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Submergent shorelines in the SW Pacific: evidence for an episodic post-glacial transgression

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ABSTRACT

High resolution seismic profiles, supported where possible by radiocarbon dates and regional stratigraphic data, indicate that the last post-glacial transgression in the SW Pacific was episodic, comprising major stillstands punctuated by rapid rises in sea-level.

On the terrigenous continental shelf east of South Island, New Zealand, a succession of shorelines (S8–S1) are recognized, as follows: S8 = *c.* −113 m, 18,000 yr BP; S7 = *c.* −88 m, 17,000 yr BP; S6 = *c.* −75 m, 15,000 yr BP; S5 = *c.* −56 m, 12,000 yr BP; S4 = *c.* −46 m, 11,000 yr BP; S3 = *c.* −28 m, 9,500 yr BP; S3a = *c.* −24 m, 9,000 yr BP; S2 = *c.* −9 m, 7,500 yr BP; S1 = 0 m, 6,500 yr BP.

With the exception of S8, and possibly S2, the shorelines are associated with wedges of sediment, the size and presence of which imply that (1) sea-level stabilized at some shorelines for a considerable period of time (up to 1–2,000 yr); and (2) the intervening rises of sea-level, estimated to have been at least 10–12 m 10^3 yr^{-1}, were too rapid to allow the reworking of the wedges into a transgressive sediment sheet, as favoured in some current models.

On the Great Barrier Reef shelf, off Queensland Australia, shorelines S8–S1 have also been recognized, with a further shoreline feature S4a occurring at *c.* −39 m. Shorelines S1a (0 m/0 yr BP), S1b (+2–3 m/6,000 yr BP) and S1c (0 m/6,500 yr BP) are recognized as discrete aspects of the post-6,500 yr BP sea-level behaviour in north-eastern Australia. The rapid rise in sea-level, at least between shorelines S5 (12,000 yr BP) and S3 (9,500 yr BP), is known to have outpaced reef growth, causing *in situ* drowning of reefs located along the deeper shorelines. All modern reefs so far drilled and dated began their development at or above S3 (−28 m, 9,500 yr BP).

Some of the shorelines, particularly S5, appear to correlate between the northern and southern hemispheres on the basis of age, succession and general depth of occurrence, suggesting (1) that they may be global features controlled by the post-glacial pattern of ice-sheet decay; and (2) that hydro-isostatic adjustment may exert only a minor control on the depth of particular shorelines, at least during the earlier parts of the post-glacial transgression.

INTRODUCTION

At the peak of the last glacial period (*c.* 18,000 yr BP), sea-level was located at and beyond the edge of the continental shelf at depths of 110–150 m, depending upon the location (Bloom, 1971; Jansen *et al.*, 1979). Also, it has been shown that different regions of the world can be expected to have experienced different patterns of sea-level change during glacial/interglacial cycles, due to the effects of hydro-isostasy (Bloom, 1967; Walcott, 1972), glacio-isostasy (Clark, Farrell & Peltier, 1978) and geoid irregularities (Morner, 1972, 1976).

In Australia and New Zealand, significant progress has been made in establishing local, relative sea-level curves for the 'Holocene' transgression from *c.* 9,000 yr BP to the present (Hopley, 1983a; Chappell *et al.*, 1983; Gibb, 1979, 1986) (Fig. 1A, B). In contrast, sea-level changes between 18 and 9,000 yr BP are poorly documented even globally (cf. Cronin, 1983)

and, for that reason, are often presented as 'envelopes' of change (e.g. Hopley & Thom, 1983; Thom & Roy, 1985). The frequently quoted sea-level curves of Milliman & Emery (1968) and Shackleton & Opdyke (1973) have helped fuel a general assumption that sea-level rose quickly and steadily from its lowstand at *c.* 18,000 yr BP to its modern level (cf. Shepard, 1963; Scholl, 1964; Jelgersma, 1979; Ludwig, Muller & Streif, 1981). However, other published sea-level curves (e.g. Fairbridge, 1961; Curray, 1965; Morner, 1969; Hopkins, 1973; Holmes & Creager, 1974; Kolp, 1976) show the post-glacial transgression as episodic, and punctuated by several stillstands or minor regressions.

Clark & Lingle (1979) produced a model for the New Zealand region showing the impact of the melting of the Antarctic ice-sheet, and the combined Antarctic and Arctic ice-sheets, on the predicted post-glacial sea-level curve (Fig. 1C). Pauses in ice-melting, or minor advances, in Antarctica are predicted to have caused two major perturbations in the post-glacial transgression, at *c* 15,000 and *c.* 12,000 yr BP. However, because Antarctic ice contributes only *c.* 20% of global glacial eustatism (cf. Fig. 1C), these fluctuations were minimized by the Arctic-induced transgression, assumed to have been continuous from 18,000 to 5,000 yr BP. More recently, Duplessy *et al.* (1981), Ruddiman & McIntyre (1981) and Leventer, Williams & Kennett (1982) have presented evidence that the Arctic ice-sheet also melted episodically. When the northern hemisphere findings are combined with the Clark & Lingle (1979) model, it becomes apparent that the global post-glacial shoreline transgression was punctuated by at least two major periods of stillstand and regression of possible global significance (cf. Kerr, 1983; Berger, Killingley & Vincent, 1985).

In this paper, we discuss high resolution seismic profiles, radiocarbon dates and regional evidence from NE Australia and eastern South Island, New Zealand, which support the concept of episodic transgression between 18,000 and 6,500 yr BP. The sedimentary implications of such an episodic transgression, and global application of the model, are briefly outlined.

A characteristic of many previously published sea-level models is their reliance on radiocarbon dates as

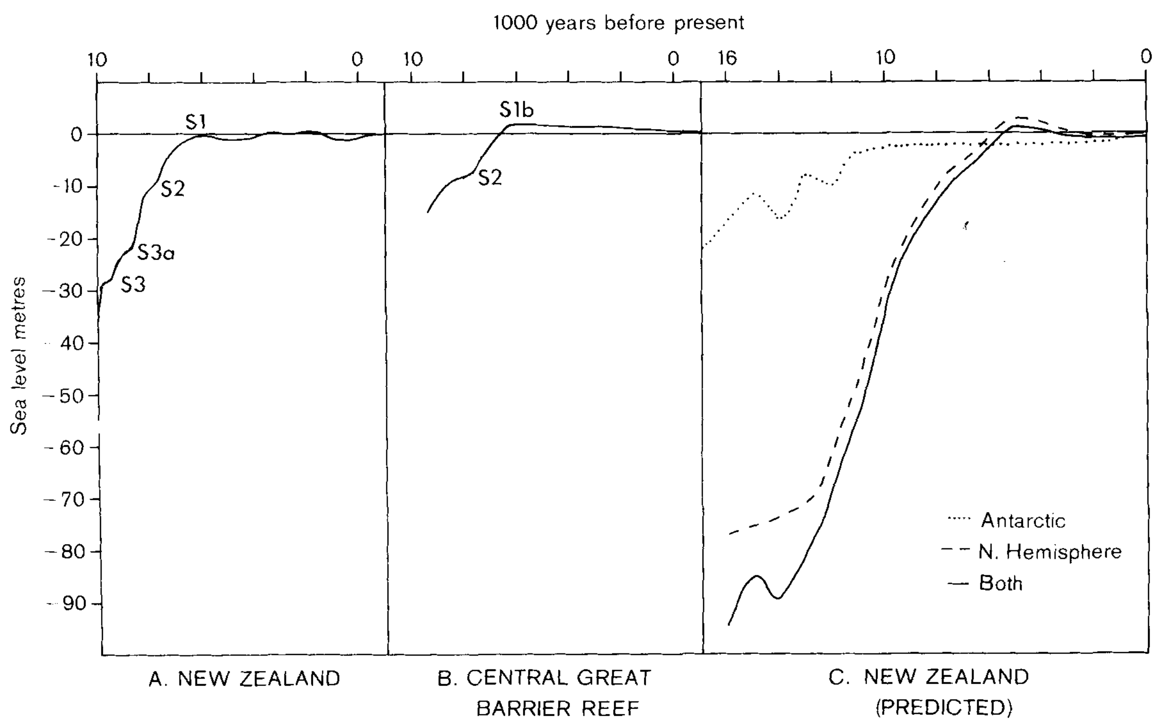

Fig. 1. Post-glacial sea-level curves from the SW Pacific. (A) New Zealand region, last 10,000 yr (after Gibb, 1986). (B) Central Great Barrier Reef shelf, last 10 kyr (after Hopley, 1983b; Belperio, 1979; Chapell *et al.*, 1983; Grindrod & Rhodes, 1984). (C) Predicted post-glacial sea-level curves for New Zealand based on the melting of the northern hemisphere and Antarctic ice-sheets since 16,000 yr BP (after Clark & Lingle, 1979).

a primary control. However, such dates have well-known problems of sample collection, preparation and analysis, together with the major problem that much datable material is difficult to relate accurately to sea-level at the time of deposition; even where intertidal species have been sampled, they may have been transported on or offshore after death but before burial. Consequently, radiocarbon-based sea-level models are almost of necessity viewed as envelopes, and radiocarbon data will rarely if ever demonstrate whether shoreline movement has been episodic or continuous, or whether geoidal variation has been dominant.

Though we utilize the available radiocarbon dates in this study (Table 1; cf. Fig. 7), primacy has been given to stratigraphic evidence. We have interpreted the available seismic data, arguing that erosional terraces or constructional sediment wedges preserved on the shelf are accurate evidence of the positions of former strandlines. In some cases such inferred strandlines can be radiocarbon dated, while for others the age has to be interpolated. In general, the estimated depth for each shoreline represents an accurate summary of many observations (cf. Table 2), whereas the age is less well controlled.

EPISODIC TRANSGRESSIVE MODEL

An episodic marine transgression across the continental shelf such as that which characterized the post-glacial transgression may be expected to leave a signature in the form of wave-cut platforms, reef-growth or clastic sedimentary wedges at each shoreline. In rapidly uplifting areas, this results in the development of conspicuous flights of emergent coastal terraces (e.g. Chappell, 1974 in New Guinea; Wellman, 1979 in New Zealand). On stable or gently submerging coasts the evidence is less conveniently preserved as a series of 'drowned shorelines', the locations of which are usually inferred from bathymetry (e.g. Veatch & Smith, 1939; Andrews, 1973; Marshall, 1977). Bathymetric inferences alone are unreliable, however, since not all bathymetric breaks represent submerged shorelines, and, conversely, not all submerged shorelines produce bathymetric breaks (compare Andrews, 1973 with Carter *et al.*, 1985). Furthermore, reliable dating of bathymetric features is difficult and differential rates of uplift can produce marked regional differences in the depths at which particular shorelines occur (e.g. Emery & Garrison, 1967; Officer & Drake, 1982).

In certain circumstances, however, a series of sediment wedges will be deposited, each terminating shorewards at a successively shallower drowned shoreline (e.g. Ewing, Le Pichon & Ewing, 1963; Knott & Hoskins, 1968; van Andel & Calvert, 1971). The sediments of such wedges often comprise sand and gravel at the inner edge, grading off to silty and muddy materials in more seaward parts. Studies of the Zealand shelf (Herzer, 1981; Carter & Carter, 1982, 1986; Carter *et al.*, 1985) suggest that wedges are preserved in circumstances where:

Table 1. Summary table of selected radiocarbon data from eastern South Island, New Zealand

Station	Latitude	Longitude	Depth of shells below sea-level (m)	Depth in core (m)	Species	Depth range (m)	Age* (yr BP)	N.Z. C^{14}no.
‡H788	44°09·6′S	172°27·9′E	59–61	0·86–0·98	*Tawera spissa*	0–*c.* 120	7340 ± 150	3892
				1·7–1·83	*Scalpomactra scalpellum*	0–90	8070 ± 170	3893
				2·13–2·27	*Scalpomactra scalpellum*	0–90	9370 ± 260	3894
				2·63–3·16	*Scalpomactra scalpellum*	0–90	8560 ± 220	3895
‡H4789	44°05·4′S	172°25·2′E	56	2·52–2·9	*Tawera spissa*	0–*c.* 120	6370 ± 110	3896
‡H790†	44°09·0′S	172°35·8′E	63	1·7–2·07	*Zethalia zelandica*	0–20	11,750 ± 250	3897
‡H810†	43°45·7′S	172°19·7′E	76	0·95–1·42	*Paphies australe*	0–3	15,100 ± 200	3898
MU 76/81	45°58′S	170°47′E	95	dredge	*Zethalia zelandica*	0–20	9780 ± 200	4618
P 152†	45°51·2′S	178°48·2′E	68	0·96–0·98	*Chione stutchburyii*	0–3	11,800 ± 250	4619
Q 257	46°02·1′S	170°33·9′E	53	dredge	mixed	—	1300 ± 50	
Q 261	45°37·1′S	171°03·6′E	166–220	dredge	*Plurigens* sp.		600 ± 50	
T 194†	46°10.65′S	171°12′E	48	0·25–0·33	*Zethalia zelandica*	0–20	9120 ± 180	

Plus 85 radiocarbon-dated sea-level markers compiled by Gibb (1986).
* Age calculated with respect to old $T_{\frac{1}{2}}$ of 5568 yr.
† Dates plotted as constraints on sea-level curve (Fig. 7).
‡ Data of Herzer (1981).

(a) the shelf is stable or undergoing gentle net subsidence;
(b) there is sufficient input of terrigenous sediment for the construction of sizeable wedges along each shoreline;
(c) the cross-shelf gradient is neither excessively shallow nor too steep (cf. Flemming, 1964; Roy, 1985); and
(d) there is no post-depositional erosion of sediment, such as can be produced by an active hydraulic regime.

Because these conditions vary with time and geography, it is not surprising that a complete succession of shoreline deposits has yet to be encountered across a single shelf transect. Where individual sediment wedges are missing, sometimes a nick-point or planation surface may nonetheless be discerned at the depth appropriate to a particular stillstand. Shoreline omissions may be due to local fluctuations in sediment supply, or to post-depositional erosion such as has been demonstrated for parts of a −56 m shoreline wedge by Carter & Carter (1985).

Data collection

3·5 kHz and Uniboom profiles available to us from eastern South Island (Fig. 2) and the central Great Barrier Reef (Johnson & Searle, 1984) have been analysed in terms of the preceding discussion. The depth at which a particular shoreline is preserved may vary between profiles, due to regional tectonic warping and hydro-isostatic rebound. However, the eastern South Island and Queensland shelves, subsiding at less than 0·2 mm yr^{-1}, both appear to have negligibly small rates of post-glacial warping relative to the development of shorelines S8–S1 (Wellman, 1979; Suggate, 1968; Hopley, 1983b).

We summarize in Table 2 the results of our analysis of shoreline depths, including the estimated mean relative sea-level for each shoreline. Most of the available profiles were collected at a recorder sweep-speed of $\frac{1}{4}$ s. Depths can thus be measured to a precision of better than ±0·5 m. When the effects of tidal and other uncertainties are taken into consideration, we estimate that the overall precision of shoreline depth measurements is ±*c.* 2 m.

The five main shoreline features measured were:

(a) *Wavecut platform terminating shorewards at a cliff.* Sea-level is measured at the nick point situated at the cliff base (Bradley, 1958) (e.g. Fig. 3A)

(b) *Sediment wedge terminating on an inferred coastal plain.* The contemporary sea-level is measured at the point of pinch-out of the sediment wedge (e.g. Fig. 3B). In some cases the inner edge of the wedge has been eroded, necessitating an estimate of its original shape.

(c) *Wavecut platform and sediment wedge combinations.* In some cases the sediment wedge pinches out at or near the seaward edge of an inferred wavecut platform, when it is regarded as contemporary with the platform. As in (a), the position of the shoreline is then taken at the base-of-cliff nick-point (Fig. 3A).

More commonly, a platform is overlain by a sediment wedge which has its apex at or near the palaeo-cliff top (cf. Fig. 3F). For all except the shoreline of maximum (interglacial) transgression, two interpretations are possible: either (1) that platform-cutting was followed by minor subsidence

Table 2. Summary data on submerged post-glacial shorelines, SW Pacific

Shoreline	Queensland			Eastern South Island			Age	Adopted eustatic depth
	Depth range	Σ observations	Mean depth	Depth range	Σ observations	Mean depth		
S1	0±2	—	0	0±2	—	0	≤*6·5	0
S2	9–12	12	10	9–10	3	9	*7·6	9
S3a	23	1	23	23–26	5	24	*9·0	24
S3	26–29	25	27·5	28–30	5	28·4	(*c.* 9.5)	28
S4a	38–41	22	39·3	38–42	4	38·9	(*c.* 10)	39
S4	44–47	17	45·7	46	2	46	(*c.* 11)	46
S5	52–59	19	56·0	52–56	12	54·6	*12	56
S6	74–75	2	74·5	72–78	15	75·4	*15	75
S7	88	3	88	88–91	6	89	(*c.* 17)	88
S8	110–114	4	111·6	109–116	8	113	(*c.* 18–20)	113

* Age C^{14} controlled; ( ) age interpolated.

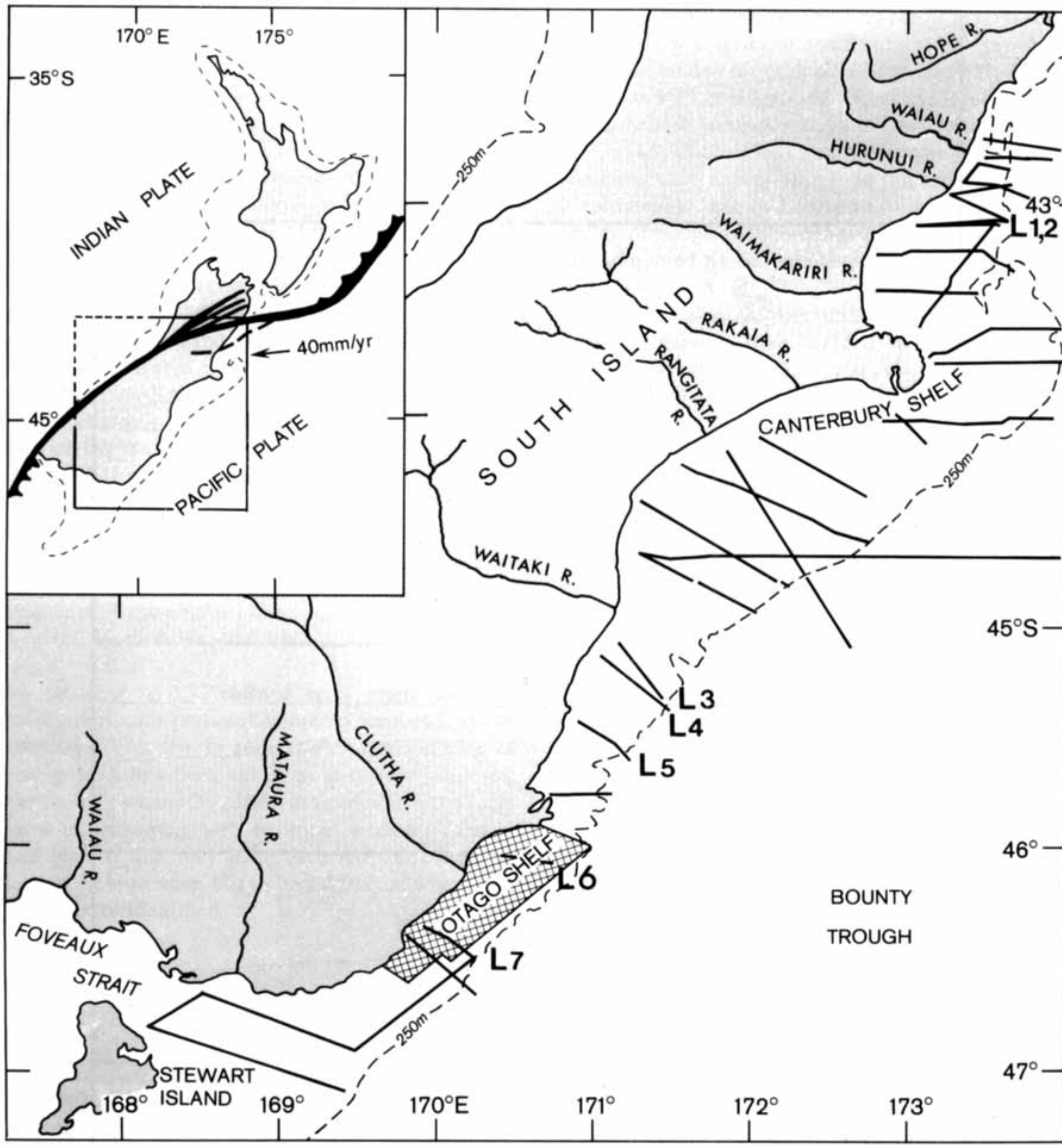

Fig. 2. Location of 3·5 kHz and Uniboom seismic profiles used for the South Island section of the study. Hatched Otago shelf is area of intense profiling with lines < 5 km apart. Inset: location of study area with respect to the New Zealand plate boundary system.

(or sea-level rise), and that the contemporary sea-level should be measured at the top of the sediment wedge; or (2) that the sediment wedge was deposited as the shoreline moved landwards during the next transgressive pulse, and that the nick-point at the back of the cut-platform marks the contemporary sea-level (Bradley, 1958). The second interpretation has been preferred for two reasons. First, the sediment wedge occasionally includes a thin basal layer, apparently related to a sea-level close to the nick-point; and, second, the wedge usually laps out against the top of the shoreline cliff irrespective of the cliff-height,

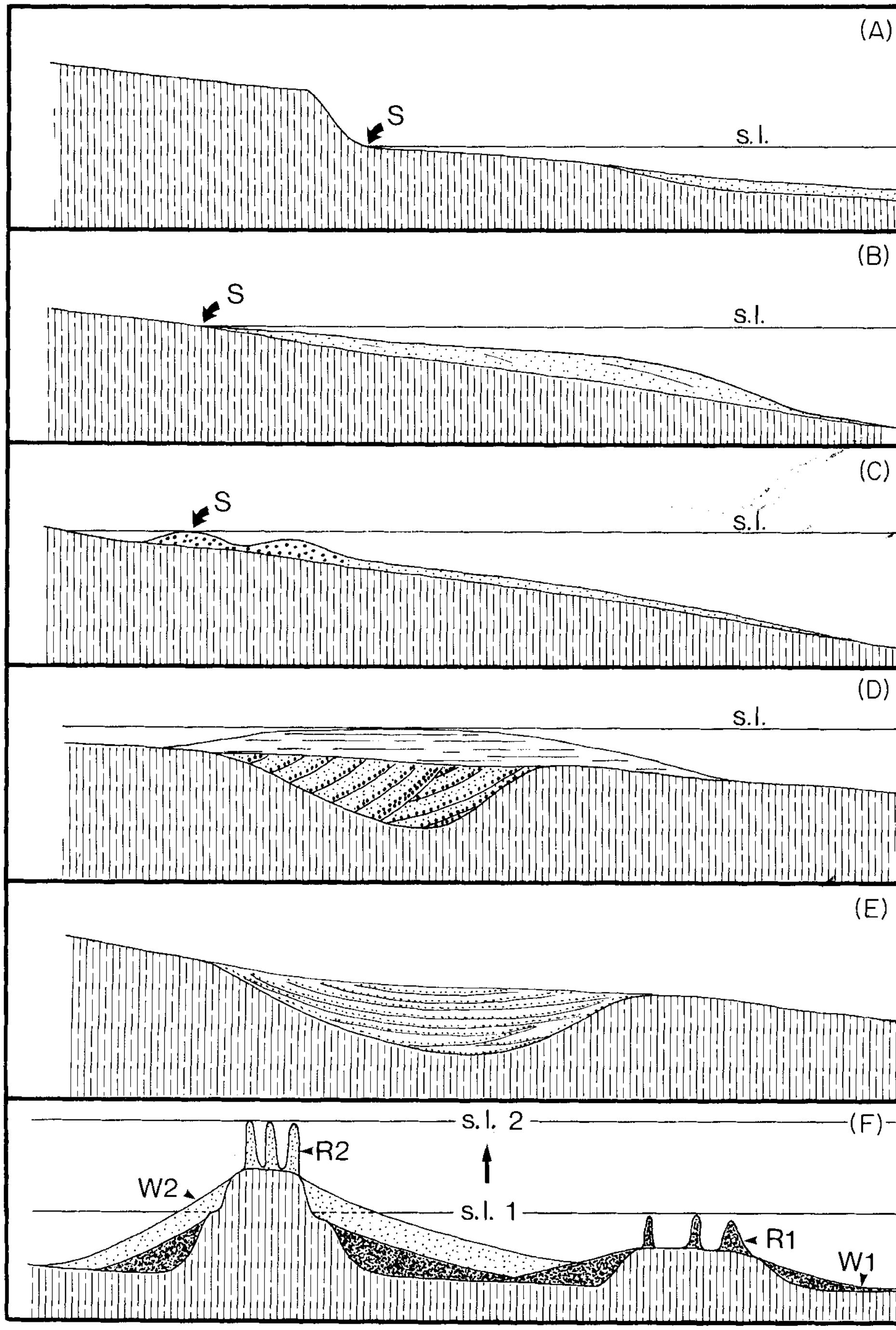

Fig. 3. Summary diagram of common types of submergent shoreline features, showing inferred positions of palaeoshorelines (S) and sea-level (s.l.). (A) wavecut terrace backed by a low cliff; (B) tapering coastal sediment wedge characteristic of wide embayments; (C) shoreline barrier ridge system; (D) river channel deposits capped by prodelta mouth-bar or mound (cf. Johnson *et al.*, 1982); (E) abandoned river channel filled with simple (?marine) drape deposits; (F) two stages of reef growth, and associated talus wedges, formed at successive sea-levels 1 and 2.

suggesting that the bulk of the wedge post-dates the formation of the cliff.

(d) *Shoreline barriers or deltaic mouth bars.* The contemporary sea-level is estimated to have coincided with the crest of shoreline barriers (Fig. 3C, D). This may result in a slight underestimate of depth, since such barriers are often built to a few metres above sea-level by storm processes (e.g. Morner, 1969).

Other evidence for drowned shorelines comes from incised channels, but comparison of Figs 3(D) and (E) shows that channel fill deposits alone cannot be used as palaeo-shoreline indicators. Accordingly, we have only used features such as that of Fig. 3(D), i.e. probable mouth-bar sediment mounds that overlie buried channels containing a coarsely cross-bedded (fluvial) fill. We interpret channels containing a simple drape fill (Fig. 3E) as fine-grained marine deposits deposited in an empty channel which has been drowned by landwards migration of the shoreline. Thus these features cannot be used to indicate a shoreline depth, unless a number of congruent measurements of the channel base defines a former base level (cf. Searle & Hegarty, 1982).

(e) *Drowned reefs.* Drowned reefs often occur in association with peri-reef sediment wedges and cut platforms (Fig. 3F). In general, the common level of reef growth has been taken as a former sea-level, particularly where the platform from which the reefs grow is associated with sediment wedges. Vertical reef growth that may have occurred subsequent to further transgression has to be subtracted where this effect can be identified.

EASTERN SOUTH ISLAND SUBMERGENT SHORELINES

South Island, New Zealand, is traversed by the Alpine Fault which marks the boundary between the Indo-Australian and Pacific Plates (see Fig. 2, inset). High rates of uplift are characteristic of the western regions near the boundary, with the consequence that early interglacial deposits typically occur as flights of emergent terraces (e.g. Cooper & Bishop, 1979). Uplift decreases exponentially away from the Alpine Fault (Wellman, 1979), and passes into stasis or slight submergence on the eastern South island shelf. The axis of tilting, or zero isobase (Lewis, 1973), generally lies a few kilometres offshore from the present east coast.

High resolution seismic profiles across several shelf sectors show a series of sedimentary wedges which pinch out landwards at depths of around 113, 88, 75, 56, 46 and 28 m (Figs 4–6). Other evidence, chiefly from onshore boreholes and emergent terraces (Suggate, 1968; Gibb, 1986), reveals the presence of two shallower shorelines at *c.* −24 and *c.* −9 m. To accommodate this, and the post-6,500 yr BP modern sediment wedge, the shorelines delimited in this study are numbered S1–S8, and their respective sediment wedges W1–W8.

Typical profiles for different shorelines are distributed along more than 500 km of shelf (Fig. 2). Correlations of particular shorelines between profiles are necessarily tentative and, given the paucity of C^{14} dates, in some cases alternative interpretations are possible. The combined evidence for post-glacial submerged shorelines is summarized below in the form of a composite sea-level curve for eastern South Island between 18,000 yr BP and the present (Fig. 7). Major shorelines are indicated by appropriate numbers, whereas lesser or uncertain features carry a letter subscript.

Shoreline S8/W8 (*c.* −113 m): Typically this shoreline is represented by a well-developed terraced surface (Figs 4 and 5A), mantled by a veneer of mixed modern and relict gravel and sand of terrigenous and biogenic origin (e.g. Carter, Carter & Griggs, 1982; Carter *et al.*, 1985). Small sediment wedges have been recorded against the shoreline locally (Herzer, 1981). The general planation of the outer shelf is inferred to have been accomplished mainly during glacial sea-level lowstands, including the last which occurred at *c.* 20–18,000 yr BP. However, modern shelf-edge current systems, such as those imposed by internal waves, are modifying this feature at the present day (e.g. Carter & Herzer, 1979; cf. Flemming, 1980).

Shoreline S7/W7 (*c.* −88 m): A well demarcated sedimentary wedge occurs with its inner feather edge at a depth of *c.* 88 m (Fig. 5B). No material for dating is available from W7, so its age can only be inferred, from its intermediate position between W8 and W6, as *c.* 17,000 yr BP (cf. Herzer, 1981).

Shoreline S6/W6 (*c.* −75 m): This shoreline is usually manifest as a well developed terrace, but locally it is associated with a moderate sized sediment wedge up to 7 m thick. Wedge 6 is buried by younger sediment on the line illustrated (Fig. 5C), but a submerged spit-lagoon complex at similar depths off Banks Peninsula has yielded a radiocarbon date of 15,100 yr BP from

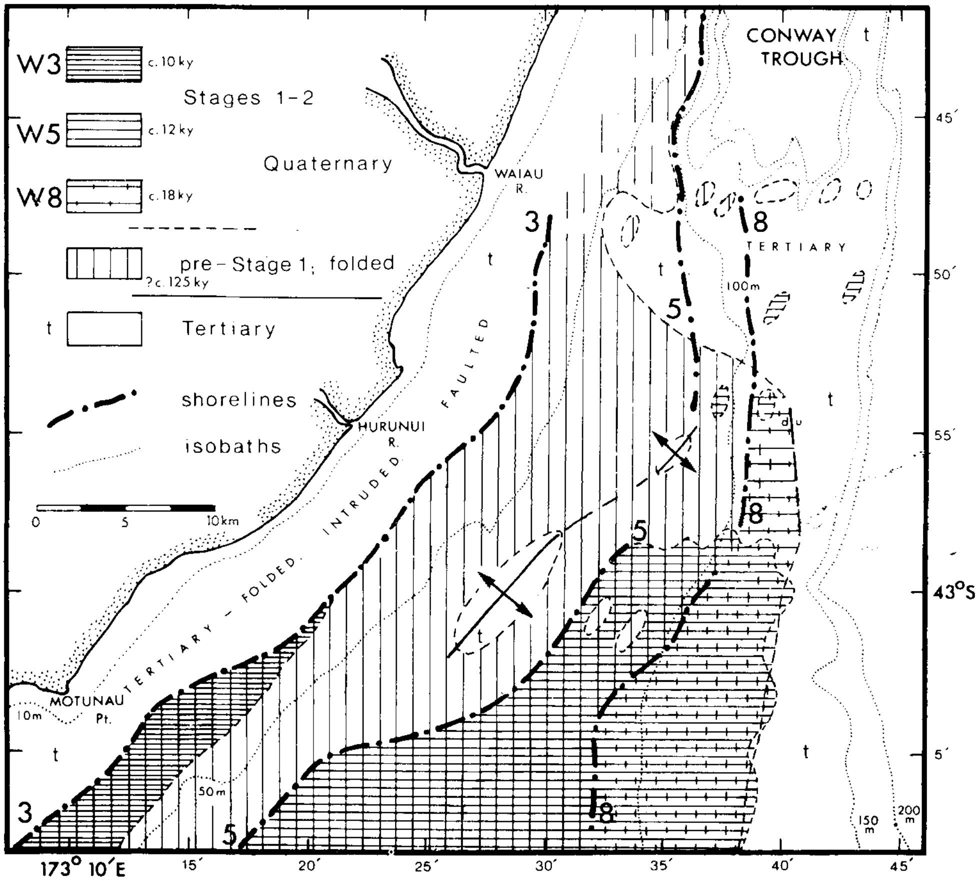

Fig. 4. Distribution of submerged shorelines S3, S5 and S8 and their respective sediment wedges, continental shelf off north-eastern South Island. Note erosion of post-glacial shoreline deposits from the actively uplifting shelf north of latitude 43 S (amended after Carter *et al.*, 1982, fig. 11).

the intertidal mollusc *Paphies australe* (Herzer, 1981, p. 62) (Table 1).

Shoreline S5/W5 (*c.* −56 m): The deposits of this shoreline form barrier ridges (Fig. 6A) and a substantial wedge (Fig. 6B), which overlaps W6 in a seawards direction. Further, in the north the more offshore part of W5, composed of mud, has been subjected to considerable post-depositional erosion, and perhaps mass-failure, resulting in a hummocky topography (Fig. 5B) (Carter & Carter, 1985). The adopted −56 m eustatic depth for S5 is somewhat arbitrary, and it is quite possible that the true depth is significantly deeper.

A submerged shoreline at mid-shelf depths (−55 to −68 m) has been described from eastern South Island by several previous authors (Cullen, 1967; Herzer, 1981; Carter *et al.*, 1982, 1985), and two well-controlled radiocarbon dates indicate an age of *c.* 12,000 yr BP for S5 (Table 1). The size of the sediment wedge built against S5 indicates that sea-level may have been constant in the vicinity of −68 to −56 m for a considerable time.

Shorelines S4 (*c.* −46 m) and S4a (*c.* −39 m): A major wedge of sediment up to 12 m thick extends across the shelf of eastern South Island, opposite the mouth of the large Waitaki River. The wedge pinches out just seaward of a −46 to −48 m platform (Figs 5C, 6C). Elsewhere S4/W4 is not well developed, being represented by small platforms and subtle breaks in slope; similar features at around −39 m may represent shoreline S4a, described below from the nearby Queensland shelf (Carter & Johnson, 1986; cf. Fig. 9).

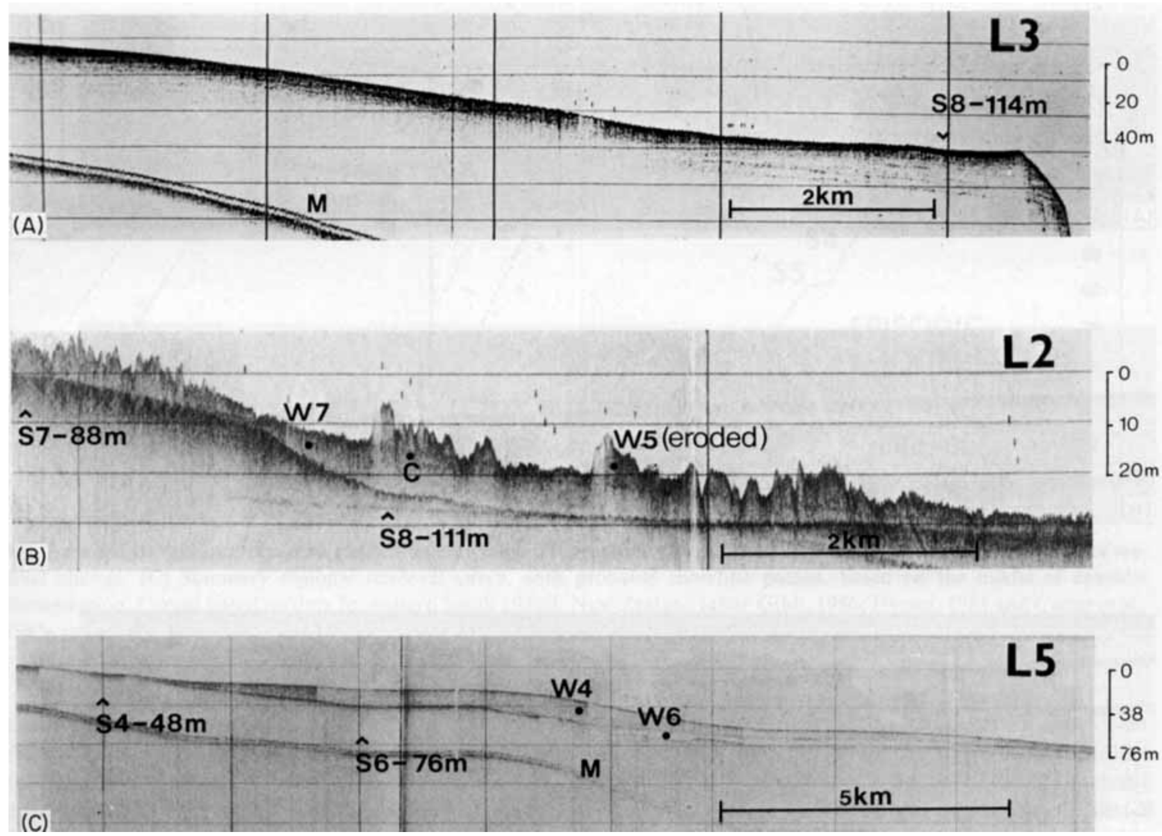

Fig. 5. Profiles of shorelines S8–S6 located on transects L2, 3 and 5 on Fig. 2. Profile L2 exhibits the eroded seaward edge of wedge W5 which overlies W7 along the faint contact (C). Bottom multiple reflection, M.

The age of S4, inferred from its intermediate position between S5 and S3, is *c.* 11,000 yr BP.

Shorelines S3/W3 (*c.* −28 m) and S3a/W3a (*c.* −24 m): Deposits of shoreline S3 are best developed adjacent to the mouth of the Clutha River, where a 34 m thick wedge has prograded seawards to depths of 90 m (Fig. 6D) (Carter & Carter, 1986). The core of this wedge comprises older deposits, including remnants of W5 and earlier Pleistocene sediments, the former preserved on an extensive terrace at −56 m. The main part of the wedge comprises accoustically transparent W1–W3 sediments which blanket a conspicuous wavecut platform at −27 m (Fig. 6D).

Radiocarbon dates from estuarine deposits in deep bores at Christchurch, some 400 km to the NE, indicate a date of 9–9,500 yr BP for the deposits of a feature at −24 m (Suggate, 1968; Gibb, 1986). Regional uncertainty regarding tectonic uplift rates means that we are unable to determine whether these dates correlate with the −28 m feature that we have named S3, or are from another, slightly younger and shallower, shoreline. In the meantime, we recognize the two as discrete features, S3 and S3a, noting that there is evidence from the northern hemisphere for two shorelines at closely similar depths (Hyne & Goodall, 1967; Kolp, 1976).

Shoreline S2/W2 (*c.* −9 m): Land-based studies, summarized by Gibb (1979, 1986), show that another shoreline was briefly occupied at a depth of about −9 m at *c.* 7,500 yr BP. This shoreline has not been identified on our profiles, perhaps because they do not go close enough inshore, or because W2 deposits have been eroded off rocky, uplifting parts of the inner shelf or have been obscured beneath modern sediment wedge W1.

Shoreline S1/W1 (0 m): Post-6,500 yr BP shoreface

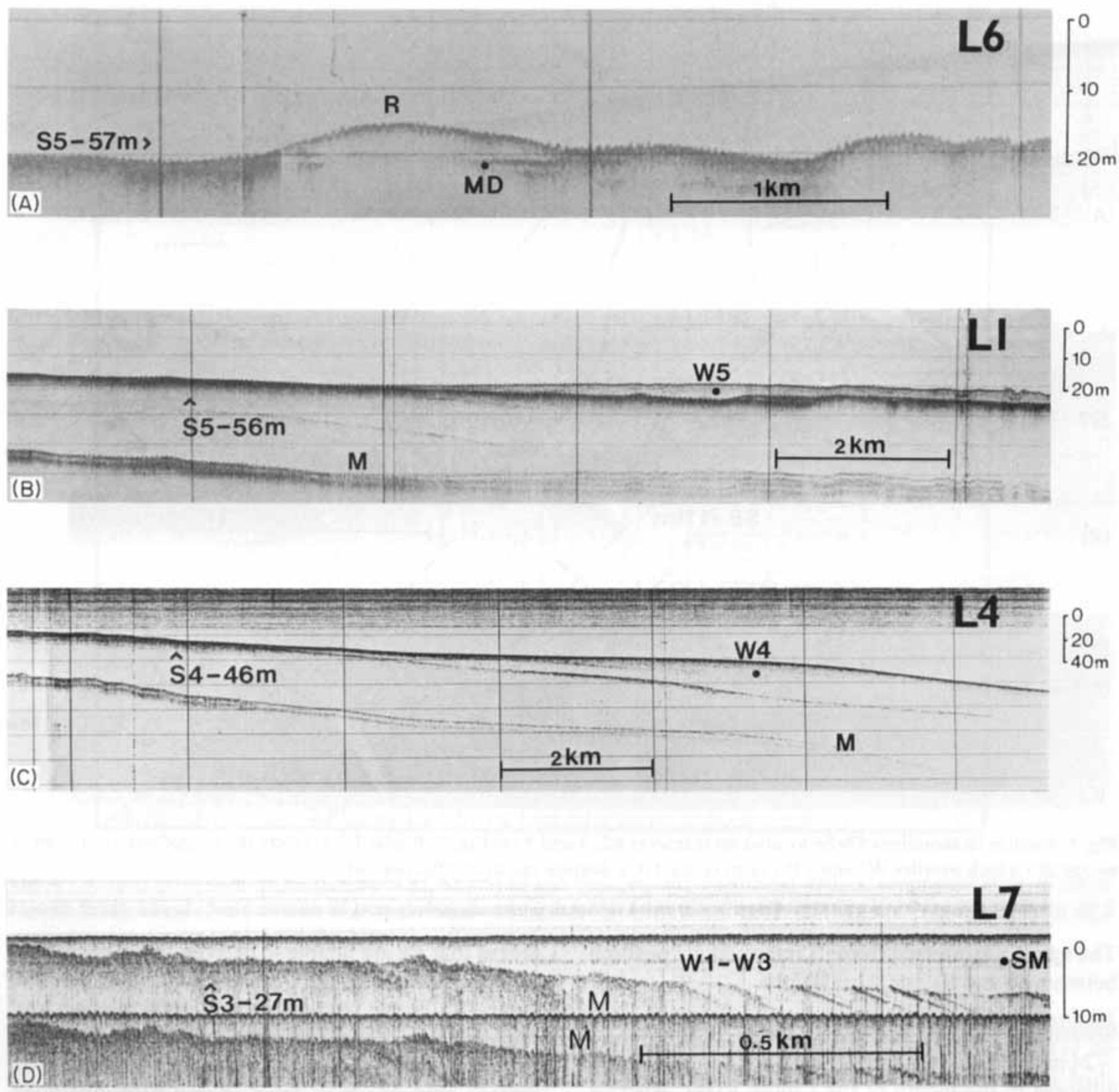

Fig. 6. Profiles of shorelines S5–S3 and associated sediment wedges across transects L1, 4, 6 and 7 on Fig. 2. Profile L6 exhibits an alternative development of the −55 m shoreline, with a barrier ridge complex (R) overlying estuarine muds (MD) radiocarbon dated at 12,000 yr BP (Carter *et al.*, 1985). Bottom multiple reflection, M. Subtow multiple, SM.

sediment reaches seawards up to 18 km off the mouths of major rivers, but may terminate only a few kilometres offshore at locations more distant from a point source (cf. Carter *et al.*, 1985). Except in protected embayments, where mud accumulates, the sediment of W1 is dominated by sand in the south, gravel in the middle and sand and gravel along the northern sector of the eastern South Island shelf (Kirk, 1979; Andrews, 1973; Herzer, 1981).

IMPLICATIONS OF EPISODIC TRANSGRESSION FOR MODELS OF TERRIGENOCLASTIC SHELF EVOLUTION

It is often assumed that the last post-glacial sea-level rise was rapid and uniform, reaching approximately its modern level at *c.* 6,500 yr BP in the southern hemisphere ('Pacific' sea-level curve) or later in the

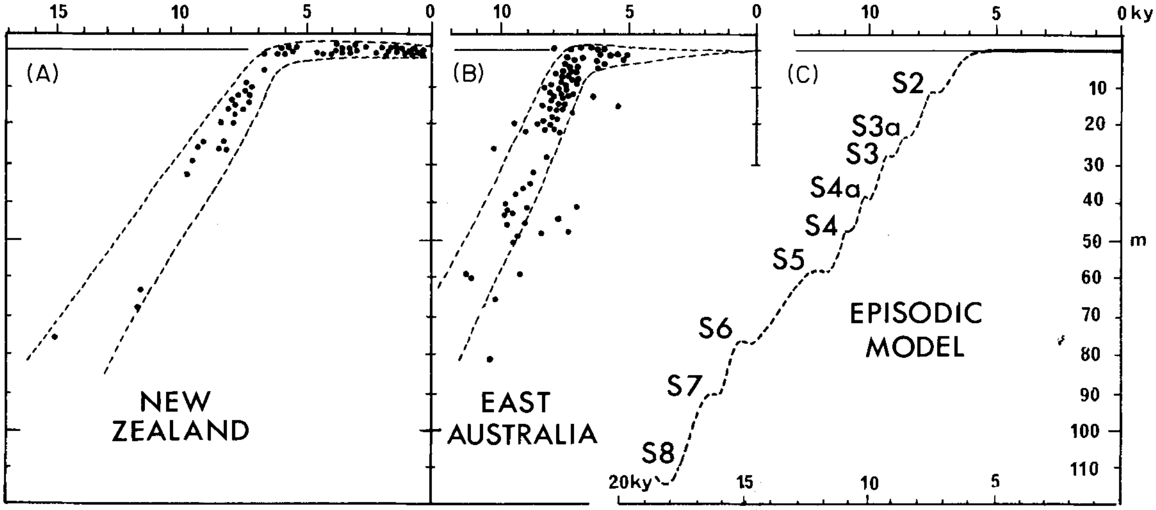

Fig. 7. (A and B) Radio carbon data and sea-level envelopes for eastern Australia and New Zealand, showing envelopes of sea-level change. (C) Summary regional sea-level curve, with probable shoreline pauses, based on the model of episodic transgression. Curves based on data for eastern South Island, New Zealand (after Gibb, 1986; Herzer, 1981 and Carter *et al.*, 1985) and eastern Australia (after Belperio, 1979; Grindrod & Rhodes, 1984; Pye & Rhodes, 1985; Thom & Roy, 1985).

northern hemisphere ('Atlantic' sea-level curve) (cf. Adey, 1978). The sedimentary response to such a transgression has been postulated to include the deposition of a thin zone of reworked sand or gravel behind the transgressing shoreline, the so-called Holocene transgressive sand sheet (Swift, Stanley & Curray, 1971). The widespread occurrence of relict coarse-grained terrigenous deposits on many middle and outer shelves has been considered consistent with such an interpretation.

However, much evidence from both northern (e.g. Kolp, 1976; Dillon & Oldale, 1978) and southern hemispheres (e.g. Herzer, 1981; Brown, 1983; Johnson, Searle & Hopley, 1982; Carter *et al.*, 1985) is instead consistent with a markedly episodic post-glacial transgression, as indeed was inferred by Fairbridge (1961). In this model, rather than moving uniformly the transgressing shoreline is viewed as migrating rapidly, or vaulting, between positions at which it was temporarily stable or regressive for significant periods of time (Sanders & Kumar, 1975; Field & Duane, 1976). Since drowned shorelines and barriers are apparently common, such a sedimentary model is widely applicable.

It is difficult to quantify the length of time occupied by successive shorelines S8–S2, except to infer from the large volumes of sediment deposited along S3 and S5 that these shorelines were occupied for the longest, perhaps for up to several thousand years, a conclusion also reached by Kolp (1976) for a -45 m shoreline in Europe. The maximum modern vertical sediment accretion rate recorded for the eastern South Island shelf is 3 m 10^3 yr^{-1} (Herzer, 1981). Applying this rate to the mean seismic thickness of 7·6 m for W5 yields an approximate accumulation time of c. 2,500 yr. For S3a, Gibb (1986), on the basis of radiocarbon determinations from onshore Canterbury, has estimated the duration of the stillstand as *c.* 800 yr.

Several significant corollaries follow the conclusion that post-glacial transgression was episodic.

(a) *Relative rates of transgression.* The relative rate of transgression between quasi-stable shorelines was sufficiently rapid to preclude the deposition of continuous shoreline sediments as a thick transgressive sheet. As commonly observed, such a transgressive sheet is thin, comprising palimpsest sediment in equilibrium with the modern hydraulic regime (Swift *et al.*, 1971; Carter *et al.*, 1985).

(b) *Absolute rates of transgression.* Rates of sea-level rise estimated previously on the assumption of uniform transgression are minima. Assuming a glacial sea-level lowstand of *c.* -110 m, uniform transgression between 18 and 6,500 yr BP would require a sustained

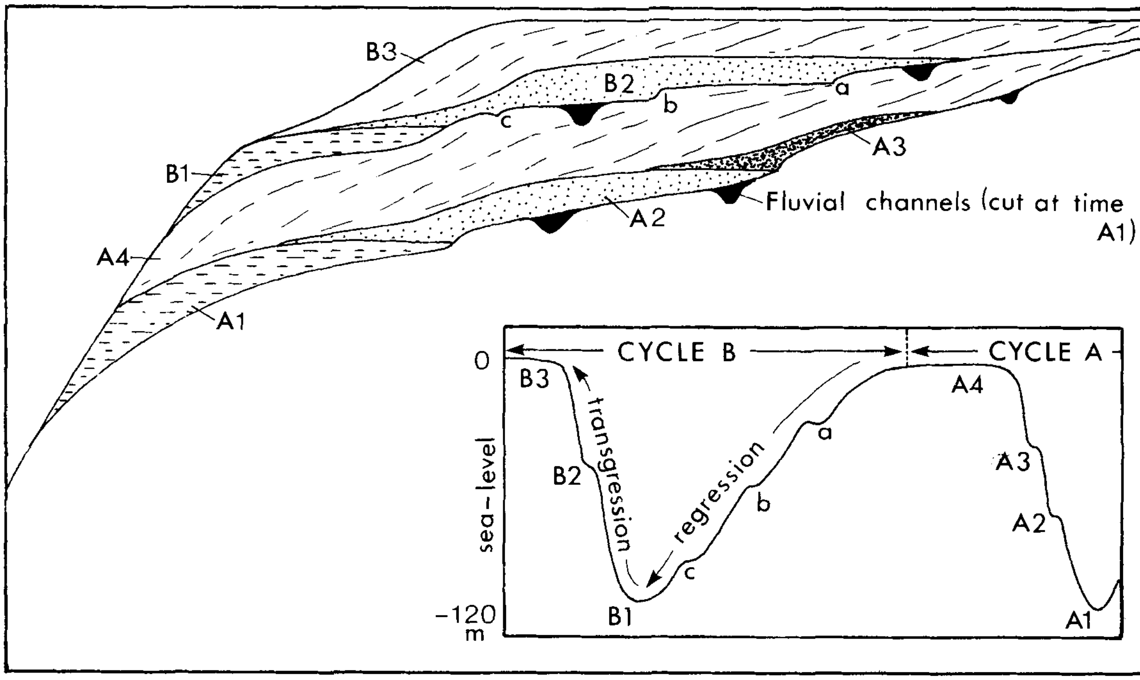

Fig. 8. Idealized stratigraphic sequence built up during two typical glacial/interglacial sea-level cycles (inset).

rate of sea-level rise of almost 10 m 10^3 yr^{-1}. However, if sea-level paused at shorelines S8–S2 for a total time of 4,000 yr, then the intervening rate of rise would have averaged 14 m 10^3 yr^{-1}, and rates as high as 20–35 m 10^3 yr^{-1} have been estimated in the northern hemisphere (Menke, 1976; Jelgersma, 1979; Cronin, 1983).

(c) *Types of submergent shoreline.* Submergent shorelines vary from wave-cut terraces along rocky coasts, to open-ocean shoreface sediment wedges, to bay-barrier ridge complexes, to drowned reefs (Fig. 3). They are often preserved in modified form, having been variously eroded or altered by marine processes which operated after sea-level had migrated further inshore (e.g. Stubblefield, McGrail & Kersey, 1984; Carter & Carter, 1985).

(d) *The resultant stratigraphic record.* Published data, and particularly globally-averaged sea-level curves based on oxygen isotopes (Shackleton & Opdyke, 1973; Broecker & van Donk, 1970), show that shoreline behaviour was generally episodic during interglacial to glacial transitions, as suggested also for the most recent glacial/interglacial transition by the data in this paper. Such episodic behaviour will result in a distinctive stratigraphic accumulation on terrigenoclastic shelves that are subject to gentle subsidence. Over a complete interglacial/glacial cycle, a composite but wedge-shaped body of mainly interglacial sediment will build up (Fig. 8), with erosive notches, channels or other unconformities on its upper surface corresponding to shoreline pauses during the ensuing glacial regression (cf. Evans, 1979, p. 130), and to river channels cut at the time of peak glacial regression (e.g. Johnson *et al.*, 1982).

Bodies of sediment similar to that of Fig. 8 have been identified in seismic studies of several modern continental shelves (e.g. van Andel & Sachs, 1964; Knott & Hoskins, 1968; van Andel & Calvert, 1971; Shideler & Swift, 1972; Lewis, 1973; Nardin *et al.*, 1981; Carter & Carter, 1982).

THE POST-GLACIAL TRANSGRESSION ON THE BARRIER REEF SHELF

The model of episodic post-glacial transgression developed for the terrigenoclastic New Zealand shelf,

if more widely applicable, has significant implications for tropical shelves with offshore coral reefs. We summarize below, therefore, application of the model to one such nearby shelf, namely the Great Barrier Reef shelf off north Queensland (cf. Carter & Johnson, 1986).

(a) *Radiocarbon-dated post-glacial sea-levels.* Present knowledge of Australian sea-level curves is well summarized in Hopley (1983a). Data concerning sea-level changes in the last 9,000 yr are relatively abundant, but there are few radiocarbon dates bearing on sea-level behaviour between 18,000 and 9,000 yr BP.

At the southern end of the Great Barrier Reef shelf, a number of radiocarbon dates have been interpreted as indicating a sea-level as low as −165 m at the peak of the last glaciation (Veeh & Veevers, 1970). There is then a complete dearth of radiocarbon dates until the oldest of the deposits cored from beneath modern reefs, at depths down to *c.* 30 m and ages of 9,000 yr BP or younger (Davies & Hopley, 1983). Not surprisingly, therefore, published sea-level curves for north Queensland are rarely extrapolated beyond 9,000 yr BP.

Since 9,000 yr BP, minimum sea-level ages against depth can be inferred from dates at the base of Holocene sequences penetrated by reef-drilling programmes (e.g. Hopley, 1982), from shallowly-submerged coastal facies such as mangrove muds (Belperio, 1979; Grindrod & Rhodes, 1984), and from hydro-isostatically uplifted beach ridge or reef-flat facies (Chappell *et al.*, 1983). Such data have been used to constrain the summary regional curve shown in Fig. 1(A), and to identify the four most recent shorelines (S1a–c and S2).

(b) *Bathymetric evidence of post-glacial strandlines.* Until recently, the main evidence cited for submergent shorelines along the Queensland coast was the presence of bathymetric notches or terraces at depths down to *c.* −160 m. (Maxwell, 1968a, b, 1969, 1973; Marshall, 1977; Searle, Harvey & Hopley, 1980). Maxwell (1973) suggested that drowned shoreline features were present at −18, −30, −37, −58, −67, −88 and −92 m. Elsewhere in northern Australia, van Andel *et al.* (1967) and Brown (1983) recorded the probable presence of four undated submerged shorelines between depths of −70 and −20 m on the Sahul shelf. However, in the absence of seismic evidence or *in situ* dated material, it is probable that some of these shelf bathymetric breaks represent shorelines predating the last glacial maximum, as argued by, for example, Hopley (1982, fig. 8.11) for the Great Barrier Reef.

(c) *High-resolution seismic evidence for post-glacial sea-levels.* Recently published high-resolution seismic profiles reveal many features consistent with the existence of former shoreline stillstands on the Queensland shelf, and, in some cases, allow the identification of certain strandlines as post-glacial (Searle, 1983a, b; Johnson & Searle, 1984). As in New Zealand, the preservation of landward feathering surficial sediment wedges is treated as good evidence for a post-glacial origin, particularly where such wedges terminate at an erosional notch. An additional line of evidence is the presence of incised post-glacial channels the bases of which show a systematic relationship to presumed former base-levels of erosion at the contemporary shoreline.

Based on these and related types of evidence, probable post-glacial shorelines can be identified at depths of 10 m (S2), 23 m (S3a), 28 m (S3), 39 m (S4a), 46 m (S4) and 56 m (S5) on the Queensland shelf. Evidence also exists for shorelines at *c.* 75, 88, 113 and 133 m, but these deeper-water features are less certainly of post-glacial age.

Selected examples of shorelines S3–S5, together with their associated sediment wedges and reefs, are illustrated in Fig. 9. More detailed descriptions, together with a discussion of the effects of episodic post-glacial transgression on the development of the Great Barrier Reef system, are presented in Carter & Johnson (1986).

GLOBAL APPLICABILITY OF THE MODEL OF EPISODIC TRANSGRESSION

The frame of reference within which late Quaternary sea-level changes were discussed changed markedly during the late 1960s and 1970s. Previous attempts to determine a single, globally-applicable sea-level curve (e.g. Fairbridge, 1961) were judged to be simplistic, since they did not take into account the effects of regional variation introduced into sea-level curves by glacio- and hydro-isostasy (e.g. Walcott, 1972; Clark *et al.*, 1978), or by geoid instability (Morner, 1976; Newman, Marcus & Pardi, 1981). Thus Newman *et al.* (1980, p. 566) concluded that 'the search for "the worldwide sea level curve" is futile because of the dynamic state of the earth's crust'; and, as a recent illustration of this, Bloom (1980) summarized the sea-level data for a selection of south Pacific coasts, showing that 'each had a distinct late Quaternary tectonic history, and the resulting position of sea level

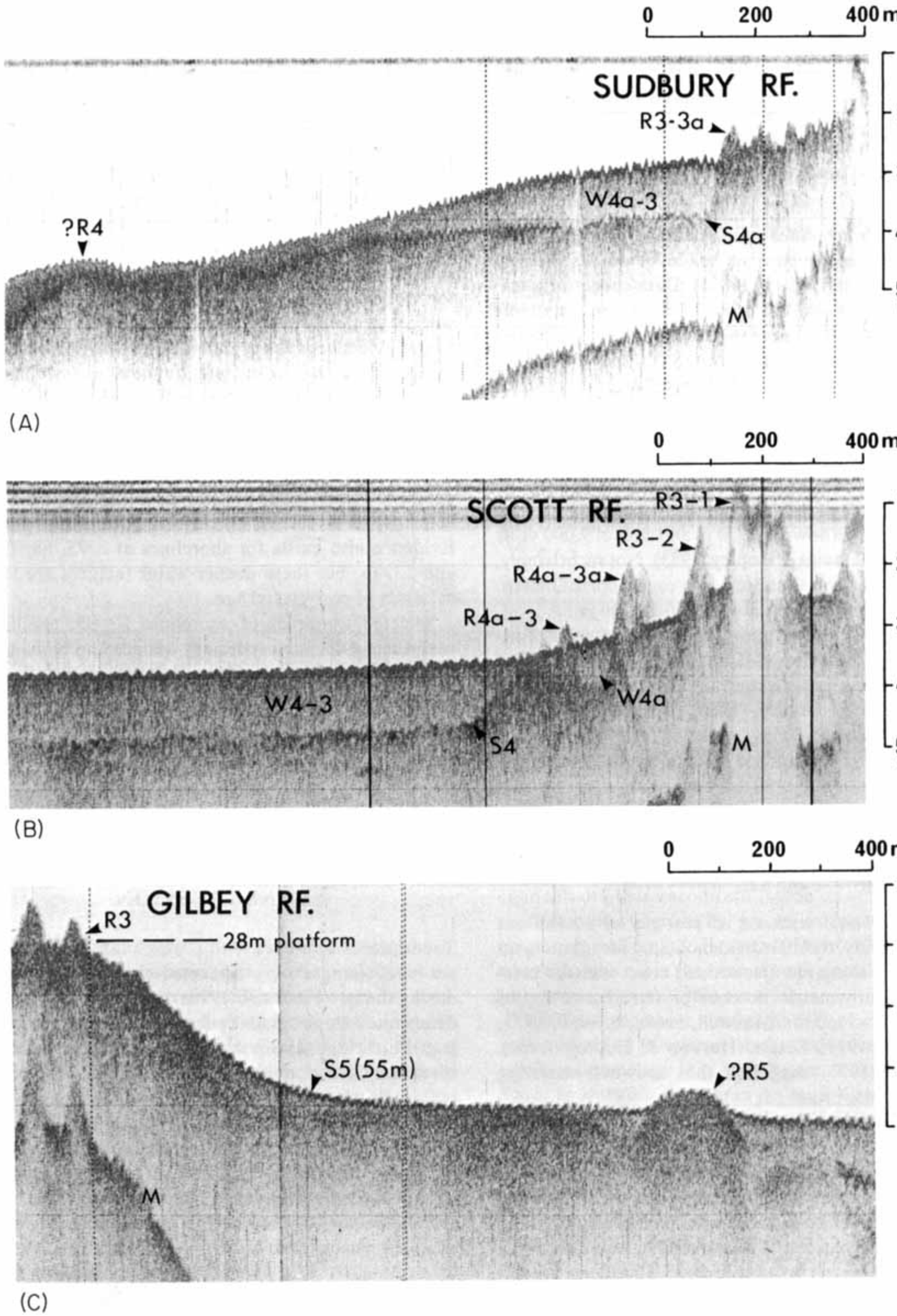

Fig. 9. Selected examples of post-glacial submergent shoreline and reef features, central Great Barrier Reef shelf, Queensland. Reefs (R) and sediment wedges (W) of shorelines (S) 1–5 indicated by appropriate letters; multiple, M.

during the last 7000 years may range from −9 m to +14 m'.

(a) *Magnitude and direction of post-glacial crustal adjustment.* Leaving aside local orogenesis, three major mechanisms are known to perturb the crust at a rate sufficient to cause significant vertical displacement of late Quaternary shorelines.

Glacio-isostacy, or ice loading and unloading, results in regional terrestrial depression and rebound that amounts to at least tens of metres, and possibly to more than 100 m, at typical rates of 10–80 cm 10^3 yr^{-1} (e.g. Morner, 1972; Jardine, 1979). Hydro-isostasy, or crustal response to the shifting water loads on the continental margin, takes place at similar rates but with typical magnitudes of only a few metres. Finally, long-term continental margin subsidence, due to thermal contraction of adjacent oceanic lithosphere, proceeds at rates as high as 10 cm 10^3 yr^{-1} for hot new crust, decreasing to 1–3 cm 10^3 yr^{-1} for crust greater than 20 Myr old (e.g. Pitman, 1978).

The particular depth at which a post-glacial submergent shoreline is preserved on the continental shelf will depend, therefore, on the particular local interaction of these (and other) factors. The magnitude of the glacio-isotatic effect is much reduced away from land (due to ice floating), and rates of glacio-isostasy on the continental shelf adjacent to an ice sheet are therefore low; also, the zone of relaxation under the 'forebulge' around an ice-sheet produces negative 'rebound' on melting (e.g. Jelgersma, 1979, fig. V-10).

Since the effects of hydro-isostasy and margin subsidence are also in general both negative, for regions inshore of the peripheral zone they counteract any positive glacio-isostatic response, whilst for regions within the peripheral relaxation zone they add to the negative glacio-isostasy.

We conclude, therefore, that post-glacial submergent shorelines from different non-orogenic, non-glaciated shelves could well match each other to within a few metres, provided only that geoid instability does not override the eustatic signature. For shelves adjacent to the major ice-caps, particular shorelines may also broadly match their temperate-tropical equivalents (if their location is such that positive glacio-isostatic rebound neutralizes negative hydro-isostasy plus margin subsidence), or they may be situated up to *c.* 10 m deeper (if they are located within the peripheral relaxation zone of the ice sheet).

(b) *Correlation of post-glacial lowstands.* The evidence just discussed leads us to expect that major post-glacial shorelines might be preserved at comparable depths (say within ±5 m) on widely separated continental shelves. Furthermore, evidence from oxygen isotope analysis, which is independent of the isostatic and geoidal problems discussed above, suggests that the concept of a globally averaged eustatic curve remains useful and valid (e.g. Shackleton & Opdyke, 1973). Recent high-resolution isotope data points strongly to an episodic glacial melt-history (Berger *et al.*, 1985). Within that context, the model of episodic post-glacial sea-level rise discussed herein raises afresh the possibility of global correlation of the major stillstands, not by virtue of absolute depth alone, but using also relative sequence and absolute age.

That few published post-glacial sea-level curves record episodic shoreline movement reflects on the difficulty of gathering convincing evidence for submergent shorelines, and particularly the problem of dating them accurately. The difficulty of separating post-glacial and pre-18,000 yr BP shorelines is probably the major reason why post-glacial shorelines have not been globally correlated hitherto; compilations such as that of Cronin (1983, fig. 5) may obscure any clear pattern of post-glacial shorelines because of their random admixture with older (interstadial) features.

Despite these problems, the early curves of Fairbridge (1961) and Curray (1965) are not dissimilar to that now proposed for the SW Pacific (Fig. 7), particularly when due account is taken of minor differences in shoreline depth caused by local iosostatic or tectonic factors. In particular, the large size of the −56 m, 12,000 yr BP sedimentary wedge and associated features in New Zealand (Cullen, 1967) and Australia (Carrigy & Fairbridge, 1954; Maxwell, 1968a) is such that the shoreline at which it formed seems likely to be a globally widespread feature, correlating with the −55 m (Fortune) shore of the eastern U.S. seaboard (Dillon & Oldale, 1978; Oldale, 1985), the Mediterranean (Flemming, 1964) and the Arctic (Creager & McManus, 1965), a −58 m shoreline (Unit D) off California (Nardin *et al.*, 1981), a −60 m terrace off Brazil (Suguio & Martin, 1982), and various features at −55 to −60 m in the Hawaiian Island (Stearns, 1978).

More tentatively, an equivalence can be recognized between the five post-glacial shorelines documented for the eastern U.S. shelf (Ewing *et al.*, 1963; McMaster & Garrison, 1966; Emery & Uchupi, 1972; Dillon & Oldale, 1978) and shorelines S3a–S8 in the SW Pacific (Table 2). The correlation is based primarily on the cross-shelf sequence of shorelines and on their presumed or proven ages. However, the

correspondence in depth of shorelines S3–S5 is striking, and suggests that the effects of inter-regional isostatic and tectonic warping may be of lesser magnitude than current models predict.

A series of shorelines also occurs at similar depths down to −60 m in Europe (Kolp, 1976; Ludwig *et al.*, 1981) and the Arctic (Holmes & Creager, 1974). However, detailed differences between carefully compiled curves from nearby areas (e.g. Jelgersma, 1979; Ludwig *et al.*, 1981; Behre, Menke & Streif, 1979) suggest that local isostatic factors may predominate over global sea-level movements for many of these curves. Though several of the identified submergent shorelines in Europe do occur at similar depths to those from the southern hemisphere (e.g. Kolp, 1976; Hopkins, 1973), radiocarbon dates do not support a direct correlation based on depth; rather, for a given depth, the European shorelines are up to 2000 yr younger than their SW Pacific counterparts (Table 3).

(c) *Controls of episodic shore-line movement.* The control on the development of similar sequences of post-glacial shorelines in different parts of the world is most likely to be the pattern of ice-sheet melting. Though our knowledge of this pattern is still rudimentary, it is noteworthy that Clark & Lingle (1979) have documented minor Antarctic ice advances at *c.* 15,000 and *c.*12,000 yr BP, times which also correspond to pauses in melting of the Laurentide ice-sheet (Leventer *et al.*, 1982), and probably relate to shorelines S7-6 and S5 respectively. A major pause in melting has recently been inferred for the Eurasian ice-sheets around 12–11,000 yr BP (Duplessy *et al.*, 1981; Ruddiman & McIntyre, 1981). Finally, in New Zealand, forest expansion and the cessation of loess deposition in central North Island (McGlone & Topping, 1977) coincided with a major decline in westerly stratospheric winds at 14,700 yr BP (Stewart & Neall, 1984).

(d) *Sedimentary models of post-glacial transgression.* Current models of the sedimentary response of the post-glacial or Flandrian transgression are heavily based upon northern hemisphere, and particularly United States eastern seaboard data (e.g. Curray, 1960, 1985; Stubblefield *et al.*, 1984; Swift *et al.*, 1971). Though the existence of submergent shoreline deposits is accepted by all writers, considerable differences in interpretation exist regarding their continual reworking to produce a widespread transgressive sand sheet (e.g. Swift, 1968; Swift *et al.*, 1972), or their episodic accumulation as the shoreline moves rapidly from one position to another (e.g. Sanders & Kumar, 1975; Rampino & Sanders, 1980).

The evidence from the SW Pacific demonstrates that a thin transgressive sediment sheet (Carter *et al.*, 1985), or a continuous pattern of shoaling patch reefs (Carter & Johnson, 1986), do occur locally, particularly in the later stages of the Flandrian transgression. However, post-glacial sedimentology is apparently mainly characterized by the effects of episodic

Table 3. Comparison of estimated depths in metres of correlative post-glacial shorelines from southern and northern hemispheres

Shore	Southern hemisphere				Northern hemisphere		(N.Z.) age
	N.Z.	S. Aus.[a]	GBR	S. Afr.[b]	U.S.A.[c]	Europe[d]	
S1	0	0	0	0	0	0	6·5–0
S2	9	13?	10	11	—	10–12	7
S3a	24	22	23	18	24	20–24	9
S3	28	31	28	—	28[1]	28–30	(*c.* 10)
S4a	39	42	39	36	40[2]	38	(*c.* 11)
S4	46	—	46	47	—	45	(*c.* 11)
S5	55	55	56	—	*c.* 55[3]	60	12
S6	75	—	75	70?	—	—	15
S7	89	88	88	80?	90[4]	80?	(*c.* 17)
S8	114	110	113	—	105?[5]	110	(*c.* 18)

Sources
a, after Sprigg (1979)
b, after Maude (1968)
c, after Dillon & Oldale (1978)
Hyne & Goodall (1967)
d, after Ludwig *et al.* (1981)
( ) Age interpolated; not proven as post-glacial.

U.S.A. names
1, Block Island Shoreline.
2, Atlantis Shoreline.
3, Fortune Shoreline.
4, Franklin Shoreline.
5, Nicholls Shoreline.

shoreline development, as previously outlined for the northern hemisphere by Sanders & Kumar (1975). Between the sediment wedges and reefs related to individual drowned shorelines, the last-glacial land surface is exposed at the seafloor, or obscured by a veneer, often only a few centimetres thick, of palimpsest or modern sediment (Davies, Cucuzza & Marshall, 1983; Carter *et al.*, 1985).

The present acceptance of a 'transgressive sand sheet' model of post-glacial sedimentation may be related to the ease with which earlier sediment wedges are modified during further shoreline transgression. A wide shelf swept by tides or ocean currents forms an ideal site for the development of a 'pseudo-sand sheet' by the reworking and modification of an initial series of episodic shorelines. Relict and palimpsest sand ribbons and sand waves are characteristic features of the sedimentology of such margins (e.g. Stride, 1963 in Europe; Flemming, 1980 in South Africa; Searle *et al.*, 1978 in Queensland; Carter *et al.*, 1985 in New Zealand).

That the evidence for transgressive sediment sheets has previously been overstressed is shown by the recent reinterpretation of the classic New Jersey shelf sequence as involving a drowned shoreline at -30 m (probably S3 of this paper), albeit modified by later erosion (Stubblefield *et al.*, 1984). However, continuous transgressive sediment sheets may develop locally, even with an overall episodic transgression, should the rate of sea-level rise slow to an appropriate figure. For example, Kidston & Heyworth (1973) have presented evidence for the deposition of a single peat-bed between *c.* -18 m and modern mean sea-level being controlled by a gradual but continuous sea-level rise during the last stages of the Flandrian transgression.

Further progress in understanding the post-glacial transgression awaits detailed coring, submersible and dating studies of individual submergent shorelines, particularly those on the middle and outer shelf for which there is presently very little information available. It is likely that elements of both episodic and quasi-continuous shoreline transgression will characterize future detailed models of post-glacial sea-level behaviour.

CONCLUSIONS

(1) The post-glacial transgression in the SW Pacific was episodic in nature, with the shoreline migrating in a series of steps from its lowstand position at 20–18,000 yr BP until it started to stabilize about its modern level at about 6,500 yr BP.

(2) In eastern South Island, New Zealand, significant post-glacial shorelines S8–S1 can be identified at depths and likely ages of -113 m/18,000 yr BP; -88 m/17,000 yr BP; -75 m/15,000 yr BP; -56 m/12,000 yr BP; -46 m/11,000 yr BP; -28 m/9,500 yr BP; -24 m/9,000 yr BP; -9 m/7,500 yr BP and 0 m/6,500 yr BP.

(3) Shorelines S8–S1 can also be identified on the Great Barrier Reef shelf, Queensland, Australia, with an additional feature, S4a, at *c.* -39 m.

(4) Rates of vertical shoreline movement of at least 10 m 10^3 yr^{-1}, and probably in excess of 12 m 10^3 yr^{-1}, characterized the transgressive phases between consecutive positions of shoreline stasis.

(5) Such rates of shoreline transgression have major implications for sedimentary response mechanisms on both terrigenous and tropical carbonate shelves:

(a) On terrigenous shelves, wedges of sediment related to particular strandlines become 'drowned' *in situ* on the shelf; in general, shoreline movement took place too rapidly for complete reworking of the coastal wedge into a transgressive blanket.

(b) In the Great Barrier Reef province, no reefs are known to have kept up with the sea-level rise which took place between S5 (*c.* -56 m) and S3 (*c.* -28 m); all modern reefs so far drilled commenced their accretion at or above the -28 m, 9,500 yr BP shoreline, and older reefs are inferred to have been drowned *in situ*.

(6) Several shorelines, particularly those 9,000 yr BP and older, are apparently able to be correlated between southern and northern hemispheres, and may be global features. Shoreline development was probably controlled by the particular pattern of ice-sheet melting which characterized the last great deglaciation.

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