Definition: The remaining rocks mapped near Benmore Dam (Figs. 1,2) belong to the Otematata Group. This includes only the terrestrial and shallow marine Black Jacks Conglomerate and the conformably overlying, marine, Spillway Formation, both of late Middle Triassic age (Ladinian of the European standard, or Kaihikuan local stage).. Like other Torlesse rocks of New Zealand, the Otematata Group includes sandstone and conglomerate of mainly quartzofeldspathic composition, metamorphosed to prehnite-pumpellyite facies, and complexly folded and faulted.

Black Jacks Conglomerate (new name, after informal name of Shu, 1964)

Definition: This forms the lower part of the Middle Triassic Otematata Group. It consists almost entirely of oligomictic boulder conglomerate. Most clasts consist of quartzofeldspathic sandstone. There are also a few units of sandstone, siltstone, claystone, shale and coal, up to 12 m, but usually less than 1 m thick.

Name: A thin fault-bound sliver of the formation crops out at Black Jacks Point (north of the area mapped in Fig. 1; at g.r. H39/87212609), after which it was named, but the main outcrop is 2 km south of there. The name has been used informally in the past, appearing on an unpublished map in the Honours thesis of Shu (1964).

Type section: The best known and most fossiliferous area of Black Jacks Conglomerate is on the peninsula 1 km east of Benmore Dam wall (Figs. 3, 4C). The southwestern limb of the isoclinal fold near fossil localities H39/f2 and f9760 is designated the type section (Fig. 3; H39/g.r. 88522263 to 88592260).

Thickness: The thickest sequence of conglomerate, still an incomplete section of the formation, is northeast of the Desolation Syncline in the triangular area northwest of the Briar Fault. By measuring from the map (Fig. 1) and averaging dips and strikes in this segment, thickness is estimated at more than 980 m.

Lithology: Conglomerate beds of the Black Jacks Conglomerate are usually thick (5-15 m), with imbricated, clast-supported roundstones, fining upwards from 61 to 2 cm in diameter (Figs. 4E,F). Clasts of quartzofeldspathic sandstone are by far the most common. In petrographic thin sections (P40540-4), most clasts consist of interlocking, sand-size, subangular quartz, feldspar and rock fragments. Harrington and McKellar (*in* Bell *et al.*, 1956) and Shu (1964) also record rare pebbles of quartzite, chert, hard calcareous mudstone, and granitic and volcanic rocks.

Course to medium grained sandstone forms matrix to, stringers within, and veneers capping the thick, conglomerate beds. The sandstones are similar in petrographic thin section (P40545) to the conglomerate clasts, but have noticeably less feldspar and more rock fragments, both often embayed, deformed and difficult to distinguish from clayey matrix. A calcareous sandstone bed also crops out in the type area of the Black Jacks Conglomerate. In thin section (B1082), only ghost outlines of former feldspar and rock fragments can be seen in the pervasive calcareous matrix, which supports scattered quartz grains. This sandstone is altered, perhaps by weathering at or near the site of deposition, but is otherwise similar to other sandstones of the Black Jacks conglomerate.

Grey siltstone, shale, carbonaceous shale and leaf coal form conspicuous beds in the type section, and in the northern extension of this ridge now under water. These lithologies are rare in the lower Black Jacks Conglomerate. Analysis of a coal (number WD1024; from a locality now under water, H39/f950 g.r. 90102272) indicates that it is a low volatile bituminous, and of comparable rank to other middle Triassic coals of Torlesse rocks (Retallack, 1979; Retallack and Ryburn, 1982).

Relationships: The lowest parts of the Black Jacks Conglomerate were everywhere found to be fault bound, so its relationships with underlying rocks cannot be seen directly. It was probably unconformable on folded quartzo-feldspathic sandstone, so abundantly represented in its clasts. Such sandstone is characteristic of Torlesse rocks of all ages. Extensive areas of it, containing *Atomodesma* fragments of possible Permian age, crop out in hills only a few kilometres east of Benmore Dam and also farther east down the Waitaki Valley near Kurow (Campbell and Warren, 1965). The nature of the contact of these rocks with the Otematata Group is not known. Andesitic rock fragments possibly derived from the Permian Akatarawa Formation have been found as rare components of sandstones and conglomerates of the Black Jacks Conglomerate (Shu, 1964). The Akatarawa Formation may have been partly covered by quartzofeldspathic sandstone or largely in a different drainage basin from that in which the Black Jacks Conglomerate accumulated.

The Black Jacks Conglomerate is conformably overlain by the Spillway Formation. This contact is confused within the Glen Begg Shear Zone, and more clearly seen in the Desolation Syncline in both Briar and Glen Begg Streams. The contact is also exposed in outlying anticlines above Benmore Dam wall and on a ridge between Honeymoon Stream and its main tributary (Fig. 1).

Palaeontology: Most of the localities for plant fossils described by Harrington and McKellar (*in* Bell *et al.*, 1956), Shu (1964) and Campbell and Warren (1965), are now submerged under the water of Benmore Dam (Fig. 5). Early in 1975, I made a series of collections from the portion of the ridge remaining unsubmerged. One locality contained only abundant remains of the marine alga, *Shonabellia.* Other localities yielded assemblages referable to the Pachydermophylletum and Linguifolietum fossil plant associations of Retallack (1977). A few fossil plant species from the old collections may be evidence of an additional fossil plant association, the Dicroidietum odontopteroidium. Notwithstanding this local, paleoecological, variation in the composition of the megafossil flora, the assemblages as a whole appear to belong to the *Dicroidium odontopteroides* Oppel-zone (Retallack, 1977) of late Anisian to Ladinian age.

A bed of calcareous sandstone near the top of the Black Jacks Conglomerate near the conglomerate walls 1 km east of Benmore Dam wall (H39/f9759 at g.r. 88652282; Fig. 3) contains abundant fossil algae, *Shonabellia verrucosa* gen. et sp. nov. (Retallack, 1983). This is evidently a codiacean alga, all of whose fossil and living relatives are marine (Johnson, 1961, p. 94). Modern algae of this family with similar habit are sublittoral plants growing from near mean low tide level to depths of about 5 m (Lucas,

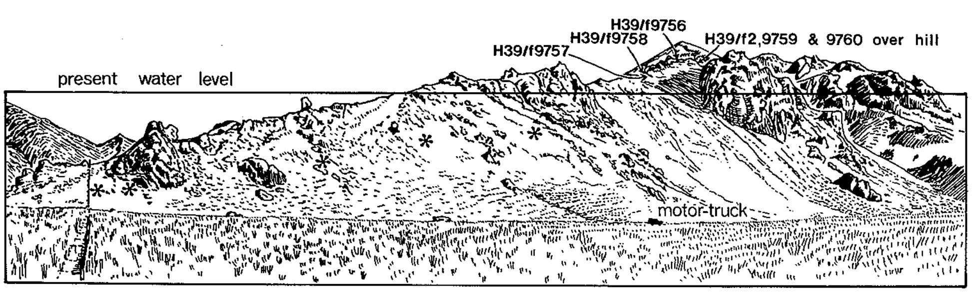


Fig. 5—Present water level and recent collections compared with the old ridge profile and plant localities (asterisks, all H39/f950 and f9665) collected by Harrington and McKellar (in Bell *et al.*, 1956) and by Shu (1964).

1936; Boney, 1966). The light requirements of such photosynthetic, green algae restrict their growth beyond depths of 90 m, although dead algae may be transported to even greater depths (Riding, 1975). The fossil algae from near Benmore Dam are not in place, but their abundance and cellular preservation in a restricted horizon, overlain and along strike from localities with fossil leaves and roots in place, are all circumstantial evidence that they once colonized a firm, nearshore marine, substrate, nearby.

Pachydermophyllum leaves were found at several localities near Benmore Dam, but dominate a distinctive fossil plant association 1 km east of the dam wall (H39/f2 at g.r. 88582261; Figs. 6, 7), the type locality of Retallack's (1977) Pachydermophylletum. This locality is within a conformable sequence overlying the calcareous sandstone with fossil marine algae, and separated from it by a 5 m thickness of wavy-bedded siltstone and shale, similar to sediments of modern tidal flats. *Pachydermophyllum* is by far the most common plant fossil here in an assemblage of unusually low diversity. These leaves were probably fleshy in life, because the laminar flanges along the woody portion of the rachis and the pinnae are transversely wrinkled, as if a three-dimensional object, rather than a planar one, had been compressed within the sediments. The stomata of *Pachydermophyllum,* known from cuticular preparations of material from other Triassic

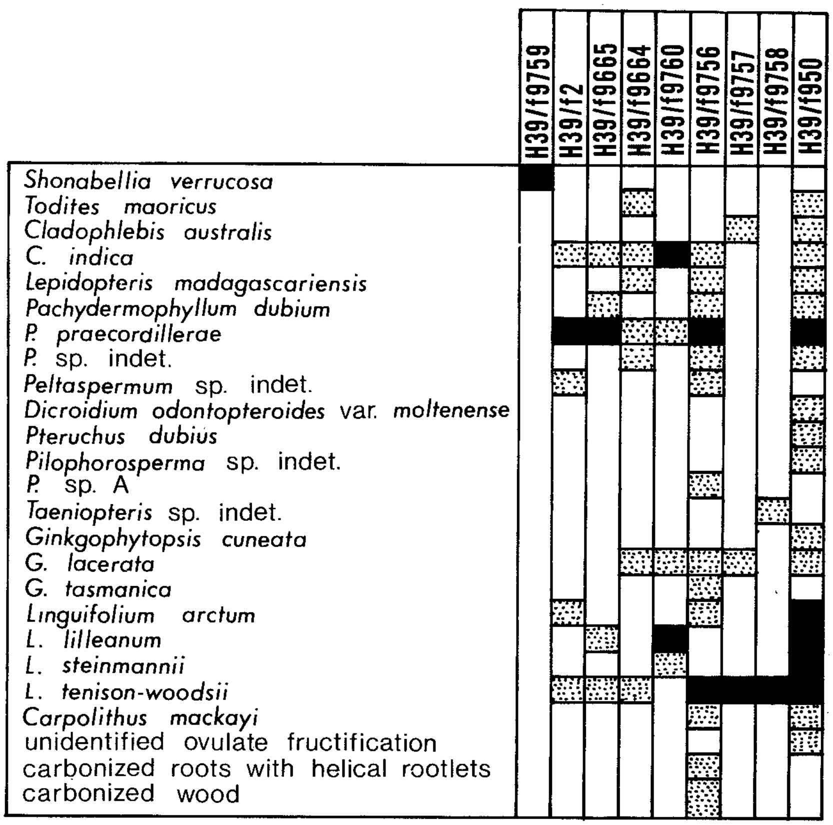


Fig. 6—Plant megafossils and localities in the Black Jacks Conglomerate. Localities (specimen numbers) are H39/f950 (B42.1-118), H39/f9469 (as for H39/f950), H40/f7516 (B96.1-8, probably a recollection of H39/950), H39/f9664 (unnumbered, Geology Dept., Univ. Otago), H39/f9665 (as for H39/f9664), H39/f9756 (B1085.1-30), H39/f9757 (B1084.1-5), H39/f9758 (B1083.1-3), H39/f9759 (B1082.1-9), H39/f9760 (B1081.1-19), H39/f2 (OU14198-204, OU14210-1); their location is indicated on Figs. 1 and 3. For description of *Shonabellia verrucosa* (n.gen., n.sp.) see Retallack (1983).

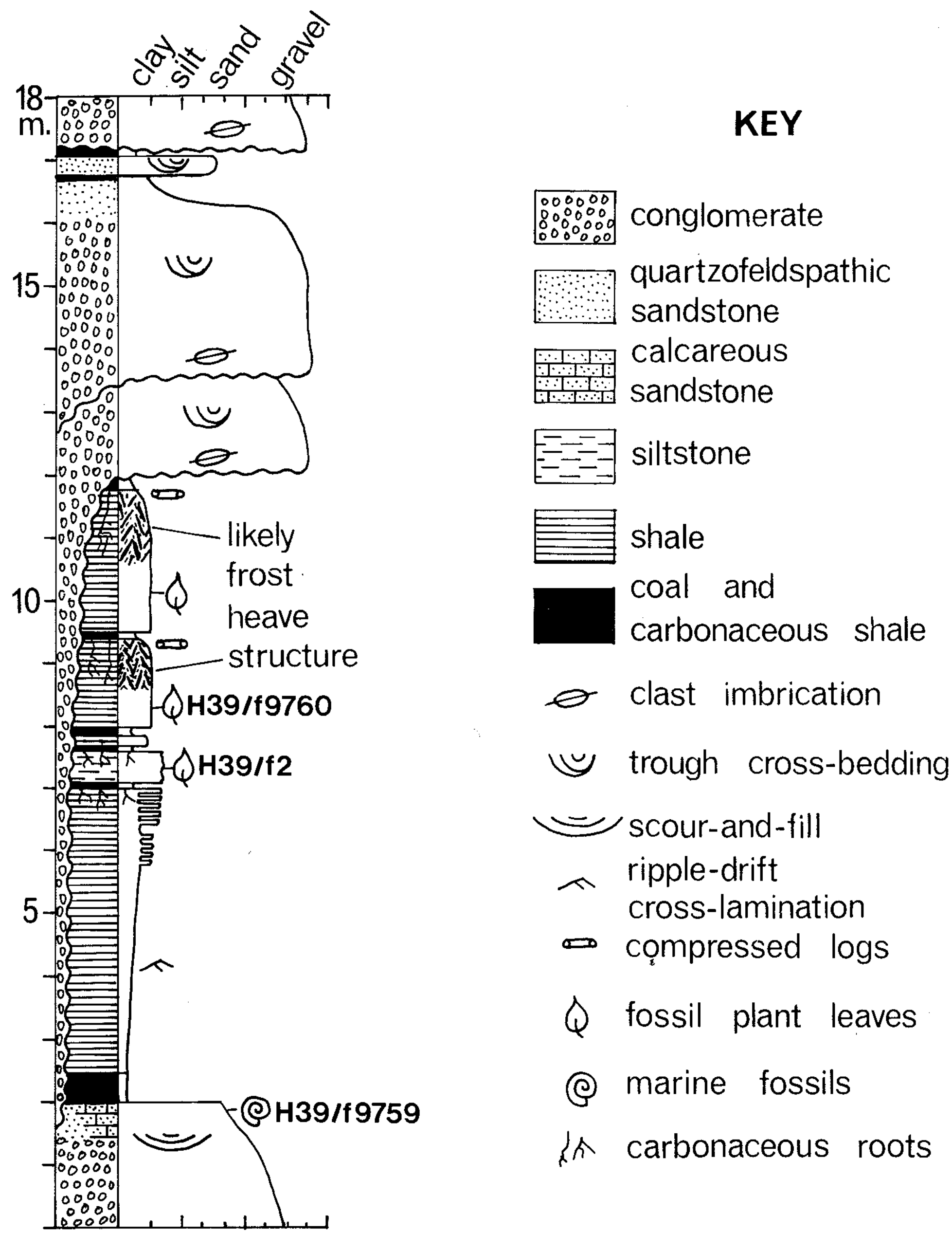


Fig. 7—Detailed columnar section of a portion of the southern limb of the isoclinal fold of the upper Black Jacks Conglomerate, 1 km east of Benmore Dam wall (Fig. 3); map H39/gr. 88592260 to 88542262.

rocks of the Gondwana supercontinent (*Pachypteris* of Townrow and Jones, 1969), have sunken guard cells at the base of a pit overhung by papillae. This is yet another feature of these plants indicative of stressful habitat. No marine or brackish invertebrate megafossils were found in association with *Pachydermophyllum* near Benmore Dam. This is also the case for Jurassic *Pachydermophyllum* in Yorkshire, England, where near-marine conditions were inferred from the presence of organic-walled microplankton (Harris, 1964, 1966). In both Yorkshire and New Zealand, *Pachydermophyllum* appears to have formed the most landward zone of mangal vegetation, or lined estuarine reaches, where marine influence was weak. In both localities also (I had an opportunity to inspect the Hasty Bank locality in Yorkshire during 1980), *Pachydermophyllum* probably formed a low scrubby vegetation, because associated fossil roots are small and because there are no logs, stumps or other features of large vegetation.

Linguifolium leaves are locally abundant near Benmore Dam, where they appear to be remains of extensive deciduous swamp woodlands. The type locality (H39/f9760 at g.r. 88582261) of the Linguifolietum (of Retallack, 1977) is only one metre stratigraphically above that of the Pachydermophylletum (H39/f2), 1 km east of Benmore Dam wall. Here thin coals of *Linguifolium* leaves separate mudstone bands 10 cm thick which contain contorted remains of *Cladophlebis, Pachydermophyllum* and *Ginkgophytopsis.* This rhythmic sedimentation may be a record of devastating spring floods in these low-diversity woodlands, followed by autumnal leaf fall. Similar conclusions were reached by Steinmann (1921) in his work on Triassic localities for *Linguifolium* in Chile.

Two distinctive horizons of sharp, disruptive, chevron folding within these leaf coals and root-bearing mudstones (Figs. 4D, 7) are here interpreted as palaeosols, formed in a frigid climatic regime in which the upper metre or so of the ground was disrupted by the combined action of roots and frost heave. Ice wedge structures (like those described by Brand, 1938, and Young and Long, 1976) are nowhere preserved, so if once present, must have been disturbed by growth of vegetaton, or denied sedimentary fill by flood-resistant surrounding vegetation. These contorted horizons are deformed quite differently from convolute laminations or desiccation cracks, as described by Potter and Pettijohn (1963). Nor is there any evidence of associated till, so they cannot be interpreted as till wedges. Nor are any of these horizons likely to be zones of structural dislocation, because both are overlain sharply by undeformed leaf coals and are eroded away laterally to the south by an overlying, conglomeratic, channel deposit, which includes no indication of comparable deformation.

Other collections of megafossil plants made by Shu (1964; Campbell and Warren, 1965; H39/f9664 at g.r. 88562291 and f9665 at g.r. 88302209) and by me (H39/f9756 at g.r. 88562291) consist of nearly equal proportions of *Cladophlebis, Pachydermophyllum, Linguifolium* and *Ginkgophytopsis.* None of these collections could be related to nearby fossil soils (sedimentary layers with fossil roots in place and other soil features), so it is uncertain whether these plants once grew in mixed associations or were mixed from several distinctive associations during deposition.

It is possible that there is also a Dicroidietum odontopteroidium fossil plant association (of Retallack, 1977) near Benmore Dam, like that known from rocks of similar age in Tank Gully (Retallack, 1979), judging from the collections made by Harrington and McKellar (*in* Bell *et al.,* 1956; H39/f950 at g.r. 88662336 to 88542317) and later collections made from the same group of localities by Shu (1964; Campbell and Warren, 1965; H/39/f9469). All of these were mixed collections from more than one locality, and all are now under water (Fig. 5). From Shu's (1964) map, it is likely that most of these fossils came from the upper Black Jacks Conglomerate, farther north along strike from the type section designated here within the Glen Begg Shear Zone. The fossiliferous rock specimens are mostly schistose black mudstone with a distinctive, oily irridescence and penetrated by numerous fossil roots. The fossil plant remains are abundant, overlapping, partly decayed, torn and deformed. This material probably once formed thick, fibrous, peaty, surficial horizons of organic soils (histosols) in low-lying parts of floodplains.

Fragmentary and poorly preserved plant remains have also been found in sandstone and siltstone veneers, capping graded conglomerate beds (H39/f9757 at g.r. 88562300 and f9758 at g.r. 88562291). There are few kinds of plants in these collections. They appear transported and were probably mixed from several former plant communities.

Depositional environment: The Black Jacks Conglomerate has numerous features of fluvial palaeochannels. Most of the thick beds of conglomerate are conspicuously graded, with the largest boulders at the base. This widespread grading was used to determine stratigraphically higher and lower parts of the Black Jacks Conglomerate, and its structure (Fig. 1). Grading is especially well expressed in a lenticular conglomerate bed overlying localities H39/f2 and f9760, 1 km east of Benmore Dam (Figs. 3, 7; H39/g.r. 88582261). The base of this bed is strongly erosional, scouring out at least 10 m of underlying sediments. The bed contains cross-bedded and imbricated, clast-supported roundstones up to 20 cm in diameter. Five hundred clasts from this bed were measured and had a Trask sorting coefficient of 1.76 (poorly sorted). This bed grades up-section into clast-supported pebble conglomerate, then granule-bearing sandstone, and a final thin layer of sandstone, siltstone and coal. The veneer of fine-grained sediments overlying the conglomerate is strongly disrupted by fracture cleavage (presumably produced during phase IV and V folding), which also obscures the imbrication of small pebbles in the upper portion of the conglomerate. Other beds of Black Jacks Conglomerate are similar. Some include even larger clasts, and show both imbrication and cross-bedding more clearly. In others, the channel-like base and grading is less obvious because they merge into adjacent conglomeratic beds without intervening fine-grained sediments. No mudflow deposits were seen among these conglomerates.

The Black Jacks Conglomerate was probably deposited by the flooding of braided streams. This interpretation is supported by its Trask sorting coefficient. To judge from values given by Emery (1955), the value determined for the Black Jacks Conglomerate is lower than usual for modern alluvial fans and higher than usual for modern shingle beaches. Such thick, graded, conglomeratic beds have only rarely been found in modern braided streams and alluvial fans; for example, by Gustavson (1974, fig. 18) and Boothroyd and Ashley (1975). These are thought to have resulted from exceptionally violent flood surges. There are similar conglomeratic deposits traceable to a violent flood during 1964 along the Rubicon River, California (Scott and Gravlee, 1968). Stream power in this case was enhanced by confining valley walls, and this may also have been the case for the Black Jacks Conglomerate.

Although marine algae were found at one locality in the uppermost Black Jacks Conglomerate, none of these conglomerates are at all like those of modern shingle beaches or beach-ridge plains, such as Dungeness (Johnson, 1938) and Chesil Beach (King, 1972). Rather than thick, multistorey, channel-like beds, seen in the Black Jacks Conglomerate, shingle beaches usually form thin, ribbon-like units, at the base of transgressive marine sequences. The shingles of beaches are generally very well sorted. Within a single bed, the pebbles may become smaller down-section into offshore sands with shell fragments, or smaller laterally along the beach from rocky headlands. Characteristically, beaches are formed of disc-shaped pebbles in distinct beds from beds of roundstones. The beds are separated by stringers of sand, and their pebbles are imbricated in opposite directions from bed to bed (Bluck, 1967; Hey, 1967; Carr, 1969).

There are several circumstantial lines of evidence suggesting that the Black Jacks Conglomerate was deposited in a rock-bound estuary with a mountainous hinterland of indurated, quartzofeldspathic sandstone. Much of this evidence has already been discussed: the clast composition, likely mangal vegetation, tidal flat deposits and marine algae which require a firm substrate. The large subrounded boulders of the Black Jacks Conglomerate, when compared with the size of clasts and the distance from their source on the Alaskan coastal outwash plain (Boothroyd, 1972), must have been derived from rock basement very close at hand. Exceptional stream power during floods, perhaps accentuated by confining valley walls, is needed in order to deposit such thick graded beds of conglomerate. Finally, the main mass of conglomerate includes a homoclinal sequence over 1 km thick, remarkably undeformed compared with surrounding rocks. Such a large mass of conglomerate is exceptional for Torlesse rocks. Sequences of Black

Jacks Conglomerate cropping out only a few kilometres to the north, as well as the lowermost Bench Sandstone in Tank Gully (Retallack, 1979) are thin and much more faulted and folded by comparison. This huge mass of conglomerate may have been deposited in a fault-angle depression, deep valley or fiord, and behaved as a competent unit during deformation.

Very similar modern alluvium to that of the Black Jacks Conglomerate is now accumulating in the braided outwash of the Scott Glacier of southeastern Alaska (Boothroyd and Ashley, 1975; Miall, 1977). Highly variable discharge in such an environment is mostly due to seasonal melting of snow, but can also be the result of erratic rainfall or the release of lakes dammed by ice. Important differences from such an environment are the lack of debris flows or any evidence of glaciation (such as striated clasts) in the Black Jacks Conglomerate. Perhaps glaciers and snowcaps were restricted to high peaks and basins, as they are in the most southerly portions of southeastern Alaska, and in much of the Southern Alps of New Zealand today. It could also be, as Garner (1959) has argued for the conglomeratic Guayas Delta of Ecuador, that large clasts were not derived directly from glaciated mountains, but were resorted from conglomerate closer to the coast. The Yallahs Delta of Jamaica is an example of a tropical conglomeratic delta at the base of a coastal mountain range (in this case up to 1500 m high). Flooding of the Yallahs Delta carried pebbles out into the sea, and is produced by high and seasonal rainfall (Burke, 1967; MacGillavry, 1970; Gupta, 1975). A comparable climate during deposition of the Black Jacks Conglomerate is unlikely, considering its grey colour, exceptionally thick conglomerate beds, possible ice-disrupted palaeosols and fossil flora of limited diversity, like other Triassic floras of high southerly palaeolatitudes.

In conclusion, it is likely that the locally overthick Black Jacks Conglomerate was deposited mainly in a fault-angle depression, fiord or valley of a mountainous rocky coast, prone to powerful floods, because of the orographic capture of rain-clouds, ice damming or snow melt, in a cool temperate to sub-antarctic climate.

Spillway Formation (new name)

Definition: This formation forms the upper part of the Middle Triassic Otematata Group. The most characteristic lithology is coarse-grained, lithic sandstone, weathering brownish-grey, with angular, white flecks (quartz grains). These sandstones are locally conglomeratic, containing, in addition to rare sandstone clasts like those characteristic of the Black Jacks Conglomerate, abundant granules and pebbles of chert, quartz and quartzite. The formation also includes thick units within which siltstone and shale are rhythmically interbedded.

Name: The formation is named from the spillway of Benmore Dam.

Type section: The type section is exposed along the road, in quarries and in the hill at the southeastern end of Benmore Dam wall, where the formation conformably overlies an overturned outlier of Black Jacks Conglomerate (H39/g.r. 87112210 to 87672249).

Thickness: The formation is at least 900 m thick in the shared limb of the two isoclinal folds south of the dam, between the Briar and Thistle Faults. This thickness was calculated by measuring from the map (Fig. 1) and averaging dips and strikes within the sequence, excepting the overturned readings from shaly units to the north.

Lithology: Sandstones of the Spillway Formation consist largely of quartz, rock fragments and feldspar, in that order of abundance (Shu, 1964; Smale, 1980b; although Smale described them as sandstone of the "Akatarawa Conglomerate"). The rock fragments are principally chert, volcanics and sediments. Minor components are heavy minerals, muscovite and fragments of granitic, metamorphic and clayey rocks. The sandstone beds are all conspicuously deformed, and are penetrated by abundant slickensided joints and veins, from which Shu has identified assemblages of quartz-pumpellyite-epidote, quartz-prehnite, quartz-calcite and quartz-laumontite. Some of these joints and faults of small displacement are at very low angles to bedding, and appear to be responsible for the irregular thickening and thinning of these sandstone beds, so well exposed in quarries near the type section.

Near Trig E, southeast of Benmore Dam (Fig. 1; I40/g.r. 90551979), sandstones of the Spillway Formation contain scattered, rounded, granules and pebbles (mostly -3 to -1 Φ in size) mainly of chert, quartz and quartzite, with lesser amounts of granitic, andesitic, felsitic, sandstone, mudstone and phosphorite clasts (described in detail by Smale, 1980b, as the "Akatarawa Conglomerate"). Similar polymictic conglomerates also crop out in the hills northwest of Otematata (Fig. 4A). Only in places are the thickest of these conglomerates clast-supported. In general, the clasts are dispersed in sandstone matrix, and the thickness of the conglomeratic horizons is independent of the thickness of the enclosing sandstone unit.

Thick, shaly units within the Spillway Formation consist either of interbedded, grey shale and siltstone in normally-graded sets, some 10-50 cm thick (Fig. 4B), or of carbonaceous shale. Some interbeds of red shale were also found on the hillside south of the intersection of the Acaena and Akatarawa Faults (I39/g.r. 90692094), and in road cuttings above the powerhouse of Benmore Dam. At this last-mentioned locality (H39/g.r. 86702341), there are also several conspicuous layers of pink, laumontite-rich, tuffaceous siltstone (Bishop, 1976; Kisch, 1981).

Relationships: The lower contact of the Spillway Formation and Black Jacks Conglomerate has already been described, but its upper contact with overlying formations has not been observed. Sandstones identical to those of the Spillway Formation extend for considerable distances southeast and southwest beyond the mapped area (Fig. 1).

Palaeontology: Despite a diligent search and extensive excavation at several outcrops with tantalizing surficial irregularities, no fossils were found in the Spillway Formation within the mapped area. Fragmentary Ladinian (Kaihikuan) marine fossils have been found in a road cutting east of Otematata Bridge (Campbell and Warren, 1965; S117/F518 = H40/f7518 at g.r. 87901879) just off the mapped area (Fig. 1), where the exposed sandstones appear identical with those of the Spillway Formation.

Depositional environment: Judging from the fossil marine algae in the upper Black Jacks Conglomerate, and shell fragments found in the Spillway Formation near Otematata Bridge, the Spillway Formation was probably deposited mainly on a marine, continental shelf. If this is the case, then marine fossils are remarkably scarce in the Spillway Formation, compared to nearby marine rocks of comparable age in Corbies Creek (Retallack and Ryburn, 1982) and Mt St Mary (Speden, 1960; Campbell and Warren, 1965). Perhaps offshore turbulence from powerful streams, hypopycnal flow of cold river water into the ocean, and mud winnowed out of the Black Jacks Conglomerate made the water too cold and turbid for abundant marine life. Similarly, I have observed that one or two kinds of mussel shells and several kinds of algae are usually the only remains of marine life washed up on boulder beaches near the turbid and cold outwash of the Franz Josef and Fox Glaciers in New Zealand. This may be contrasted with the great variety of shelly remains found on shingle beaches elsewhere in New Zealand, as described by Morton and Miller (1973).

Sediments at or near the contact between the Spillway Formation and the Black Jacks Conglomerate (Fig. 1) were probably deposited in a variety of shallow marine and coastal mudflats and sandbars. For example, the shoestring sandstone exposed in opposite limbs of the Desolation Syncline in both Briar and Glen Begg Streams has some low-angle cross-bedding and mudstone granules, and probably formed an offshore bar.

The polymictic conglomerates of the Spillway formation may have formed in nearshore shingle spits and bars, extending from rocky headlands. The variety of clasts compared with those of the Black Jacks Conglomerate were presumably derived from a more varied and larger source terrain. This may have included the Permian Akatarawa Beds, because Smale (1980b) found rare altered felsitic and andesitic volcanic clasts and also suggested that some cherty clasts bore radiolaria and that others had replaced limestones. Interbedded cherts (some with possible radiolaria), volcanics and marble are also characteristic of Torlesse rocks of late Carboniferous age in lower Kakahu Gorge, southeastern Canterbury (Hitching, 1979). The abundance of quartzose clasts, their high sphericity, roundness and small size in the Spillway Formation are evidence that they have travelled far in turbulent environments (Smale, 1980b). In addition, these conglomerates are well-bedded, ungraded and crudely imbricated, as is usual for spits and bars.

Widespread 0-50 cm thick, fining-upwards, siltstone-shale sequences (T2 and T3 of Bouma, 1962) in shaly units of the Spillway Formation are more likely either deposits of storms or submarine fallout from hypopycnal flow of turbid flood-waters, rather than turbidites of a deep ocean basin. The shallow water origin of these shaly units is especially evident from the oscillation ripples which form the top of many of the siltstone interbeds (as in "sandy tempestites" of Seilacher, 1982). Like similar ripples described by Potter and Pettijohn (1963), these have strongly concave troughs which are symmetrical in cross-section. A particularly fine set of such ripples is exposed in plan, near the contact of shale and sandstone, in a road cutting 400 m south of the spillway of Benmore Dam (H39/g.r. 87362228).

Spörli *et al.* (1974) suggest that red mudstones of Torlesse rocks are either abyssal red clays, or are submarine tuffs from volcanic activity along mid-oceanic ridges. For reasons already discussed, an abyssal or mid-oceanic origin of red shales in the Spillway Formation is unlikely. There may have been some Triassic volcanic activity, which produced nine beds of vitric tuff within 5.5 m of the sequence near Benmore Dam, along the road above the Power Station. Such evidence for Triassic volcanism is exceptionally rare in Torlesse rocks of New Zealand (Bishop, 1976). The tuffs are ripple-marked and interbedded with shale, so have been redeposited. They are also altered extensively to laumontite (Bishop, 1976; Kisch, 1981). Their pink colour and silty texture is so different from the dark red shales of the Spillway Formation that they are unlikely to be related. The thin red shales were more likely derived from pre-existing red-beds, soils or palaeosols. Strongly ferruginized horizons associated with limestone breccia in the Akatarawa Formation may have been of similar origin.

RECONSTRUCTED TRIASSIC ENVIRONMENT OF THE OTEMATATA GROUP

The reconstruction (Fig. 8) summarizes conclusions from each of the preceeding sections for a time within the Ladinian (Kaihikuan local stage) part of the Middle Triassic, when *Pachydermophyllum* shrubs colonized mudflats near the present location of Benmore Dam. The following account describes the likely panorama, processes and climate.

Folded sandstones and shales form a jagged, mountainous skyline, but there are also rounded hills of weathered granitic rocks and some light bands of limestone and reddish volcanics in places. Long, rocky ridges extend from the snowy tops into the ocean. A deep, narrow valley, with steep walls, is being steadily filled with outwash gravel. A wide, grey band of anastomosing channels is littered with large, bouldery, gravel bars, left behind by violent flood surges.

Between the stream channels and valley walls, old river flats have been vegetated by broadleaf woodlands, including ferns (*Todites*) and seed ferns (*Dicroidium* and *Lepidopteris*). In swampy places, fibrous, peaty, organic horizons have formed on the weakly-developed woodland soils. On river flats near the sea, *Linguifolium* dominates a deciduous woodland of low diversity, including *Ginkgophytopsis* and *Cladophlebis*. Mudflats of estuarine margins are overgrown with a low, scrubby mangal, largely of *Pachydermophyllum.* Around rocky headlands nearby, the ocean is thick with waving masses of green codiacean algae (*Shonabellia*).

Violent floods in the estuary are considerably dampened when they reach the sea, so that few large pebbles are transported far offshore. Near the coast, pebbles from nearby headlands, and sand from coastal streams and longshore drift are piled into bars and spits by tides and currents. Farther offshore, grey silt and mud settle in thin, graded units from periodic floods. A suspension of mud in the sea for a considerable area around the estuary and hypopycnal flow of cold river water makes the sea too cold and turbid for abundant marine life.

Judging from the low diversity of the fossil flora, the presence of likely deciduous

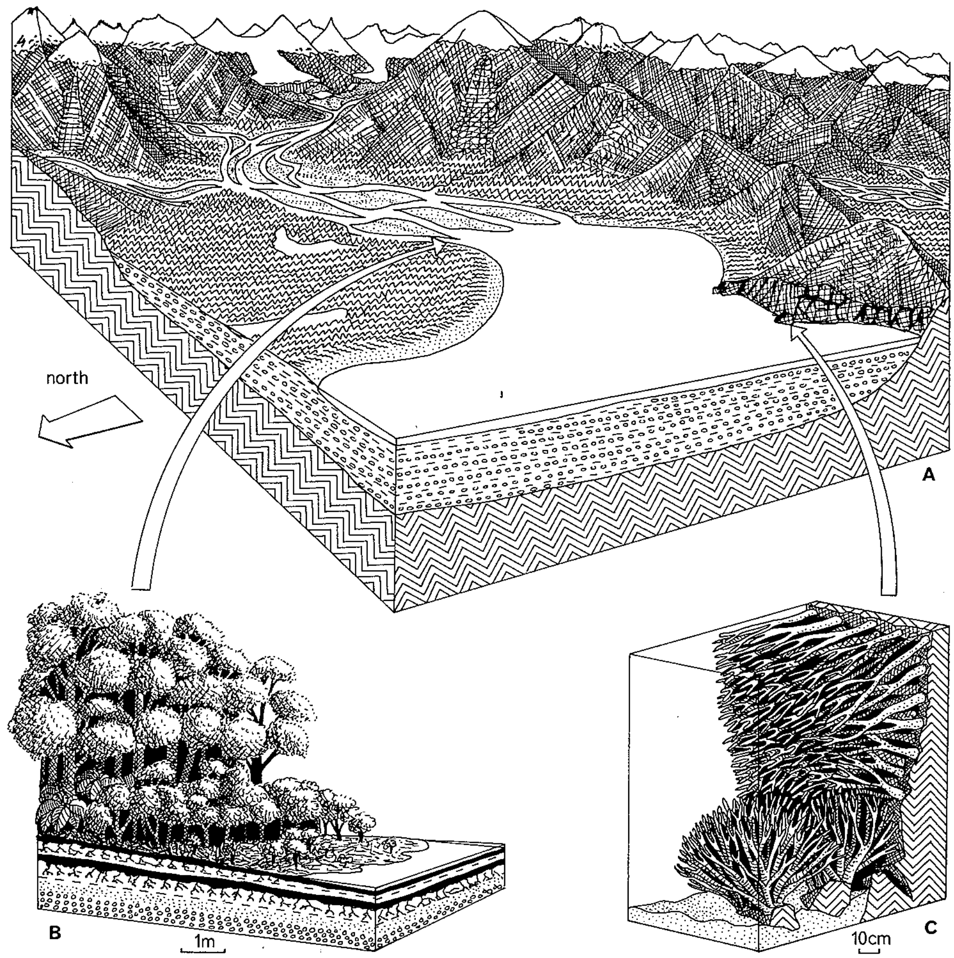


Fig. 8 — Reconstructed environment of the middle Otematata Group during Middle Triassic time (Ladinian international and Kaihikuan local stage).

plants, and sedimentological similarities with the Alaskan coastal plain, climate was probably cool temperate and seasonally snowy. The ice-disrupted paleosols are evidence of periglacial conditions, but considering the abundant fossil logs and roots, the climate was not too frigid for the growth of trees.

ACKNOWLEDGEMENTS

I thank D. C. Mildenhall (New Zealand Geological Survey, Lower Hutt), J. D. Campbell, D. S. Coombs, C. A. Landis (Department of Geology, University of Otago) and L. M. and E. R. Force (U.S. Geological Survey, Reston) for helpful discussions and hospitality. I. G. Speden and E. McGregor (New Zealand Geological Survey, Lower Hutt) generously supplied grid references converted to the new metric maps, which have not yet been published for this area. This project was funded by a Commonwealth Postgraduate Award tenable at the University of New England, Armidale, N.S.W., Australia.

REFERENCES

Adams, C. J. D., 1979. Age and origin of the Southern Alps. *Bulletin of the Royal Society of N.Z.* 18: 73-78.

Andrews, P. B., I. G. Speden and J. D. Bradshaw, 1977. Lithological and palaeontological content of the Carboniferous-Jurassic Canterbury Suite, South Island, New Zealand. *N.Z. Journal of Geology and Geophysics* 19: 791-819.

Bell, S., H. J. Harrington and I. C. McKellar, 1956. Lower Mesozoic plant fossils from Black Jacks, Waitaki River, South Canterbury. *Transactions of the Royal Society of N.Z.* 83: 663-678.

Bishop, D. G., 1974. Stratigraphic, structural and metamorphic relationships in the Dansey Pass area, Otago, New Zealand. *N.Z. Journal of Geology and Geophysics* 17: 301-335.

——— 1976. The Torlesse terrane of the Waitaki Valley. *In* D. S. Coombs, J. D. Campbell, I. C. McKellar, C. A. Landis, D. G. Bishop (Eds.): Regional geology of southern part of the South Island, New Zealand Geosyncline. *25th International Geological Congress, Excursion Guide* 59C: 11-13.

Bluck, B. J., 1967. Sedimentation of beach gravels: examples from South Wales. *Journal of Sedimentary Petrology* 37: 139-167.

Boney, A. D., 1966. *A Biology of Marine Algae.* Hutchinson, London.

Boothroyd, J. C., 1972. Coarse-grained sedimentation on a braided outwash fan, northeast Gulf of Alaska. *Technical Report of the Coastal Research Division, Department of Geology, University of South Carolina, Columbia* 6-CRD, pp. 127.

Boothroyd, J. C., and G. M. Ashley, 1975. Process, bar morphology and sedimentary structures on braided outwash fans, northeastern Gulf of Alaska. *In* A. V. Joplin and B. C. McDonald, (Eds.): Glaciofluvial and glaciolacustrine sedimentation. *Special Publication of the Society of Economic Paleontologists and Mineralogists, Tulsa* 23: 193-222.

Bouma, A. H., 1962. *Sedimentology of Some Flysch Deposits.* Elsevier, Amsterdam.

Brand, E., 1938. Diluvial Eiskeile bei Aschaffenberg. *Senckenbergiana* 20: 412-417.

Burke, K., 1967. The Yallahs Basin: a sedimentary basin southeast of Kingston, Jamaica. *Marine Geology* 5: 45-60.

Campbell, J. D., and G. Warren, 1965. Fossil localities of the Torlesse Group in the South Island. *Transactions of the Royal Society of N.Z.* 3: 99-137.

Carr, A. P., 1969. Size grading along a pebble beach, Chesil Beach, England. *Journal of Sedimentary Petrology* 39: 297-311.

Carter, R. M.; C. A. Landis, J. J. Norris, D. G. Bishop, 1974. Suggestions towards a high level nomenclature for New Zealand rocks. *Journal of the Royal Society of N.Z.* 4: 5-18.

Dunham, R. J., 1962. Classification of carbonate rocks according to depositional textures. *In* W. E. Ham, (Ed.): Depositional environments in carbonate rocks: a symposium. *Special Publication of the Society of Economic Paleontologists and Mineralogists* 14: 139-181.

Emery, K. O., 1955. Grainsize of marine beach gravel *Journal of Geology* 63: 39-49.

Folk, R. L., 1962. Spectral subdivision of limestone types. *In* W. E. Ham, (Ed.): Classification of Carbonate Rocks. *Memoir of the American Association of Petroleum Geologists* 1: 62-84.

Force, L. M., and E. R. Force, 1978. Triassic rocks of the Black Forest-Haldon area, MacKenzie Country, South Island, New Zealand. *N.Z. Journal of Geology and Geophysics* 21: 747-760.

Garner, H. F., 1959. Stratigraphic-sedimentary significance of contemporary climate and relief in four regions of the Andes Mountains. *Bulletin of the Geological Society of America* 70: 1327-1368.

Gobbett, D. J., 1973. Permian fusulinacea. *In* A. Hallam, (Ed.): *Atlas of Palaeobiogeography,* pp. 151-158. Elsevier, New York.

Gupta, A., 1975. Stream characteristics in eastern Jamaica, an environment of seasonal flow and large floods. *American Journal of Science* 275: 825-847.

Gustavson, T. C., 1974. Sedimentation on gravel outwash fans, Malaspina Glacier foreland, Alaska. *Journal of Sedimentary Petrology* 44: 374-389.

Harris, T. M., 1964. *The Yorkshire Jurassic Flora. II. Caytoniales, Cycadales, Pteridosperms.* British Museum of Natural History, London.

——— 1966. Dispersed cuticles. *Palaeobotanist* 14: 102-105.

Hey, R. W., 1967. Sections in the beach-plain deposits of Dungeness, Kent. *Geological Magazine* 104: 361-370.

Hicks, D. M., 1981. Deep-sea fan sediments in the Torlesse zone, Lake Ohau, South Canterbury, New Zealand. *N.Z. Journal of Geology and Geophysics* 24: 209-230.

Hitching, K. D., 1979. Torlesse geology of Kakahu, South Canterbury. *N.Z. Journal of Geology and Geophysics* 22: 191-197.

Hornibrook, N. de B., and Y. K. Shu, 1965. Fusuline limestone in the Torlesse Group near Benmore Dam, Waitaki Valley. *Transactions of the Royal Society of New Zealand, Geology* 3: 136-137.

Howell, D. G., 1981. Submarine fan facies in the Torlesse terrane, New Zealand. *Journal of the Royal Society of New Zealand* 11: 113-122.

Johnson, D. W., 1938. *Shore Processes and Shoreline Development.* Wiley, New York.

Johnson, J. H., 1961. *Limestone Building Algae and Algal Limestones.* Colorado School of Mines, Boulder.

King, C. A. M., 1972. *Beaches and Coasts.* Arnold, London.

Kisch, H. J., 1981. Coal rank and illite crystallinity associated with the zeolite facies of Southland and the pumpellyite facies of Otago, southern New Zealand. *N.Z. Journal of Geology and Geophysics* 24: 349-360.

Lucas, A. H. S., 1936. *The Seaweeds of South Australia. Part II. Introduction and the Green and Brown Seaweeds.* Government Printer, Adelaide.

MacGillavry, H. J., 1970. Turbidite detritus and geosyncline history. *Tectonophysics* 9: 365-393.

Miall, A. D., 1977. A review of the braided-river depositional environment. *Earth Science Review* 13: 1-62.

Morton, J., and M. Miller, 1973. *The New Zealand Sea Shore.* Collins, London.

Oliver, P. J., 1979. Structure and tectonic history of the Mesozoic rocks of the foothills of the Southern Alps in mid-Canterbury. *Bulletin of the Royal Society of N.Z.* 18: 105-111.

Oliver, P. J., J. D. Campbell, and I. G. Speden, 1982. The stratigraphy of the Torlesse rocks of the Mt Somers area (S81) mid-Canterbury. *Journal of the Royal Society of N.Z.* 12: 243-271.

Potter, P. E., and E. J. Pettijohn, 1963. *Paleocurrents and Basin Analysis.* Academic Press, New York.

Retallack, G. J., 1977. Reconstructing Triassic vegetation of eastern Australasia: a new approach for the biostratigraphy of Gondwanaland. *Alcheringa* 1: 247-277.

Retallack, G. J., 1979. Middle Triassic coastal outwash plain deposits in Tank Gully, Canterbury, New Zealand. *Journal of the Royal Society of New Zealand* 9: 397-414.

——— 1983. Middle Triassic megafossil marine algae and land plants from near Benmore Dam, southern Canterbury, New Zealand. *Journal of the Royal Society of New Zealand* 13: 129-154.

Retallack, G. J., and R. J. Ryburn. 1982. Middle Triassic deltaic deposits in Long Gully, near Otematata, north Otago, New Zealand. *Journal of the Royal Society of New Zealand* 12: 207-227.

Riding, R., 1975. *Girvanella* and other algae as depth indicators. *Lethaia* 8: 173-179.

Ross, C. A., 1963. Standard Wolfcampian Series (Permian), Glass Mountains, Texas. *Memoir of the Geological Society of America* 88, pp. 205.

——— 1979a. Ecology of large, shallow water, tropical foraminifera. *In* J. H. Lipps, W. H. Berger, M. A. Buzas, R. G. Douglas, C. A. Ross (Eds.): Foraminiferal ecology and paleoecology. *Short Course Notes of the Society of Economic Paleontologists and Mineralogists* 6: 54-59.

——— 1979b. Fusilinacea. *In* R. W. Fairbridge, D. Jablonski (Eds.): *The Enclyclopedia of Paleontology,* pp. 333-336. Dowden, Hutchinson and Ross, Stroudsburg, Pennsylvania.

Scott, K. M., and G. C. Gravlee, 1968. Flood surge on the Rubicon River, California — hydrology, hydraulics and boulder transport. *Professional Paper of the United States Geological Survey* 422M, pp. 40.

Seilacher, A., 1982. Distinctive features of sandy tempestites. *In* G. Einsele and A. Seilacher (Eds): *Cyclic and event stratification,* pp. 333-349. Springer, New York.

Sheppard, D. S., C. J. Adams and G. W. Bird, 1974. Age of metamorphism and uplift in the Alpine Schist Belt, New Zealand. *Bulletin of the Geological Society of America* 86: 1147-1153.

Shu, Y. K., 1964. *Greywacke structure and petrography around Benmore Dam, north Otago.* Unpublished Bachelor of Science with Honours thesis, Department of Geology, University of Otago, Dunedin.

Smale, D., 1980a. Phosphorite intraclasts in Torlesse sandstones and conglomerates, South Canterbury. *N.Z. Journal of Geology and Geophysics* 23: 273-276.

——— 1980b. Akatarawa Conglomerate (Permian), Lake Aviemore, South Canterbury. *N.Z. Journal of Geology and Geophysics* 23: 279-292.

Speden, I. G., 1960. The Jurassic age of some supposedly Triassic mollusca described by Wilckens (1927) from Mt St Mary. *N.Z. Journal of Geology and Geophysics* 3: 510-523.

Spörli, K. B., 1979. Structure of the South Island Torlesse in relation to the origin of the Southern Alps. *Bulletin of the Royal Society of N.Z.* 18: 99-104.

Spörli, K. B., and T. P. Barter, 1973. Geological reconnaissance in the Torlesse Supergroup of the Kaimanawa Ranges along the lower reaches of the Waipakiti River, North Island, New Zealand. *Journal of the Royal Society of N.Z.* 3: 363-380.

Spörli, K. B., K. J. Stanaway and W. R. H. Ramsey, 1974. Geology of the Torlesse Supergroup in the southern Liebig and Burnett Ranges, Canterbury, New Zealand. *Journal of the Royal Society of N.Z.* 4: 177-192.

Steinman, G., 1921. Rhätische Floren un Landverbindungen auf der Südhalbkugel. *Geologische Rundschau* 11: 350-354.

Stevens, G. R., and I. G. Speden, 1978. New Zealand. *In* M. Moullade, A. E. M. Nairn (Eds.): *The Mesozoic A. The Phanerozoic Geology of the World II,* pp. 251-328. Elsevier, Amsterdam.

Suggate, R. P. (Ed.), 1978. *The Geology of New Zealand. Volume 1.* Government Printer, Wellington.

Townrow, J. A., and J. Jones, 1969. On *Pachypteris pinnata* (Walkom) from Tasmania. *Papers and Proceedings of the Royal Society of Tasmania* 103: 63-67.

Young, G. M., and D. G. F. Long, 1976. Ice wedge casts from the Huronian, Ramsay Lake Formation (2,300 m.y. old), near Española, Ontario, Canada. *Palaeogeography, Palaeoclimatology and Palaeoecology* 19: 191-200.

Received 5 November 1982; accepted 27 April 1983