THE GEOMORPHOLOGY AND GEOCONSERVATION SIGNIFICANCE OF LAKE PEDDER

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Lake Pedder is important not just for its aesthetic, recreational, wilderness and biological values, but also for the intrinsic and scientific value of its landforms. This facet of the Pedder environment was never taken into account during the decision-making process prior to construction of the dams that inundated the area. The objectives of this paper are to provide an accessible documentation of those landform values, and to assess their geoconservation significance.

Lake Pedder is at once a landform in its own right, a nested set of component landforms, and part of a broader landform community. The lake basin is the product of glacial activity on the Frankland Range and the partial damming of the Serpentine River by sediment discharged from the glaciers. The meandering channel of the Serpentine River downstream of Lake Pedder is a fascinating landform in its own right. Lake Pedder itself probably first formed due to glacial activity prior to the most recent Glacial Climatic Stage. Landforms produced by lake water activity include the beach and its spectacular bedforms (mega-ripples), together with smaller phenomena such as the ferro-manganese concretions known as Pedder Pennies. Landforms produced by wind action include the extensive Lake Pedder dune system and smaller dunes around the Maria Lakes. Lake Pedder appears to have been migrating progressively eastwards.

There are different types and assemblages of landforms just as there are different species and communities of plants and animals. Landforms enrich and sustain our lives in the same manner as do the plant and animal species that surround us. The retention of geodiversity is an essential element of any properly comprehensive approach to nature conservation and sustainable management. This paper reviews criteria that define the conservation significance of landforms before assessing the significance of Lake Pedder in terms of its geoconservation and geodiversity values. A search for counterparts reveals Lake Pedder to be unique at a world scale. A number of its genetically-related landforms and its component landforms are also revealed as being significant at international and national levels. Lake Pedder is a place of immense geoconservation significance that on the basis of its geomorphological values alone would seem easily to meet the criteria for inclusion on the List of the World's Natural and Cultural Heritage.

Key Words: Australia, Tasmania, Lake Pedder, geomorphology, geodiversity, geoconservation, glaciation, lacustrine, fluvial, significance, Pleistocene, Holocene

INTRODUCTION

The Lake Pedder basin was formed as the result of glacial and glaciofluvial sediments being swept from the Frankland Range into the Serpentine Valley (Davies 1967). This impeded the discharge of the Serpentine River and partially impounded its waters east of the glaciofluvial fans (Figure 1). Although celebrated for its scenic beauty and subject to some limited investigation of its biota (Bayly *et al.* 1972), the geomorphology and Quaternary environments of the Lake Pedder area were never studied in any detail prior to construction of the hydro-electric development within the Lake Pedder National Park that resulted in the controversial inundation of the area.

In its final report the Commonwealth Government's Lake Pedder Committee of Enquiry concluded:

> "(a) The Lake Pedder National Park had very significant scientific values, particularly in relation to its geomorphology, biology and ecology.
>
> (b) The Hydro-Electric Commission made only a token investigation of these values prior to the submission of its Report on the

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Figure 1: General view of Lake Pedder and the Frankland Range from the air, viewed southwestwards (photo: K. Kiernan).

Gordon River Power Development.

(c) This investigation was totally inadequate and failed to identify any of the significant features of the Park or of the lake itself." (LPCE 1974, p. 143).

Given the geomorphic importance of Lake Pedder (Jones, in: LPCE 1974, Timms 1992), it is appropriate that this aspect of the Pedder environment be given close attention in deliberations regarding draining of the artificial water storage and restoration of the natural lake. It is doubly important since it was the geomorphic character of the lake that defined much of the aesthetic experience that was the primary motivation for most of those who campaigned against construction of the dams that resulted in its drowning.

From a geomorphological viewpoint three principal questions arise concerning the restoration of the geomorphological complex that is the natural Lake Pedder: What was there?; Was it important?; Can it be retrieved or restored? The first objective of the present paper is to describe the geomorphology of Lake Pedder and update the interpretation of its genesis and evolution in the light of contemporary understanding of late Cainozoic climatic changes and landscape evolution in southwest Tasmania (Part A). Based on this, the geoconservation significance of Lake Pedder and its implications for the maintenance of geodiversity are assessed (Part B). A second paper in this volume assesses the prospects for recovery of the Lake Pedder landform complex if the artificial water storage that presently covers the natural Lake Pedder were removed.

Lake Pedder and its surrounding plains now lie below the level of the artificial Huon-Serpentine Impoundment. Hence, it is inaccessible for direct investigation, even though the water depth is generally less than 15 m. Some bathymetric and other information obtained by Tyler *et al.* (1993, 1996; Tyler 2001) represents the only post-flooding data relevant to the geomorphology that is available for the original lake basin. Hence, this study has had to be based primarily on the limited pre-flooding geomorphic data, the air and ground based photographic record of the area prior to flooding, and investigation of some accessible margins of the storage a little over 20 years after the dams were filled. The writer is also personally familiar with the original character of the area in general terms, having visited Lake Pedder more than 30 times prior to the flooding, albeit as a young bushwalker rather than as a trained geomorphologist. In order to minimise potential confusion caused by the fact that the name Lake Pedder was also given to the artificial impoundment that resulted from construction of the Huon and Serpentine dams, use of the name Lake Pedder will here be restricted to the original lake.

Figure 2: View eastwards from the Frankland Range to Lake Pedder on the floor of the upper Serpentine Valley. The Frankland Range curves around the southern margin of Lake Pedder and the ridge extending onto the plain beyond the lake is Mt Solitary. The Mt Anne massif and Schnells Ridge are in the background (photo: K. Kiernan).

PART A: THE GEOMORPHOLOGY OF LAKE PEDDER

ENVIRONMENTAL CONTEXT

Topography

The Lake Pedder basin lies in the upper reaches of the broad valley of the Serpentine River, which is locally flanked to the south by the glacially sculpted Frankland Range and to the north by the lower Coronets Range. The uppermost part of the Serpentine River catchment lies north-east of Lake Pedder, comprising small streams that flow from the Marsden Range and Mt Wedge areas, and a large swampy plain where these waters gather (Figures 2 & 3). The Serpentine River shares with the southward-flowing Huon River a drainage divide that is very pronounced on the Frankland Range but very subdued on the plains between the Frankland Range and its outlier, Mt Solitary, and to the northeast of Mt Solitary.

Lake Pedder (42^{o} 55' S, 146^{o} 10' E) lies at an altitude of ~300 m. When full, its area totals 9.7 km^2 but in summer the shallow sand bed of the lake facilitates considerable lateral contraction of the lake margins, and the exposure of wide beaches. Under these conditions the maximum depth of Lake Pedder is ~3 m (Bayly *et al* 1972). The mean discharge of the Serpentine River above the gorge through which it enters the Gordon River was 29 cumecs prior to construction of the Serpentine Dam, while that of the Huon River above the Scotts Peak damsite was 13 cumecs. The mean annual discharges for these two rivers were respectively 911 m^3 X 10^6 and 407 m^3 X 10^6 (SWTRS 1975).

Bedrock geology

An appreciation of the bedrock geology is important because of its influence on evolution of the preglacial topography that conditioned the patterns of glaciation. It is also important for understanding the source and nature of the sediments involved in the evolution of Lake Pedder; natural postglacial sedimentation in Lake Pedder prior to construction of the dams; and any sedimentation likely to have occurred in the Pedder basin since the dams were filled. The following geological data is derived primarily from Boulter (1978), Turner *et al.* (1985) and Calver *et al.* (1990) (Figure 4).

The broad topography of the Lake Pedder area is dominated by the Frankland Range, a strike ridge of folded Precambrian quartzites that are resistant to erosion, while the Serpentine River Valley is cut in less resistant phyllites and schist. These rocks represent the more metamorphosed rocks of the

Figure 3: View northwards through buttongrass across the eastern end of Lake Pedder from the eastern end of the Frankland Range. The Coronet Range rises from the northern end of Pedder Beach with the Sentinel Range to the north of the Coronets. The prominent summit on the centre right skyline is Mt Wedge. The Maria Lakes complex lies east of the Lake Pedder dune system in the upper headwaters of the Serpentine River (photo: K. Kiernan)

Tyennan Region, and contrast with the less metamorphosed rocks of the Jubilee Region to the east. The fold pattern evident in the Pedder area extends over most of southwest Tasmania and is perhaps the most striking structural landform aspect of the whole region. The axis of the Frankland Range follows a major structural trend, the orientation of which changes from east-west at the southern end of the range and Mt Solitary, to a northwest-southeast trend west of Lake Pedder. On its northern side Lake Pedder is flanked by the lower range of the Coronets, the southwest - northeast orientation of which is similarly determined by another major structural trend.

Minor carbonate units occur in nearby areas. They are known to exist in the Serpentine Valley, as at the eastern end of McPartlans Pass (Calver *et al.* 1990, p. 79), and in the upper reaches of the Huon River Valley in the Scotts Peak area a few kilometres southeast from Lake Pedder (Godfrey 1970, Skinner 1974, Kiernan 1980). Aspects of the plant geography of the Lake Pedder area are consistent with the presence of carbonates, and indeed bear some similarity to that of alkaline pans formed in karst valleys elsewhere in southwest Tasmania (L. Gilfedder *pers. comm.*). In some areas the surficial sediments may only thinly mantle carbonate bedrock, but other explanations for this aspect of the vegetation may also be available.

The Lake Edgar Fault (Figure 5), 11-12 km southeast of Lake Pedder, follows a major Cambrian wrench (Calver *et al.* 1990). This fault provides a classic example of a structure that has been intermittently active over 500 million years, and is also one of the best expressed fault scarp landforms in Tasmania (McCue *et al.* 1996). A major earthquake felt throughout Tasmania in 1880 is thought likely to have occurred on the Lake Edgar fault, although it's epicentre is not well constrained (Michael-Leiba 1989). More recent general seismic activity in the area has been documented by Shirley (1980) who has shown a direct correlation between increased siesmicity in the filling Lake Gordon - Huon Serpentine storage area during 1972-1978, and total water load in the combined impoundment (see also Richardson 1989).

The geology of the mountain areas strongly emphasises rock types whose weathering and erosion is prone to liberate relatively clean and coarse detritus such as cobbles, gravels and sand, with silts and clays forming a much smaller component. This situation contrasts strongly with that in eastern Tasmania, and even at nearby Mt

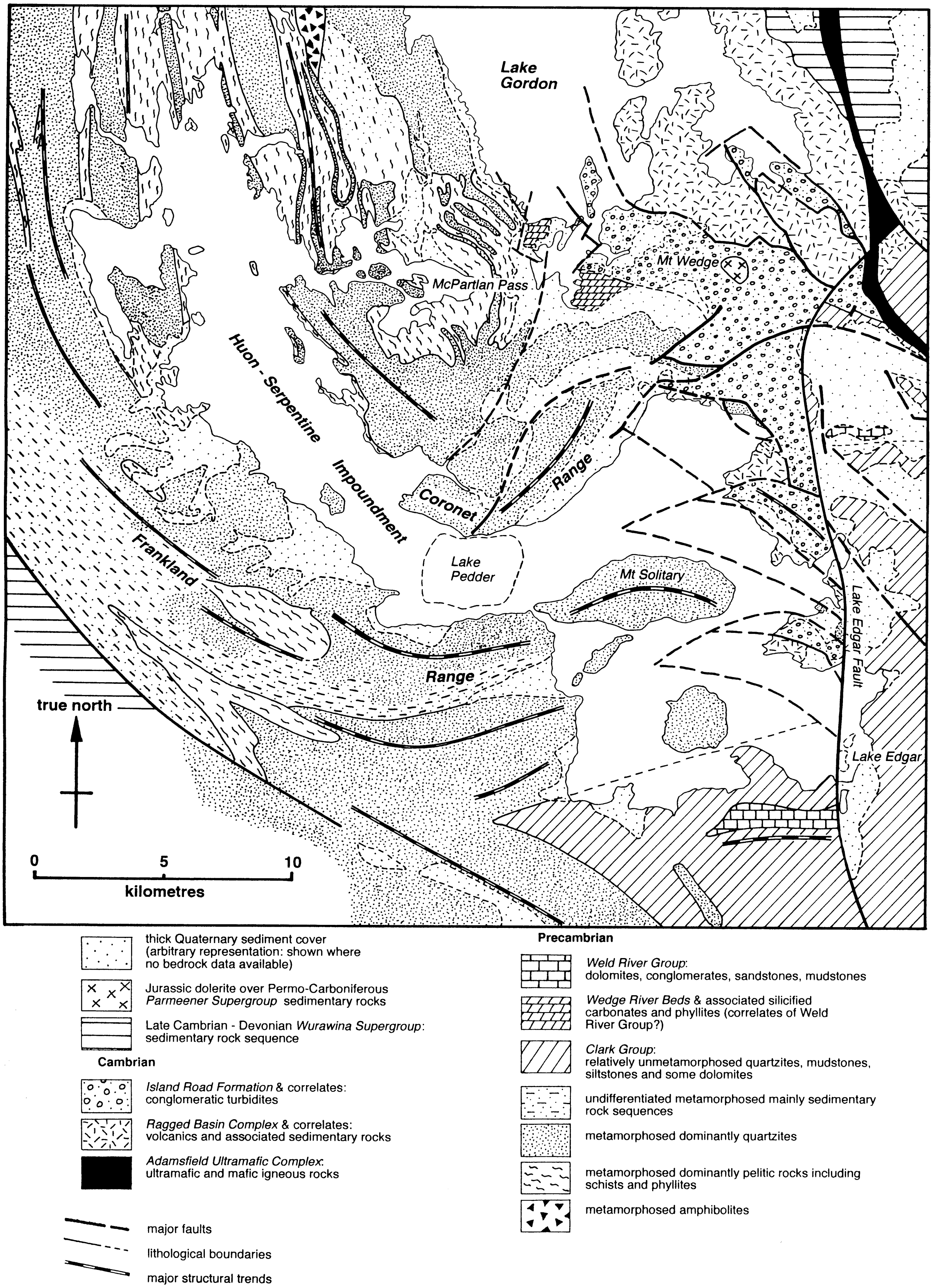

Figure 4: The bedrock geology of the Lake Pedder region, showing major structural trends. Adapted from Brown *et al.* (1995), Boulter (1978), Seymour & Calver (1995) and Turner *et al.* (1985).

Figure 5: Vertical airphoto of Lake Edgar and the Lake Edgar Fault scarp, prior to construction of the Scotts Peak Road and flooding of the Huon - Serpentine Impoundment. North at top, main lake 1.1 kilometre in longest dimension. The prominent fault scarp running from the top to bottom of the photo is thrown down to the right (east); this caused the ponding that produced Lake Edgar (airphoto taken 16th February 1961, Tasmania South West Project, Run 1, Image T360-23, © Department of Primary Industries, Water & Environment, Tasmania).

Anne, where widespread Jurassic dolerite and some other rock types give rise to considerable volumes of clay-rich sediment.

Surficial geology

The Pedder 1:50,000 geological map sheet (Turner *et al.* 1985) focuses on the bedrock geology and is of negligible assistance in determining the extent and nature of the Quaternary sediments. While the map does provide a broad indication of the areas where Quaternary sediment occurs in a sufficient volume to prevent confident prediction of the underlying bedrock, the Quaternary is ignored in other areas where the surficial sediment is thinner or prediction of the obscured bedrock is easier (e.g., the moraines around Lake Surprise on the Frankland Range are not shown). Where the presence of Quaternary material has been depicted it remains undifferentiated.

In the absence of detailed Quaternary mapping, Figure 6 attempts to provide a broad indication of the geomorphology and Quaternary geology based on an interpretation of air and ground photographs with some very limited ground survey, together with comments on till distribution provided by Peterson (1969). Detailed mapping of the geomorphology and Quaternary geology of the Frankland Range is in progress but is necessarily a lengthy process that will take some time to complete. However, on the basis of work already completed some general comments are possible. In broad terms, the Pleistocene sediments of the area are dominated by cold-climate deposits, notably till, glaciofluvial gravels and sands, and mass movement deposits the majority of which are probably of periglacial origin. Holocene sediments include fluviatile, lacustrine, palludal and aeolian material.

Pleistocene sediments
Till occurs most conspicuously as minor end moraines in the cirques high on the Frankland Range and as lateral moraines that extend downslope from some of these cirques. Some other diamictons beyond the limits of the most conspicuous moraines are likely to be till but exposure is limited and a glacial origin has not been confirmed. Given the presence of extensive tills that lack any morainal morphology well beyond the principal moraines in the nearby Mt Anne area (Kiernan 1990a) it is highly probable that glaciers from the Frankland Range once extended further across the floor of the Serpentine Valley in some places than is recorded by the sharply-crested lateral moraines which are probably relatively recent. Below the break of slope at the foot of the Frankland Range are broad mounds mantled by glaciofluvial and alluvial sediment that may be buried moraines rather than wholly glaciofluvial aprons. The tills of the Frankland Range comprise predominantly coarse materials, commonly boulders, cobbles and gravels in a sandy matrix.

Glaciofluvial sediment forms a major complex of coalescing fans at the discharge points of meltwater channels that extend towards the Serpentine Valley from the cirques (Figure 7). Sections through the fans reveal them to comprise cobbles, gravels and sand. The fans extend out onto the floor of the Serpentine Valley and have deflected the Serpentine River to the northern side of its valley (Davies 1967). However, this glaciofluvial material appears less widely distributed than is commonly the case in Tasmania's dolerite mountains. Tills in the dolerite areas are typically boulder clays derived from deeply weathered dolerite and the corresponding glaciofluvial sediments comprise rounded dolerite cobbles, gravels and clays that were swept far downstream. In contrast, the western glaciers commonly eroded more siliceous rocks to produce tills dominated by boulders and sand. Hence, the volume of glaciofluvial sediment relative to till in the west is relatively low and the glaciofluvial sediment does not extend as far (Davies 1967). This includes the glaciofluvial sediment that discharged westward from the Mt Anne massif where dolerite and its weathering products forms only a relatively small proportion of the sediment.

Mass movement deposits are widespread on the flanks of the mountains. They comprise diamictons in which gravels occur in a sandy matrix together with angular clasts that include relatively large blocks. Given the proximity of glacigenic deposits to the mass movement deposits and the fact that some of the glaciofluvial aprons appear to overlap some slope deposits, the latter are interpreted as being of at least broadly similar age to the glaciofluvial material. Angular rubbles believed to be the product of frost wedging accumulated during the period from ~20 ka BP to ~15 ka BP at an altitude of only ~ 80 m in Kutikina Cave on the lower Franklin River, 35 km northwest of Lake Pedder (Kiernan *et al.* 1983). On the basis of their general character, their relationship to glacigenic sediments and the known occurrence of frost shattering to such low altitudes in adjacent parts of southwest Tasmania, the Frankland Range slope mantles are interpreted as being primarily relict periglacial features.

Holocene sediments
For the most part the vegetation cover on the slopes of the Frankland Range comprises scrub, heathy vegetation and buttongrass plains (Balmer & Corbett. 2001). There are few areas where the ground surface is bare and able to serve as a source of minerogenic sediment, and only very limited evidence of piping processes. Hence, under the present Holocene conditions there is little active disturbance of the regolith by soil erosion or landslide activity. Forest occurs locally on the slopes of the Coronets and in some sheltered positions on the slopes of the Frankland Range where Quaternary sediments form the regolith. In these areas there is again little evidence of regolith instability under natural conditions. Overall, large scale erosion, transportation and deposition of coarse mineral material seems to have been relatively limited during the Holocene, with such mineral sediment as has been deposited representing fine material reworked from the glacigenic sediments.

The conspicuous fan morphology at the foot of the Frankland Range is the product of Pleistocene glaciofluvial and alluvial sedimentation. Some localised fluvial supplementation of these fans has occurred during the Holocene. In its lowest reaches near its confluence with the Gordon River the Serpentine River has developed a steep gorge, where prior to dam construction the river had sufficient capacity to transport substantial boulders. However, in its upper reaches the very gentle gradient of the river allows it to transport only very small calibre material. In this area a spectacular assemblage of meanders and oxbow lakes is present, making the Serpentine River a feature of geomorphological interest and geoconservation significance in its own right (Figure 11). Near Lake Pedder the banks were generally well cloaked in vegetation and there was little exposure of the bank sediments. However, air photographs reveal occasional small sandy beaches which suggests that

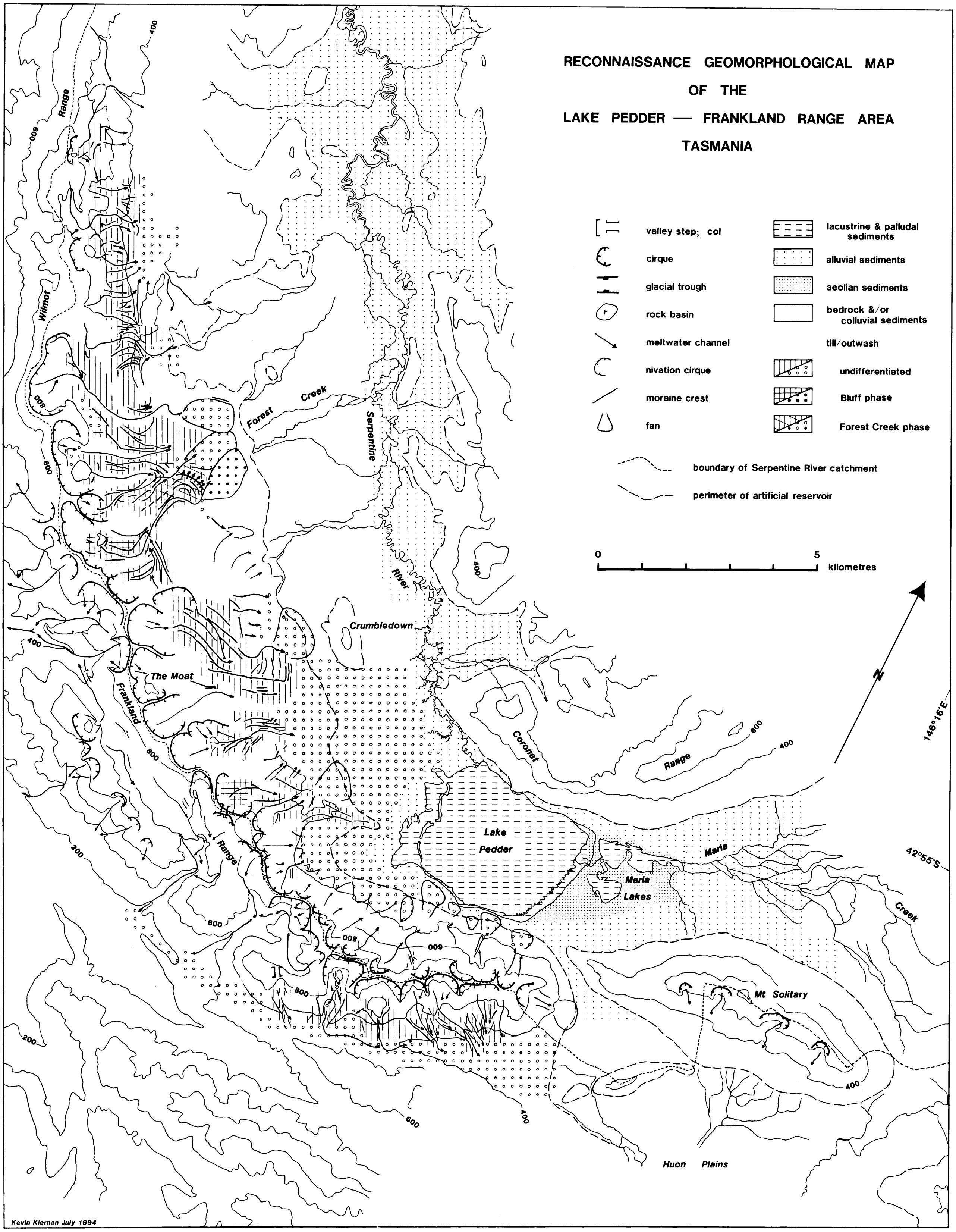

Figure 6: Reconnaissance geomorphology and Quaternary geology of the Lake Pedder region. This map has been compiled from air photographs, topographic maps, oblique photos and some direct inspections, but is essentially a draft map to guide fieldwork and ground truthing. Potential moraine sites are indicated for ongoing verification or rejection; not all have yet been confirmed.

Figure 7: Alluvial fans at the foot of the Frankland Range on the southern side of Lake Pedder, viewed from the air (photo: K. Kiernan).

quartzitic sand and silt formed an important component of the stream load. At the outlet from Lake Pedder fluviatile sands are overlain by peats and minor organic silts.

The broad plains that characterise the Lake Pedder area have been the sites of substantial sediment accumulation. Although during times of heavy rain the streams on the buttongrass plains could be sufficiently vigorous and deep as to make it sometimes difficult to cross the narrow trenches through which they flowed, for the most part water circulation on the natural plains was sluggish. On those parts of the plains most distant from the slopes, allogenic mineral sedimentation is at its least relative to autogenic organic sedimentation. Extensive peat blanket bogs characterised the plains (Pemberton 2001). The organic content of such peats varies from 25-80% with the mineral content dependent on the substrate (Hannan *et al.* 1993) and on the extent of minerogenic sediment influx, which in the Lake Pedder area was highest on the steeper slopes and negligible on the plains. Forest tends to develop rather than sedgeland where shallower organic soils overlie mineral soils (Pemberton 1989). The virtual absence of forest from the slopes of the Frankland Range suggests little pedogenic alteration of the substrate and hence the probability of little "dirty" sediment. Being well drained, there was little development of muck peats on the steeper slopes and hence little potential for organic material from this source to be washed into Lake Pedder.

Natural lacustrine sedimentation in Lake Pedder was most pronounced in the southwestern corner of the lake and along the western shoreline where creeks deposited sand reworked from the glacigenic deposits. Negligible organic detritus was incorporated in this material. Deposition of these sands caused some active progradation of the shoreline in this part of the lake. However, these sediments appear to have been redistributed along the entire western shoreline by a predominantly clockwise natural circulation of the lake waters towards the Serpentine River outlet, hence no major delta morphology developed.

The aeolian deposits of the area are most spectacularly evident in the lunette dune system at the eastern end of Lake Pedder. The lunette comprises predominantly medium-fine grained quartzitic sands, often tinged pink in colour. Grain size characteristics are provided by Kiernan (1985). These dunes were the product of saltation of lake floor sands at times when the lake water level was low and the easternmost part of the lake bed was exposed to the prevailing westerly winds. The Pedder dunes comprise cross-bedded sands capped by peat beneath which only limited pedogenic alteration of the sand has taken place. No palaeosol development has been reported nor are any palaeosols evident among the extensive collection of photographs examined by the writer.

Holocene silts have accumulated in some depressions. The glacial outwash truncated by the Lake Edgar Fault has been interpreted as dating from the Eliza Stage which is no younger than middle Pleistocene (Kiernan 1985, 1990a) and hence its truncation does not demand movement any more recently. However, Lake Edgar itself, and a smaller companion lake, are sag ponds formed against the fault scarp which is up to 5 m high. That Lake Edgar has not been filled by silt probably implies relatively recent movement of the fault.

LANDSCAPE EVOLUTION

The initial formation of Lake Pedder

Fish & Yaxley (1966, p. 255) followed Carey (1960) in interpreting Lake Pedder to be the remnant of a formerly much larger lake, apparently of structural origin. In Carey's view, four large lakes formed in the Gordon-Huon area due to eastward tilting that flattened and even reversed the drainage, causing ponding. One of these lakes supposedly lay in the Albert River area; another east of the Hamilton Range north of the Gordon River; and another larger lake in the middle Gordon area. Carey considered the largest of these putative lakes to have formed in the Huon-Serpentine area. His map of this latter lake (Fish & Yaxley 1966, p. 55) closely resembles the hydro-electric impoundment subsequently established in the Huon-Serpentine area. The natural Lake Pedder was interpreted as a remnant of Carey's supposed large lake, not yet completely silted up. This proposition was actually later advanced by some advocates of the hydro-electric development in an effort to suggest that the environmental impact entailed in creation of the new reservoir was relatively minimal. In the absence of contrary geomorphological opinion, workers in some other disciplines have partly followed Carey's interpretation (e.g. Bayly *et al.* 1972). Carey evidently further considered that some Tasmanian lunettes, windblown sand masses similar to that which forms the dune complex at Lake Pedder, were in fact "earthquake mounds" formed as a result of subsidence causing a reduction in pore space such that water was forced out in jets carrying slush and mud to form mounds (Fish & Yaxley 1966, p. 271). McCue *et al.* (1996) erroneously interpreted Lake Pedder as a sag pond formed against the Lake Edgar Fault Scarp, but this feature lies several kilometres east of Lake Pedder.

While at a superficial level it may be easy to envisage a larger lake as Carey suggested, no significant evidence to support this proposition appears to be available. The broad and flat nature of the Serpentine Valley floor may give an impression of possible aggradation in a lacustrine situation, but no evidence of any large scale lacustrine sediments being present in the valley has yet been forthcoming. Valley floors over much of southwest Tasmania have this same general form, and nowhere is there any evidence for their being relict lake-beds rather than simply the result of differential fluvial erosion of lithological units of variable resistance to erosion, and of predominantly fluvial sedimentation. Davies (1959) interpreted accordant surfaces that are widespread across Tasmania as multicyclic erosion surfaces that had developed at or near base level. He attributed the lowermost to marine processes and the higher ones to fluvial processes. The floor of the Serpentine Valley broadly coincides with Davies' Upper Coastal Surface (365 - 460 m altitude), which is widespread throughout Tasmania. While the age, origin and significance of these surfaces is unclear, it would be drawing a long bow to ascribe them to former lakes when no evidence for this has been found on any of them.

Davies (1967) has presented a convincing case for Lake Pedder having instead been formed as a result of glacigenic sedimentation. This remains the conventional explanation for the formation of Lake Pedder but aspects of it warrant re-examination in the light of more recent knowledge.

Glaciation of the Lake Pedder area

No detailed studies of the glacial phenomena of the Lake Pedder area have ever been conducted, but important reconnaissance information has been provided by Peterson (1968, 1969) and Davies (1967). The Frankland Range stretches for some 26 km across the prevailing westerly airstreams and lies 35 kms inland from the coast. Because it is the only high ridge between Lake Pedder and the sea it forms the first major orographic barrier to the prevailing westerly airstreams. As a consequence, during the Glacial Climatic Stages of the Late Cainozoic the Frankland Range was a site of significant glacierisation (Figures 8 & 9). The altitudes of the lowest cirque floors in the Frankland Range are among the lowest anywhere in Tasmania, and similarly the height of the effective snowfences is also very low (915 - 1060 m). There are no confirmed sites of past glacier development on the lower hills to windward of the Frankland Range (Peterson 1969).

Glaciers formed on several ranges in the Pedder area, leaving a legacy of cirques and moraines. The northern end of the Frankland Range is wider and more deeply dissected than the southern end, and offers benches rather than gullies as snow accumulation sites. Hence the cirques are smaller and shallower at the northern end of the range than beneath the higher snowfences further south. The largest cirques in the range are shaded from the afternoon sun but in general there are less shading walls at the northern end. The Wilmot Range represents a northward extension of the Franklands. Evidence of past glaciation is much less conspicuous in the Wilmots than in the Franklands, possibly due to its lower altitude and a relative lack of topographic benches on its lee side where snow could accumulate. Some small cirque-like hollows also occur on the southern slopes of Mt Solitary. While cirque glacier development in this area seems probable it has not been confirmed. Like the ice that flowed down the western slopes of Mt Anne (Kiernan 1990a) glacigenic sediment from this source was probably restricted to the present Huon catchment although a little outwash may have reached Lake Pedder over the very low divide in the Huon Plains area. Although early interpretations of the Mt Wedge area suggested ice was restricted to one high altitude cirque (Peterson 1969), it is now evident that glaciers once descended from Mt Wedge to below 500m altitude on its northeastern flank. This begs the question as to whether ice from this source also invaded the uppermost Serpentine catchment, and the fate of any proglacial sediment from that source.

All the cirques identified in the Frankland and Wilmot ranges by Peterson (1969) lay below snowfences that offered shade from the afternoon sun, including the cirques on the southern face of the Frankland Range south of Lake Pedder. The importance of shading is well illustrated by the form of the moraine that surrounds the partial rock basin of Lake Surprise. As Peterson observed, most glacial erosion appeared to be focused high on the range but glacial sediments extended to as low as 360m altitude, with the most pronounced lateral moraines often lying on the western side of the ice tongues.

As recognised by Davies (1967) the pattern of glaciation in the Lake Pedder area was strongly influenced by the orientation of different parts of the Frankland Range (Figure 10). Adjacent to the middle reaches of the Serpentine Valley the Franklands stretch north-south across the prevailing westerly airstreams. During the late Cainozoic glaciations this part of the range formed a natural snowfence that favoured the accumulation of snow on its leeward eastern flank. Cryogenesis in this position led to the development of glaciers that were best developed, if not quite wholly confined, to the eastern flank. In addition to snow accumulation being favoured on the leeward flank, this side of the range was also sheltered from the hottest afternoon sun, such shading favouring longevity of the snow-pack. Glaciers that descended the slopes of the range transported considerable quantities of rock debris, some of which was deposited as lateral moraines and some of which travelled further downslope to the glacier terminii, in some cases being swept further downstream by the glacial meltwaters. This glaciofluvial sediment formed a thick mantle on the floor of the Serpentine Valley, forcing the river to the northern side of its valley.

However, that part of the Frankland Range immediately adjacent to Lake Pedder is oriented more WNW-SSE and hence provides a less favourable snowfence while at the same time offering less effective protection from insolation (Figure 10). As a consequence, on this part of the range glacier development was much less on the northern flanks above Lake Pedder than it was on the more southerly slopes of the range. This change in the orientation of the range resulted in less extensive glaciers and less effective glacial erosion upslope from Lake Pedder. Hence, less glacigenic sediment accumulated towards the headwaters of the Serpentine than further down the valley. These two factors - the accumulation of glacigenic sediment on the floor of the Serpentine Valley west of Greycap and its relative absence upstream - resulted in convexity of the valley thalweg and the ponding of water on the valley floor east of Greycap (Davies 1967, Johnson 1972).

But just how extensive were the glaciers, and how long ago did they first cause Lake Pedder to form? A conspicuous feature of many Tasmanian cirques is the presence of glacially abraded surfaces beyond the major lateral moraines that extend downslope from major cirques (Peterson 1969). From studies in at least some of the mountain areas it is evident that the best preserved moraines represent the maximum extent of the ice during the late Last Glacial Stage, at which time the form of these glaciers was largely controlled by the form of their host cirques. This implies that the most marked glacial modification of the Tasmanian mountain landscape, during which time the cirques themselves were actually initiated, commonly predates the late Last Glacial Maximum (Kiernan 1985, 1990b). Hence, both the age of the Lake Pedder landform complex and the impact of environmental change during its evolution warrant reconsideration.

Much early work on Tasmanian glaciation was based on the use of moraines to define the glacier limits. However, it has since been confirmed that the maximum ice limits in most areas are defined not by intact moraines but only by till deposits, often buried by slope deposits or other sediments, and having no recognisable moraine morphology. This is probably due in large measure to the antiquity of the earlier, most extensive glaciations and the time available for degradation and burial of the depositional landforms that they produced. The maximum extent of glaciation in the Lake Pedder area has never been determined and the possibility must be acknowledged that ice descended to lower altitudes than indicated by the remaining lateral

Figure 8: The Citadel Moat cirque in the Frankland Range, showing glacially - abraded rock bar on lower LHS and mechanically - weathered summits that protruded above the ice cover (photo: K. Kiernan).

Figure 9: Moraines below cirques in the Coronation Peak - Double Peak sector of the Frankland Range. Lake Pedder is visible in the distance (photo: K. Kiernan).

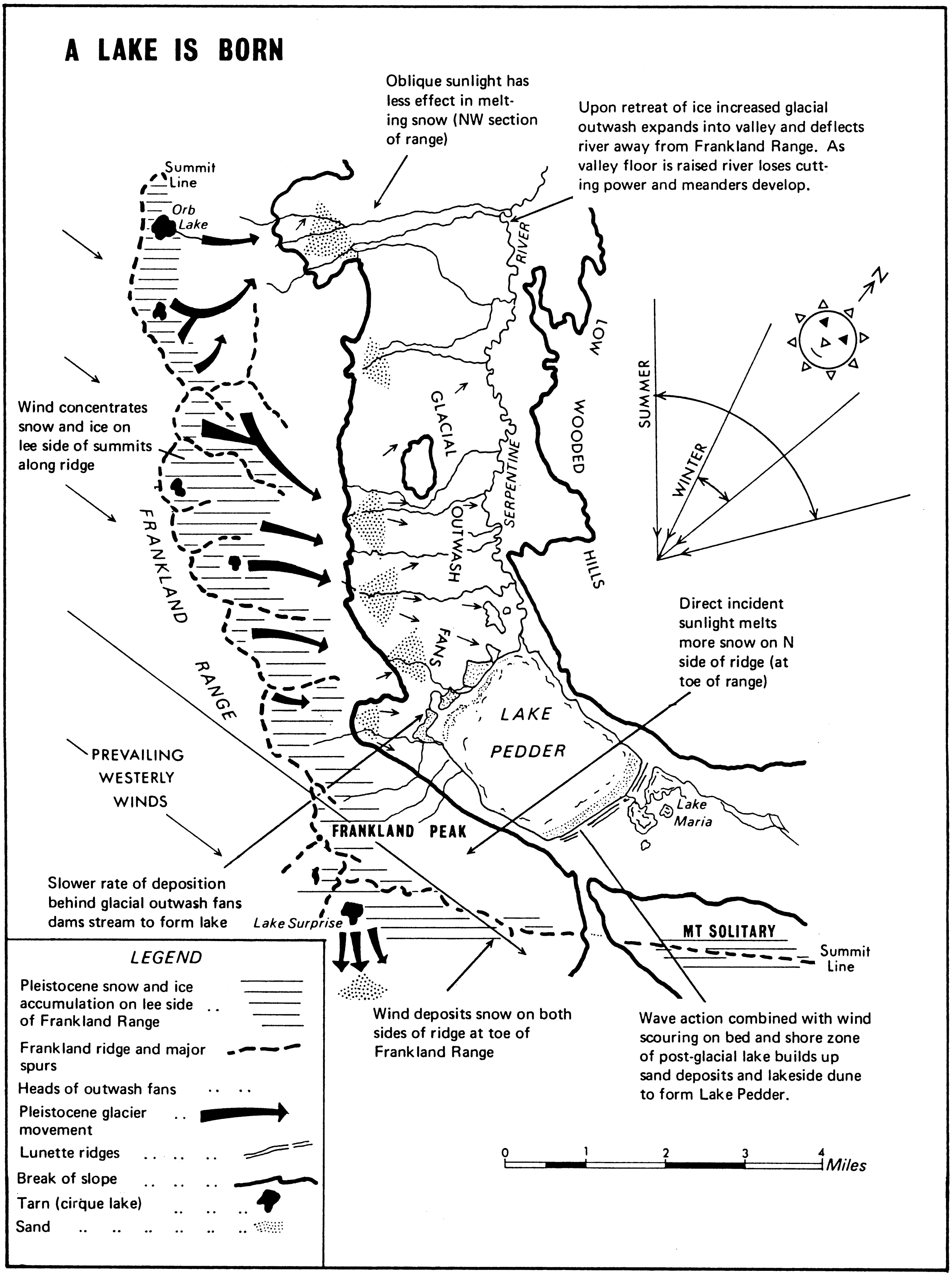

Figure 10: Simplified map showing how the orientation of the Frankland Range influenced the distribution of glaciers and glacial sediments. Map from Johnson (1972), adapted from Davies (1967).

moraines. In addition, while the importance of drifting and snowfence effects in conditioning the locations of cryogenesis and subsequent glacial landscape modification have been emphasised (Peterson 1968, 1969, Derbyshire 1968, 1971), more recent work in areas such as Mt Owen in the West Coast Range (Kiernan 1990b) and the Mt Anne massif in southwestern Tasmania (Kiernan 1990a) has revealed considerable glacier build-up on windward western slopes at the times of most intense glaciation. This often produced little clear evidence of glacial erosion such as recognisable cirques on the windward flanks but nevertheless glaciers on these slopes deposited considerable volumes of glacial sediment downslope. Hence, the existing moraines on the slopes of the Frankland Range that retain their fresh, primary topographic form do not necessarily define the maximum ice limits. Neither are the glaciological and palaeoclimatic conditions deduced from existing moraine and headwall morphology necessarily applicable to the most extensive phase or phases of glaciation. Accordingly, the possibility must be allowed that the original natural impounding of Lake Pedder may have involved glacial events significantly more extensive and older than hitherto envisaged.

The landforms allow an estimate of climatic conditions during past glaciation. However, there are minor discrepancies between former snowlines implied by cirques and moraines and these differences hint at multiple glacial events. The influence of the bedrock structure and the preglacial topography to which it has given rise complicates the interpretation of former snowlines from cirque floor levels. In broad terms, ice velocity is the direct determinant of glacier power and is directly proportional to the net gain or loss of mass. The concavity of overdeepened cirque floors relates partly to ice velocity, which is fastest at the equilibrium line altitude (ELA) ("snowline") where the specific mass balance is, by definition, zero, and the resultant velocity vector is parallel to the ice surface (Andrews 1975). The mean altitude of the cirque floors in the Frankland Range is ~650m, the lowest well defined floor being at ~570m altitude (Bluff Tarn) and the highest at ~780m (The Moat). In the Wilmot Range the cirque floors range from 650m (Lake Wilmot) to 780m (Islet Lake). An alternative methodology for ELA determination is based on the altitudinal relationship between the headwall in the nevé area and the glacier terminus (Burrows 1977). The ELAs evident from the moraines on the flanks of the Frankland Range are generally higher than those implied by the cirque floors. Near Orb Lake, for instance, the water surface lies at ~620m but the moraines imply an ELA nearer 700m altitude. At Surprise Lake the innermost moraines imply an ELA at ~ 780m, the outermost moraines an ELA at ~700m, but the floor of the lake, which is ~40m deep (Peterson 1969) suggests an ELA at ~560m. While many uncertainties beset reconstructions of this kind (Meirding 1982) there seems to be some evidence to suggest that cutting of the cirques on the Frankland Range may demand a lower ELA and considerably more intense glaciation than that indicated by the lowest lateral moraines in the respective troughs, and that more than one glaciation is involved.

Based on climatic data from Strathgordon and adopting the standard lapse rate of 0.6^{o}C/100m, the present theoretical snowline in the Lake Pedder area lies at ~2030m altitude. The ELAs implied by the lowest cirques of the Frankland Range imply lowering of the snowline by up to 1460m, which in turn implies a depression of mean annual temperature with respect to the present value by up to 8.8^{o}C, or ~7.8^{o}C if lowering of the atmospheric envelope in response to low glacial sea levels is taken into account. However, wind drifting and topographic interference with the meso-scale climate will be emphasised by snowline lowering, increased albedo and frost (Soons 1979). These palaeotemperature figures are broadly consistent with those calculated for the glacial maximum in other parts of Tasmania but considerably exceed those postulated for the late Last Glacial Stage (Kiernan 1983, 1985, Colhoun 1985). The ELAs and palaeo-temperatures implied by the sharply-defined moraines of the Frankland Range more closely approach the latter.

While some earlier workers recognised evidence for multiple glaciation of Tasmania (Lewis 1945) later studies suggested that in fact only a single glaciation had taken place (Jennings & Ahmad 1957, Jennings & Banks 1958). Although new evidence subsequently arose to suggest a second glaciation (Paterson 1965, Derbyshire 1968), for many decades landscape evolution in Tasmania was perceived in the context of a monoglacial model. This monoglacial perspective appears implicit in previous interpretations of Lake Pedder, no suggestion of more than a single glaciation having been raised in any previously published discussions concerning the origin of the lake. However, it is now clear that the Tasmanian mountains were subject to repeated glaciations during the late Cainozoic, with the glaciers that developed during the late Last Glacial Maximum being relatively limited in extent (Colhoun 1976, Banks *et al.* 1977, Kiernan 1983, 1989, 1990b). Contrasts in the degree of post-depositional modification of moraines on the Frankland Range provide equivocal evidence that they represent more than a single glaciation. At ~300m altitude downstream from Sanctuary Lake the prominent end moraines overlap an earlier set of moraines that are very degraded. If the Lake Pedder area has been repeatedly glaciated, and given what is now known about the relative extent of the ice masses during the different glaciations elsewhere in Tasmania, it is conceivable that ice has previously covered much of the Serpentine Valley floor. Hence, the volume of glacial sediment covering the valley floor may be considerable in some areas.

Studies elsewhere in the Tasmanian mountains have commonly revealed glaciofluvial sediments to be relatively thick in some situations and relatively thin in others. Davies (1967) observed that despite higher rates of ice accumulation and ablation in the west than in the east, and correspondingly more rapid mass throughput and glacial erosion, the glaciofluvial sediments in the west are less widely distributed due to their lesser content of well rounded cobbles, gravels and clays. In the absence of documented sections through the sediments on the mountain flanks and valley floor, the extent to which the aprons that extend across the floor of the Serpentine Valley from the Frankland Range are formed of outwash as opposed to till mantled by outwash cannot be resolved. If the latter situation exists, it may be that Lake Pedder is more the product of glacial deposition than of glaciofluvial deposition.

Subsequent evolution of the Pedder landscape: Lake Pedder as a set of nested landforms

Whatever the precise mechanisms entailed in the ponding of water on the floor of the Serpentine Valley east of Greycap, much of the general character of Lake Pedder stemmed from subsequent geomorphic processes and events. In particular, the nature of the sediments that reached the Serpentine River, the hydrological regime of the Serpentine (including the role Lake Pedder played as a natural water storage that regulated river flow), and the impact of lakewater circulation and aeolian processes, all played major roles in subsequent evolution of the lake. Johnson (1972) identifies several characteristic landform features of a dynamic nature inherent in the evolution of the lake: the sand bar; the sub-aqueous dunes; the lunette or lakeside dunes; the beach; and the lagoon system. With some modifications this forms a broad framework for the discussion that follows.

Fluvial environments and landforms

Between Lake Pedder and the steep gorge in its lowermost reaches, the Serpentine River follows an intricately meandering course with numerous oxbow lakes and cutoffs (Figure 11). This contrasts with the braided channel system characteristic of closely proglacial rivers (Sugden & John 1976). The development of such a sinuous channel by the Serpentine River reflects a relatively constant postglacial discharge and supply of fine sandy sediment. The seasonally torrential meltwater flows that characterised the proglacial environment during the late Last Glacial Stage have been replaced by a less seasonal regime and the moderation of flow peaks. The postglacial advent of a much more substantial vegetative biomass and the formation of Lake Pedder itself which acts as a natural storage that regulates the discharge of the Serpentine, have been important factors in this change.

While the low gradient of this reach of the Serpentine Valley reduces the capacity of the stream to carry sediment under its present discharge conditions, the nature of the sediment reaching the river also differs from that which would have reached it during the colder periods of the Pleistocene. The present interglacial conditions favour chemical weathering and the production of fine calibre detritus, in contrast to the predominantly mechanical weathering of the Last Glacial which favoured the production of larger rock fragments by frost shattering and other processes. Most of the sediment presently being derived from the mountain slopes comprises fine materials reworked from the cold-climate sediments. There are no steep gradient tributary channels in sufficiently close proximity to the present thalweg of the Serpentine Valley to supply the river with coarse calibre clastic load.

Sediment type has the capacity to influence all aspects of river morphology (Schum 1968). With an increase in discharge and a decrease in sand or bedload major morphological changes may ensue. These can involve a decrease in channel width and increase in channel depth (thus changing channel shape), decreased meander wave length and increased sinuosity. Streams that carry a higher proportion of bedload tend to have relatively straight channels, with meandering channels being prevalent where the load is predominantly a suspended one. Any change in channel length can effectively shift a sediment source towards or away from the area of deposition, and changes in sediment type can reflect not only climatic and tectonic changes but major river adjustments to these. With a change from bedload to suspended load sinuosity will increase and conversely the width: depth ratio will decrease. When a meander wave-length changes, it will do so as a function of the 0.5 power of discharge, but if sediment type changes a major wave-length change will occur with only a minor discharge change (Schum 1968).

The meandering channel pattern of the Serpentine River downstream from Lake Pedder contrasts strongly with that of Maria Creek, the most upstream part of the Serpentine River system. Here a particularly well developed network of braided channels is exhibited by the major streams that drain into Lake Pedder via the Maria Lakes (Fish & Yaxley 1966, figure 5.10). The channel pattern in this case testifies to widely varying discharge conditions, with relatively coarse materials being

Figure 11: The meandering Serpentine River downstream from Lake Pedder, prior to filling of the Huon-Serpentine Impoundment (photo: K. Kiernan).

Figure 12: View towards the Frankland Range across the beach and seasonally - exposed sand bar at the eastern end of Lake Pedder (photo: K. Kiernan).

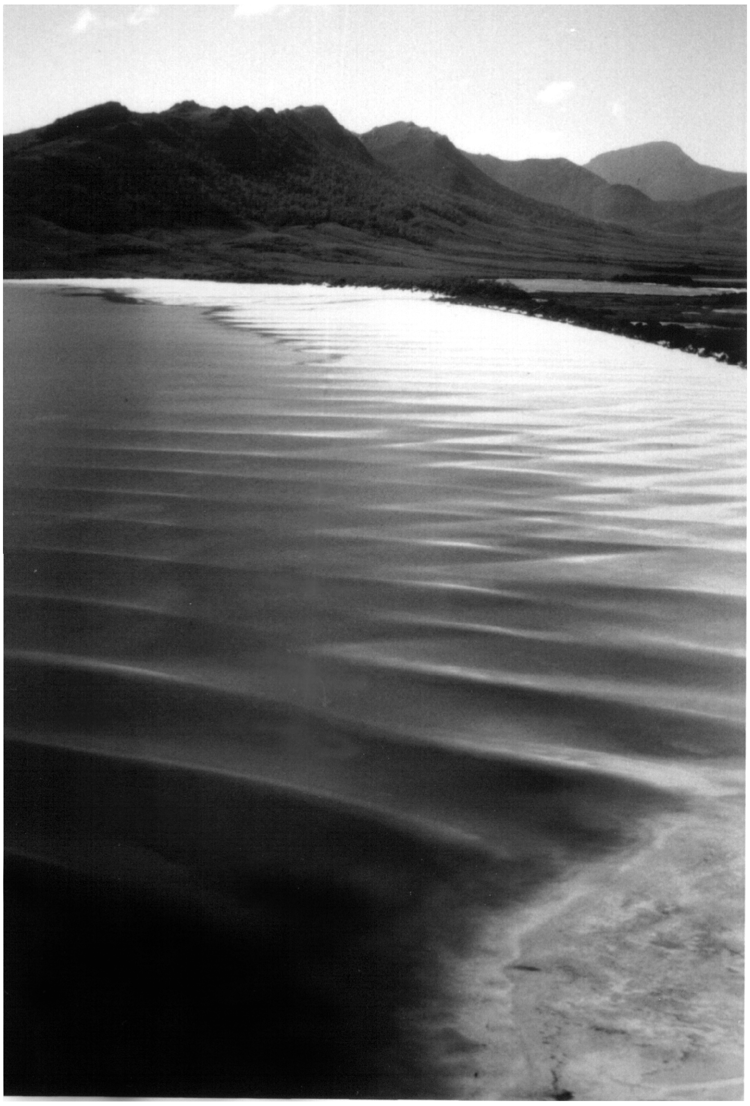

Figure 13: Mega-ripples on the lake bed at the eastern end of Lake Pedder (Photo: K. Kiernan).

deposited under high discharge conditions but the sediment load exceeding the capacity of the stream under low discharge conditions. The possibility exists that some of this morphology was inherited and modified from the Pleistocene channel network. These contrasts in the fluvial environments and landforms comprise one further significant element in the geomorphology of the Lake Pedder area.

Lacustrine environments and bedforms

The principal natural lake basin is that of Lake Pedder, but a complex of smaller and shallower lakes and swamps, the Maria Lakes, is present immediately to its east, discharging into Lake Pedder via Maria Creek. Prior to the construction of the Serpentine and Huon dams which created the present artificial reservoir there was little evidence of any higher level fossil shorelines. Such shorelines characterise many other glacial lakes, where they imply formerly higher lake levels.

Underwater contours of Lake Pedder are provided by Bayly *et al.* (1972). However, Tyler *et al.* (1993) suggest that they be regarded with caution due to the less than ideal circumstances under which they were obtained. The western shoreline of Lake Pedder is indented by embayments behind vegetated promontories and is joined midway along its length by a sinuous creek from the Franklands. The bed of the lake shelves gently eastwards to a basin ~1.5m deep under summer conditions, with a deeper trench ~3m deep in the south-eastern corner of the lake. The lake basin ended abruptly ~600m from the eastern shore in a step that rises up to the main Pedder beach (Tyler *et al.* 1993, Tyler 2001). The sand bar (Figure 12) is formed of the finer components of the glaciofluvial sediments. The size and shape of the bar is conditioned by seasonal changes in water level and wave action, modifying the configuration of the lake in such a way as to dampen the effect of different water inflow and outflow rates (Johnson 1972).

Mega-ripples (Figure 13) developed on the surface of the sand bar and extending into the lake at right angles to the beach were visually arresting because of the sawtoothed appearance they imparted to the edge of the lake. Current ripples such as these are formed under unidirectional flow and transverse to that flow. Ripple length therefore refers to the horizontal distance at right angles to the crest between two trough-points (Reineck & Singh 1980). Mega-ripples morphologically similar to those at Lake Pedder are well known from coastal environments where examples 5-100m long form under low energy conditions (Southard 1975, Boothroyd 1978). The Lake Pedder examples represent the Type 1 mega-ripples of Dalrymple *et al.* (1978), having essentially straight rather than sinuous crests. As at Lake Pedder, such mega-ripples may have smaller ripples on the stoss side. Subject to seasonal modification, their orientation and profile attest to a predominantly clockwise circulation of water in Lake Pedder.

The Pedder mega-ripples are not developed to any significant extent north of Maria Creek, where the beach under moderately well exposed summer conditions was up to ~350m wide. South of the Maria Creek delta, however, the summer Pedder Beach was ~180m wide, the strand-line being set back ~120-130m relative to that north of the creek. Immediately south of Maria Creek a single row of sand wedges produced by the mega-ripples projected out up to 220m such that the apex of the wedges approximated the strandline further to the north, although extensions that reach at least another 100m beneath the lake waters are discernible on air photos (e.g., Southwell 1983, plate 104). The wedges immediately south of the creek have an average breadth of 37m at their beach margin. Further south, however, their form changes dramatically, such that the basal width virtually doubles to a mean figure approaching 80m with that part exposed above water level seldom projecting more than ~120m. About halfway down this stretch of the beach, up to five further sequences of sand wedges of similar form are discernible from air photos deeper beneath the lake surface, the main axis of each approximating the position of the thalweg of the trough between the wedge set immediately inshore. A diamond pattern of bedforms results from this juxtaposition of wedge sets.

Towards the southern end of the beach the wedge above water level extends a mean distance of ~120m into the lake, but beyond its apex are further wedges that extend 91m, then a further 46m, then another 45m, then 60m, and finally another 80m to a point ~440m from the innermost beach strandline. No further wedges appear to exist beyond this point although this cannot be wholly confirmed since the heavily tannin-coloured lake water obscures observation of the lake bed as the water depth increases. The position of the apex of the outermost set approximates the apex position of those discernible through the water immediately south of Maria Creek.

Superimposed on the mega-ripples are various cross lineations, depressions, ripples and channels. These are very evident when the lake is viewed under low water conditions. These smaller ripple bedforms are developed by water movements at right angles to those responsible for the mega-ripples. They probably form as tributary inflows to the lake diminish and the water level declines each summer. At such times the migration of the visible mega-ripples is halted or slowed and shallow wave action assumes greater prominence in shaping minor bedforms. The very gentle gradient of the beach also facilitates changes in the position of the strandline due to wind action across the lake, a process that further facilitates the evolution of bedforms as the water subsequently withdraws across the sand. The action of tributary streams and small springs through the sand further enriches the fascinating and highly photogenic assemblage of bedforms that characterise Pedder Beach.

While much of the lake bed comprises sand, a higher proportion of gravel is present on the northern side of the lake. Some of the beaches near the Coronets consist of gravel, which formed the substrate occupied by some of the most interesting of the plant and animal species recorded from the lake (Bayly *et al.* 1972). This was also the environment richest in the disc-shaped ferro-manganese concretions known as "Pedder Pennies" (Tyler 1979, Tyler & Buckney 1980) (Figure 14). Pedder Pennies comprise a pebble of quartzite as the nucleus, surrounded by a rim that consists of 40 - 50% iron oxide and 0.03 - 0.1% manganese. The origin of Pedder Pennies is somewhat enigmatic, although morphologically similar concretions have been recorded from a number of other sites in both marine and freshwater environments. Apparent precursors to the hard and polished forms found in Lake Pedder are to be found in Lake Maria and Lake Edgar, both also now beneath the surface of the Huon-Serpentine Impoundment. In these latter lakes some pebbles exhibit a gelatinous rim of blue-green algae, bacteria and sometimes thallose liverworts, often found in pools colonised by *Restio* spp. The absence of apparent proto-pennies in Lake Pedder suggests the lake may once have been shallower. Alternatively, the Pennies in Lake Pedder may have been derived from elsewhere, possibly the Maria Lakes (Tyler 1979, Tyler & Buckney 1980). However, the discoid shape of Pedder Pennies is a hydrodynamically poor one from the point of view of potentially allowing their transport by a low energy stream. Moreover they are not confined to the Maria Creek delta but occur across much

Figure 14: Pedder pennies. The largest penny is 46mm diameter at the widest point (photo: K. Kiernan).

of the northern half of the lake almost as far west as the Serpentine River outlet. The ferro-manganese rims are likely to have been broken if they had been transported any distance by a vigorous stream.

Drained by Maria Creek which discharged into Lake Pedder, the Maria Lakes were seasonally isolated from the geomorphic processes in the main Pedder basin by the exposure of the intervening sand bar each summer. The principal inflows came from upper Maria Creek, which entered the Maria Lakes complex at its eastern end, and from a small stream that meandered northwards from the gap between the Frankland Range and Mt Solitary. The lakes in this area were much shallower than Lake Pedder and strictly lacustrine water circulation within them appears to have been insufficient for major unidirectional current-derived bedforms such as the Pedder beach mega-ripples to develop. Bedforms in the lakes appear to have been the product primarily of local water disturbance by the wind and the current of inflowing streams.

Aeolian environments and dune evolution

During the cold periods of the Pleistocene, stronger winds and a much less complete vegetation cover than now (Bowden 1983, Macphail 1979) would have facilitated considerable aeolian transport of sand from the braided stream beds at the foot of the Frankland Range by the westerly winds. This is in contrast to the proposition by Bayly *et al.* (1972) that the dunes at the eastern end of the lake "probably date from the last arid (post-Pleistocene) period". There is little evidence for Tasmania having experienced a phase of Holocene aridity as was once commonly assumed. Accretion and erosion of the frontal dune is a contemporary process, conditioned by the width of beach exposed but also by wind activity at particular times.

The dunes are highest and steepest north of the point at which Maria Creek crosses the Pedder beach. The dune may have been more fixed in position here due to the presence behind it of the creek, which had the capacity to check its eastward migration by transporting back downstream all the sand that spilled into it. A parallel situation on the Turakina River, New Zealand, is illustrated by Cotton (1942, figure 266). However, the dunes north of Maria Creek are also more protected from fire than the dunes to the south, being flanked to the west by Pedder beach and to the east by lower Maria Creek and the most downstream of the Maria Lakes.

The most extensive area of dune landforms lies south of Maria Creek where the frontal dune rises 3-4 m high. Immediately behind the frontal dune at the southern end, where the identifiable sand mass is narrowest, lies at least one further major dune ridge. Behind this there are traces of another one or two degraded ridges, then some extensively blown-out masses, parabolic dunes and isolated remnant sand mounds that terminate on the margin of a plain ~500m east of the frontal dune. Further to the north, but still south of the Maria Lakes complex, the sands extend eastwards for more than

1 km, and are bisected by a meandering stream. Several hundred metres to the east of the stream remnant mounds of sand, orientated broadly east-west, rise from shallow swamps. North of Maria Creek the frontal dune rises 5-6 m above the beach. At least three narrow ridges are present between the beach and Maria Creek. The frontal dune in this area is set back ~30 m eastwards of its position south of Maria Creek, and appears to correspond to one of the degraded ridges further to the south. In this area the sand mass extends eastwards for 3 km up the course of Maria Creek, where degraded sand mounds are again present.

Linear ridges of sand that are aligned broadly east-west are striking features, one extending for 600-700m along the northern margin of the most downstream of the Maria Lakes, with another formed along the southern shore of the water body immediately to the east, its eastern end curving northwards as a small lunette behind a narrow beach. Similar linear features occur immediately south of the Serpentine River at the outlet to Lake Pedder, the longest again extending for 600-700m. The position of the linears at Maria Lakes suggests their form is related to development along the margin of water bodies, and although some of those in the Serpentine area are somewhat enigmatic a similar origin appears likely.

The permanent Pedder beach comprises that part of the sand bar that is generally not inundated during winter, in effect a narrow strip a few metres wide along the northern end of the eastern shoreline. The hydrodynamic processes responsible for the bar, and the lunette behind the beach, control the beach morphology (Johnson 1972). The wide summer beach of Lake Pedder represented the easternmost part of the lake bed, exposed during times of low water level in the lake basin. This fluctuation in lake levels arose from the limited capacity of the Serpentine River, which was unable to drain all the winter rains that reached the lake, but which during summer drained more from the lake than was replenished by precipitation.

Aeolian activity on the lake margin was most pronounced when the low summer water levels exposed this broad sandy source area. Aeolian sands blown from the exposed lake bed extend over an area of at least 3 km^2 at the eastern end of Lake Pedder, with smaller accumulations along the shorelines of some smaller water bodies. The eastern sandsheet is broadly triangular in plan with its apex extending northeastwards. The best known landform is the main frontal dune system that extends along the entire eastern shoreline of Lake Pedder (Figure 15). Much smaller dunes bound the larger of the Maria Lakes.

Any smooth sand sheet is inherently unstable. Ephemeral sand ripples with a wave length of up to ~1 m form transverse to the wind with a lag of coarse grains forming the ripple crests and fine grains saltated into the intervening depressions. As wind strength increases ripples diminish due to a loss of size sorting (Bagnold 1941, p. 188). Sand dunes represent deformable obstructions to air flow that do not depend on fixed obstructions. Where there exists any free sand patch of greater than a few metres extent, part of it will increase in size and thickness to form a mound. A pocket of low velocity air will develop in the lee of the mound, promoting deposition there. The natural profile of any dune comprises a steep downwind slip (depositional) face and a gentle windward slope where erosion and transport occurs. In the Lake Pedder case, the windward western face of the dune was always cliffed due to wave action when the lake level was high during winter (Figure 15).

Pels (1971) has distinguished between "true lunettes" formed from lake floor sediments and "crescentic dunes" formed from beaches, and there are elements of both in the constructional sand landforms of Pedder. The Lake Pedder lunette bounds the entire eastern end of the lake, but is highest behind the permanent beach. Johnson (1972) attributes development of the lunette to the cutting by wave action of a shore platform in the unconsolidated deposits on the floor of the valley. Seasonal drying of the lake bed facilitates aeolian transport of the finer sand particles to form the lunette. The truncated western face of the lunette implies that the lake and sand bar were naturally expanding eastward at the expense of the lunette itself. Hence, accelerated erosion of the face of the lunette during filling (or draining) of the Huon-Serpentine Impoundment, while perhaps alarming to non-specialist bushwalkers viewing it at the time, would more rationally be viewed by a specialist geomorphologist as being merely a very temporary acceleration in the rate at which this natural process of landscape evolution operated.

More calm periods occur over winter than in summer, but the fact that the lake is full in winter means that any wind is liable to generate waves that will impinge on the dune face causing dune erosion. This occurs to a much lesser extent north of Maria Creek due to the intervention of the permanent beach even through the winter. During winter winds from the northwesterly quadrant are at their maximum (23-33% of the time at 9:00 am; 35-45% at 3:00 pm). Windspeed is less than 28 kph for the majority of the time. Hence, high water levels, limited exposure of sand source areas and the prevalence of northwesterly winds favour erosion of the dune south of Maria Creek over the winter.

Figure 15: The main lunette at Lake Pedder, backing the beach at the eastern end of the lake. Note the naturally-eroded face, caused by undercutting and collapse in response to natural wave action when the lake level rose to the dune foot each winter (photo: K. Kiernan).

In summer the full Pedder beach is exposed as a source of sand for dune accretion. In summer winds blow from the southwesterly quadrant for a greater proportion of the time than in winter, favouring sand accumulation towards the northeast.

Ongoing evolution: a migrating lake

The site at which the glacigenic sedimentation responsible for impounding the lake occurred is relatively fixed in position by the location of the glacial cirques on the Frankland Range from which the sediment originated, and the glacial troughs and meltwater channels down which the sediment was delivered onto the valley floor. Hence, it is unlikely that Lake Pedder ever extended any significant distance further westward. While some minor infilling by fluviatile sediment is to be anticipated, and appears evident at the southwestern corner, evidence also exists to suggest that the eastern margin of Lake Pedder was migrating eastward at the expense of the lunette (Johnson 1972). The entire lake may have been migrating rather than shrinking to any significant extent. Although other explanations may be available, the presence of the proto-Pedder Pennies in Lake Maria and mature Pennies in Lake Pedder which may be lag, may lend support to the migration hypothesis.

PART B: THE GEOCONSERVATION SIGNIFICANCE OF LAKE PEDDER AND ITS CONTRIBUTION TO GEODIVERSITY

Introduction

Just as plants and animals enrich and sustain our lives, so do landforms and the wider geological environment (Kiernan 1991a). Maintaining geodiversity is an essential element of any properly comprehensive approach to nature conservation or sustainable development. Landforms such as Lake Pedder have their own intrinsic value quite apart from their importance as habitat for biological species, or their utility to humans as a source of scientific, educational, recreational, economic, aesthetic or spiritual goods. Landforms are simply part of the world that warrants our respect and custodianship.

Three main areas are addressed in these concluding pages. First, the concept of landform conservation is briefly reviewed; second, a classification of Lake Pedder is outlined, to define its geomorphic species; and third, an assessment is made of the geoconservation significance of Lake Pedder and its contribution to geodiversity. The focus here is solely on the geomorphology of Lake Pedder, and only on the scientific value of Lake Pedder from a geomorphological perspective. No attempt is made here to address the value of Lake Pedder to the biological or other sciences. Nor is any attempt made to assess the aesthetic, wilderness or other values that were considered by the Commonwealth Government's Lake Pedder Committee of Enquiry to be the pre-eminent issues when that Committee recommended draining the storage and investigation of alternatives to drowning of the natural lake (LPCE 1974).

Geoconservation: Concepts and Practice

In his submission to the Lake Pedder Committee of Enquiry (LPCE 1973, p. 46), Mr B.C. Jones, a lecturer at RMIT, proposed that Lake Pedder "like the complement of its flora and fauna, any landscape ... has its intrinsic value in terms of its scientific interest, namely:

- its process of evolution in geological time (its inherent and distinctive properties and potential);
- its comparative rarity (analogous to biological endemism);
- its reference quality (analogous to biological gene pool);
- its natural limitations and non-renewable resources."

Many nature conservation programs continue to focus solely on plants and animals. This is despite the diversity that exists in the geological environment, among rocks, landforms, soils and geoprocesses; despite the fact that landforms are the stage upon which all terrestrial life exists; and despite the strong influence landforms exert upon the nature and distribution of the plants and animals that are generally the focus of conservation efforts. More recently, the importance in their own right of the physical features of the earth is being recognised. The fact that many landforms are relict or time transgressive phenomena demands that particular care be taken, since seed collection, captive breeding programs or other initiatives that are sometimes attempted to retain plant and animal species are not viable in the field of geoconservation.

A range of perspectives may be employed in considering the conservation significance of landforms (Kiernan 1991a):

- that landforms are important only if humanity can utilise them in some way (eg for aesthetic, recreational or economic reasons);
- that landforms are important because they serve as habitat for plants and animals that are themselves important;
- that landforms are important in their own right and have their own intrinsic value.

In the past, utilitarian and habitat considerations have tended to predominate on those occasions when earth heritage features have been taken into account in scientifically - based conservation initiatives (Davey 1984, Rosengren 1984). Less regard has been paid to intrinsic values that are based on the assumption that geological, geomorphological and pedological phenomena are just as appropriately included in the moral embrace of individuals as are people of different skin colour, other animals, other sentient beings, other living things: that the boundaries are arbitrary, and that the basic premise ought be respect for all things, animate or inanimate; the avoidance of unnecessary harm or damage to any part of a cosmos because all warrants respect in its own right. However, some writers give greater emphasis to recognising intrinsic values and this perspective is being translated into geoconservation (Nash 1990, Kiernan 1990c, 1997, Sharples 1993, 1995).

Landforms are now increasingly accepted as being worthy targets for conservation, though not always for scientific or moral reasons as is more widely the case in bioconservation. Nevertheless, geoconservation is now a well-established strategy within the nature conservation frameworks of several overseas countries. In Britain, for instance, 2,200 sites of significance in the earth sciences had been identified by 1989, of which 1,400 had formally been notified as Sites of Special Scientific Interest (SSSI's).

The Operational Guidelines issued by the World Heritage Bureau in February 1994 make explicit provision for landforms and geological features. A number of sites have been added to the World Heritage List partly for geoconservation reasons. Few if any sites have yet been listed solely for scientifically - based geoconservation reasons, although geoconservation has been significant in the listing of such sites as the Grand Canyon, the Rocky Mountains, Plitvice Lakes and Sagarmartha. The predominantly biocentric training of those responsible for the assessment of nominations probably underlies the limited attention given to geomorphological values. The inadequate training in the earth sciences received by most nature conservation managers, is a problem in many nature conservation agencies.

Commonwealth and state government initiatives

At a national level, the criteria for the Register of the National Estate (AHC 1990) provided a variety of criteria under which landform sites could be listed. Committees charged with consideration of Geological Monuments or Geological Heritage have been established by the Geological Society of

Australia in some states. Their principal focus has generally been upon bedrock sites rather than landforms, and some political difficulties have arisen due to the resistance of some powerful mining and economic geology interests to nature conservation proposals. As overseas, there is a dearth of trained personnel for such work. While few biologists fail to be exposed to bioconservation during the course of their education, exposure to geoconservation is essentially non-existent for geology graduates in Australia, perhaps in part due to the source of sponsorship for much geological education. The situation would be as unsatisfactory with respect to zoology as it is in the earth sciences if the meat industry was generally perceived as being the sole justification for pursuing zoological studies, and was the principal source of its funding.

Nonetheless, demonstration of the extent to which the need for landform conservation has been recognised at a national level is offered by legal documents submitted by the Commonwealth Government in connection with its responsibilities as a signatory of an international treaty, specifically in relation to the Tasmanian World Heritage Area of which Lake Pedder formed part. During the hearings of the Commission of Inquiry into the Lemonthyme and Southern Forests the Commonwealth engaged professional consultants in the area of geomorphology. One proof of evidence submitted by Commonwealth counsel suggested that some landforms in the Inquiry area were of World Heritage significance in their own right. It also proposed that a requirement to encompass complete geomorphological systems and communities was a proper interpretation of the integrity provisions of the Operational Guidelines issued by the World Heritage Bureau. The introduction of geomorphology to the Inquiry's deliberations spawned several contributions including consultants reports (Exhibits 33, 34, 65 A-B, 79 A-D, 107A, 119A, 120A, 122 A-G, 130, 176 A-D, 177, 184 A-B). Many hours of testimony and many pages of transcript were devoted to landform conservation during the subsequent court hearings, the present writer alone spending nearly six hours in the witness box. In its final report the Commission of Inquiry into the Lemonthyme and Southern Forests devoted two chapters to exploring the significance of the landforms of the area (roughly 20% of the space devoted to qualifying areas) (Helsham *et al.* 1988).

The Tasmanian World Heritage Area nomination (Australia 1988) prepared jointly by the Tasmanian and Commonwealth governments and subsequently sent to Paris by the Australian Government, invoked landform values in successfully arguing its case that the area qualified for listing in terms of all four possible criteria for natural heritage areas. Among the significant implications of this document are the facts that:

- as a signatory to an international convention, Australia argued in a formal submission that geomorphological phenomena were sufficiently important as to warrant World Heritage listing;

- that landforms warrant protection in nature conservation strategies;

- that geoconservation strategies demand the recognition and protection of "landform species" and "landform communities" (Australia 1988, p.39); and

- that regard must be paid to landform variety, the sources of that variety and the need to safeguard it.

The nomination argued that the Tasmanian wilderness karsts are important because of the variety in their geologic, topographic, biokarstic, climatic and palaeoclimatic context. Since that time, the Commonwealth Government has acted to halt limestone quarrying that was damaging the Exit Cave Karst System, within the extended Tasmanian World Heritage Area.

More recently, the Australian Government has successfully argued, partly on geo-conservation grounds, for the World Heritage listing of Macquarie Island and Heard Island.

The decision by the Electricity Commission of New South Wales to relocate a proposed dam in order to safeguard an important landform represents a case of a state agency involved primarily in resource exploitation acting to protect an important landform site. Slaven Cave, near Lithgow, was threatened with inundation through the proposed construction of a reservoir on Thompsons Creek to provide cooling water for the Mt Piper thermal power station. A report on this landform concluded that it was a geomorphological feature that should be protected and managed as a geomorphological monument of great significance (Kiernan 1988a). In that case, it was argued that Slaven Cave was Australia's only known example of the particular class of landform it represented, that, "in essence, it is the only representative of its species (genus?) known in this country." It was suggested that "unlike a rare plant or animal, with geomorphic phenomena it is not possible to collect seeds, transplant the item to a botanical garden or transport a breeding pair to a safer locale. In that sense, geomorphic phenomena are more vulnerable and rare than some rare and endangered biological species".

Tasmanian government initiatives
At a state level, the obligation to safeguard landforms is acknowledged, although progress has been incremental rather than dramatic. Most of the existing system of State Reserves and National Parks exists to safeguard aesthetic, recreational and biological resources. Although significant geoconservation sites are present within some parks (Dixon 1991), little if any consideration was given to the scientific values of the geomorphology or geology in establishing most reserves prior to the Lemonthyme and Southern Forests Committee of Inquiry in 1987. A very few small reserves have been established solely to safeguard earth science features, as at Eugenana. A more modern approach to defining nature conservation lands would necessarily give more prominence to geoconservation and geodiversity, but the advent of earth science expertise in the Parks Service has largely coincided with a dramatic decline in the amount of land being set aside for conservation. The Tasmanian World Heritage Area Management Plan (PWS 1999) acknowledges and recognises the importance of sites of geoconservation significance. Geodiversity was explicitly considered during the compilation of the Forests and Forest Industry Strategy with a number of areas having been identified as important solely on the basis of their geoconservation significance (Podger *et al.* 1990), but this was not effectively followed up during the Regional Forest Agreement process.

Where features of high nature conservation value exist outside of formal reserves, these too should receive appropriate protection. Some steps have been taken in this direction in Tasmania. For example, the *Forest Practices Act* 1985 provided for the establishment of a Forest Practices Code which from the outset has addressed landform conservation. Training in landform conservation forms an integral part of the courses that must be undergone by Forest Practices Officers.

Some areas in State forest have already been categorised for special management to safeguard geomorphic values. None of the areas have the legislative security theoretically attached to national park status. However, Lake Pedder was flooded despite already being a national park, and the devastation caused to the banks of the Lower Gordon River by boat wakes occurred despite the site also being within a national park with the apparently added protection of being a World Heritage Area. The real determinant of survival of areas of conservation significance, irrespective of land tenure, is often public awareness, vigilance, and the diligence and competence displayed by the relevant land management authority.

An accepted value
Geoconservation has made considerable advances over recent decades, and is well-established within some agencies at a conceptual and policy level, both in Australia generally and in Tasmania in particular. The Tasmanian advances have been made with negligible political pressure having been exerted on the agencies involved, and appear to be more the product of evolving perceptions of what is appropriately the concern of land managers involved in nature conservation. This evolution has occurred since the time that the Huon and Serpentine dams were filled, when a Commonwealth Government committee of enquiry was moved to conclude that in failing to properly document the very considerable geomorphological, biological and ecological values of Lake Pedder, the investigation that preceded development of the power scheme was totally inadequate (LPCE 1974, p.143).

The report of the 1995 Inquiry into the Proposal to Drain and Restore Lake Pedder held by the Australian House of Representatives Standing Committee on Environment, Recreation and the Arts concluded "It is unfortunate that the beautiful, geologically unique lake was ever flooded...in future, a much greater weight must be given to the preservation of ... geological diversity ..." (Commonwealth of Australia 1995). The Tasmanian Public Land Use Commission (TPLUC 1995) recommended that geodiversity conservation become a primary objective of the management of protected lands, and with the passage of the *Regional Forest Agreement (Land Classification) Act 1998* this objective is now enshrined in state legislation.

The scientific significance of landforms
Scientific values alone obviously cannot define the significance or value of any natural place, because the concept of significance is rooted in the values of the observer. A broad perspective on the significance of the Australian Alps, for instance, is presented by Davey (1989, p. 340-341) and it is one that might equally be applied to the assessment of Lake Pedder. Davey recognises that in the Alps nature conservation, commodity resources, the evidence of continuity of human use, aesthetic values, landscape values, scientific values, community image and perception, education and recreation are important values. The assessment criteria of the Australian Heritage Commission also consider a broad perspective: the contribution that may be made by a place to representation of the range of natural, prehistoric and historic places; the associations of a place with significant people in the past; aesthetics; cultural or social associations, or the significance of a place in being a focus of public sentiment towards those things; or the potential a place offers for providing insight into Australia's natural or cultural heritage (AHC 1990).

While the geomorphology plays a role in all these potential viewpoints from which the significance of Lake Pedder might be assessed, of those value groups identified by Davey (1989) nature conservation, scientific and educational values are those most obviously linked with geomorphology to the average non-specialist. Aesthetic values and natural beauty are also likely to be linked to landforms in such eyes. The nature conservation values identified by Davey relate to four elements: phenomena (endemism, rarity and status, specific taxa (genetic), sites, forms and structures, and habitats); processes; diversity and complexity; and gradients. The scientific values he recognised are threefold: understanding of phenomena and processes; development of explanations about wider classes of phenomena or processes; and type and reference localities. The educational values are twofold: clarity of expression; and display of full suites of related phenomena.

From the point of view of the earth sciences, Rosengren & Peterson (1989) outline two broad criteria. First, a place may make a contribution to defining the physical characteristics of a region (on some scale); or it may be important in displaying past and present geological and geomorphological processes, and allowing analysis of the evolution of a region (on some scale). They recognise that important geological sites may include type sections, contacts between different formations, structures and fossil exposures; while geomorphological sites may include places that are representative of types of terrane, places where the relationships between the geology and geomorphology can be determined, where landforms or indications of geomorphic processes allows interpretation of landscape evolution and rates of environmental change. The Australian Alps, for instance, is "significant to the earth scientist because of geological, tectonic, and geomorphological evidence for the nature of continental evolution and late Cainozoic climatic change observed there" (Rosengren & Peterson 1989).

As Davey (1989) cautions, from a scientific perspective, credible conclusions on significance must be based on data, not supposition. Adequate information is needed to achieve this. But as the sad history of the Lake Pedder flooding has shown, holding operations based on reasoned and informed judgement may be appropriate where inadequate resources have been made available to allow informed decisions to be made before actions are taken that will compromise the values potentially at stake.

The public perception of significance is often biased towards crude criteria such as size or spectacle. Even scientific observers may be biased by training or habit to narrow perspectives, such as a wholly biocentric one. Geoconservation needs to be based on the recognition and effective management not just of outstanding sites, but also of sites that are representative of their class. An important issue in landform conservation, as in biological conservation, is the development of taxonomic or typological systems that allow different categories of phenomena to be recognised. Such typologies are increasingly being developed and employed in Tasmania as a framework for listing the classes of features that exist and which need to be represented in order to maintain geodiversity (Kiernan 1984, 1995, 1996, Soutberg 1990, Sharples 1993, 1995).

Notwithstanding the need for taxonomic differentiation of landforms, reductionist perspectives and strategies are no more satisfactory with respect to many landform sites than they are for biological sites: both commonly require a systems perspective, a fact increasingly accepted with respect to karst systems (Davey 1984, Kiernan 1988b, 1991b, 1994a), but still inadequately embedded in perceptions regarding conservation requirements for other geomorphic domains.

A geomorphological classification of Lake Pedder

Just as biota is classified according to genetic criteria, facilitating assessment of the conservation status of different classes of phenomena, so too does genetic classification form a logical basis for the recognition of different classes of landforms. Lake basins represent a "class" of landforms that is divisible into several different "orders" or "families". Different orders of lakes include those formed by structural conditions and tectonic processes, by fluvial processes, by karstic processes, by periglacial processes, by volcanic processes, by glacial processes and so forth. For such an approach to be usefully employed as an aid to identifying appropriate targets for landform conservation there must be an objective framework, a good basic inventory of the range of landforms that exist, trained geomorphological expertise sufficient to facilitate proper assessment, and just as much flexibility as is needed when research in the life sciences inevitably demands taxonomic revisions (Kiernan 1990c, 1991a, Soutberg 1990).

A broad classification of Lake Pedder

Progress in the area of lake classification is reviewed by Timms (1992). A number of writers both overseas and in Australia have developed morphogenetic schemes of classification for lakes (e.g., Penck 1894, Forel 1901, Russell 1895, Davis 1887, 1903, Cotton 1942, Hutchinson 1957, Fairbridge 1968, Bayly & Williams 1973). Hutchinson recognises eleven categories of lakes, namely those resultant from (1) tectonic activity, (2) volcanism, (3) landslides, (4) glaciation, (5) solution, (6) fluviatile action, (7) wind action,

(8) shorelines, (9) organic accumulation, (10) made by organisms, and (11) meteorite impact. Bayly & Williams recognise the first eight of Hutchinsons's categories, adding only human - made lakes to this list. Most of their categories are subdivided. Timms (1992) suggests there is much to recommend the heirarchical approach such as has been applied to wetland classification by Riley *et al.* (1984) and Paijmans *et al.* (1985). Timms differentiates between lakes and swamps on the basis of water depth (1m), differentiating four principal classes: permanent or near permanent lakes, seasonal lakes, intermittent lakes, and episodic lakes. Within the permanent class he recognises (1) floodplain lakes (including billabongs and waterholes in channels), (2) lakes in coastal dunes and on beach ridge plains, (3) in terminal drainage basins, (4) associated with lava flows, (5) crater lakes, (6) karst lakes, (7) glacial lakes, and (8) man-made lakes.

Previously erroneous interpretation of Lake Pedder led Fish & Yaxley (1966, p. 261), in their discussion of Tasmanian lakes, to classify both it and Lake Edgar as lakes associated with earthquake activity, which in the case of Lake Pedder is a misconception sometimes still repeated (e.g., McCue *et al.* 1996). Whilst Lake Edgar does indeed have such an origin, being a sag pond formed against the Lake Edgar Fault Scarp, Lake Pedder (Figure 16) is now known to be of glacial origin (Davies 1965, 1967, Johnson 1972, *this paper Part A*).

Fairbridge (1968) identifies six principal types of glacial lake, namely: (1) ice scoured basin; (2) subglacially scoured troughs; (3) moraine-dammed basins; (4) ice-dammed basins; (5) isostatically warped basins; and (6) kettle lakes. As a lake formed through damming by glacigenic sediment, Lake Pedder most nearly matches category 3 of this schema (moraine-dammed basins).

Different glaciological conditions give rise to important differences in the landforms that result from glaciation. The principal differences are imposed by the thermal characteristics of the ice mass, ie. whether the glacier system involves either (1) cold ice, that is, ice at a temperature below the pressure melting point; or (2) warm ice, which is sufficiently close to the pressure melting point to contain liquid water. Both types of ice can exist in either polar or alpine environments, but in general cold ice is more characteristic of polar or continental scale glaciation. Warm ice is the norm in areas of temperate maritime glaciation where there are high rates of accumulation, mass throughput and ablation, resulting in greater geomorphic work. Hence, important differences exist between the types of lakes that tend to be formed by continental-scale glacier systems, and those that are produced in landscapes shaped by mountain glaciers.

Fairbridge (1968) therefore differentiates two categories: (1) continental glacial lakes; and (2) mountain glacial lakes. Clearly, Tasmanian glaciation was of mountain type rather than being of continental scale. All studies of Tasmanian glacial landscapes undertaken to date have indicated that the glacial environment of the island was of temperate maritime type (Peterson 1968, Derbyshire 1968, Colhoun 1985) and that they involved warm-based ice, even in the most inland and potentially continental situations (Kiernan 1985, 1990b). Lake Pedder therefore belongs in the class of glacial lakes that are the product of mountain glaciation and warm ice.

The origins of mountain glacial lakes are very diverse. Hence, under the Fairbridge (1968) classification, Lake Pedder falls into the second broad category, mountain glacial lakes. Fairbridge recognises six types of mountain glacial lakes: (a) cirque or corrie lakes; (b) rock-scoured rock basins; (c) paternoster lakes; (d) piedmont lakes; (e) kettle lakes and stagnant ice depressions: and (f) moraine - dammed and fluvial wash - dammed lakes. Lake Pedder falls into group (f). Expanding upon this group, Fairbridge notes:

> "These lakes are characteristic of mountains which experienced long histories of retreat and readvance thus creating extended valleys with numerous barriers. They are numerous in the Northern Rockies, which are at relatively low latitudes, yet in their mid-continental positions they are susceptible to marked changes in climatic regime even during an interglacial epoch. In Glacier National Park (Montana) fluvial-wash dams maintain Kintla, McDonald and the two lower Medicine Lakes, while moraines dam Bowman and Quartz Lakes (Campbell 1914)."

However, Fairbridge here refers only to situations in which a glacier flowed along the length of the valley in which the lake was formed. The situation at Lake Pedder was very fundamentally different because damming occurred by sediment discharged from a tributary valley.

The schema adopted by Timms (1992) may be summarised roughly as follows:

1. Lakes formed in contact with ice
    - a) ice surface lakes
    - b) lakes dammed by glaciers
    - c) lakes dammed by ice sheets
    - d) frontal (proglacial) lakes

Figure 16: View from the air across Lake Pedder beach, showing the outlet channels from the Maria Lakes (Maria Creek), the lunette on the lakeside edge of the broad aeolian sand mass, and mega-ripples on the lake bed. The photo depicts the beach at early autumn level as the lake basin begins to fill (photo: K. Kiernan).

2. Lakes in rock basins and associated with depressions caused by erosion
   - a) ice scour lakes
   - b) cirque lakes
   - c) glaciated valley (including paternoster) lakes
   - d) clint lakes
   - e) piedmont lakes

3. Lakes formed in glacial deposits (moraines, drift or outwash)
   - a) moraine dammed
     - (i) terminal moraines
     - (ii) recessional moraines
   - b) drift basins
   - c) kettle lakes
   - d) lakes in ground moraine
   - e) lakes dammed by outwash filling a valley
   - f) lakes formed in meltwater channels

Lake Pedder fits case 3(e).

To this broad framework might be added some important subdivisions, such as differentiation in 3 (a) between lakes formed behind end moraines and those formed behind lateral moraines.

A more comprehensive and satisfactory scheme of glacial lake classification would follow from the morphogenetic classification advanced for glacial landforms by Sugden & John (1976). According to this, landforms produced by glacial deposition can be subdivided thus:

1) linear features

   - a) parallel to ice flow
     - (i) subglacial forms with streamlining
     - (ii) ice-pressed forms
     - (iii) ice marginal forms
   - b) transverse to ice flow
     - (i) subglacial forms

(ii) ice-pressed forms
(iii) ice front forms

2) non linear features lacking consistent orientation

a) subglacial forms
b) ice-pressed forms
c) ice-surface forms

Each of these categories is further subdivided by Sugden & John (1976). Such an approach is partly evident in the classification of modern glacial lakes by Embleton & King (1975), and this aspect of their schema can readily be extended for the classification of glacial lakes in deglaciated areas: (1) lakes formed in lateral valleys dammed by ice [sediments] in the main valley; and (2) lakes in main valleys dammed by ice [sediments] from lateral valleys. Case (2) applies to Lake Pedder.

The formation of Lake Pedder conceivably resulted from the formation of lateral moraines (1a-iii) or possibly buried end moraines (1b-iii), but it certainly involved glaciofluvial sedimentation. Glaciofluvial landforms can similarly be divided (Sugden & John 1976) into:

1) ice-contact forms
a) linear features
(i) parallel to ice flow
(ii) transverse to ice flow
b) non linear features

2) ice-distal forms

Landforms in category (2) are controlled primarily by the proglacial topography but are also divisible at least into: (a) linear features; and (b) non linear features. The glaciofluvial landforms implicated in the natural impounding of Lake Pedder are likely to have been primarily proglacial outwash aprons, formed from sediment washed downslope from the glacier snouts but also spreading laterally.

A nested set of landforms within a highly integrated landform community

Lake Pedder evolved in the context of a temperate maritime glacial system at mid southern latitudes. This environmental context is relatively restricted in occurrence which helps narrow the search for comparable features. As expressed to the Lake Pedder Committee of Enquiry by Mr B.C. Jones "a small number of independent geological and climatic factors had combined in a specific and highly unusual arrangement in space in a particular sequence to create the terrain centred on Pedder" (LPCE 1973).

The landform community of which Lake Pedder forms an integral part includes the surrounding mountains and broad valley bottom, the natural snowfences, cirques, glacial headwalls, glacial troughs and meltwater channels of the Frankland Range; the moraines and till deposits; the outwash aprons and glaciofluvial sediments; the meandering course of the Serpentine River and the contrasting braided channels of Maria Creek; the Maria Lakes lagoon system; and of course the Lake Pedder basin itself. Viewed separately, some of these phenomena, such as the Serpentine River and the complementing Maria Creek channels, are very worthy geoconservation targets in their own right. Together they form a set of features that are much more valuable than the sum value of each of the individual component landforms. The complexity of the Lake Pedder landform assemblage is partly due to the history of multiple glaciation and its likely impact on the evolution of the area. No formal landform classification system advanced to date adequately embraces this diversity.

Similarly, no formal landform classification system presently exists that would adequately embrace the set of nested landforms that Lake Pedder contained: the lake basin itself and the wide range of associated fluvial, lacustrine and aeolian landforms. A remarkable complexity of highly interdependent geomorphic progresses produced within this very compact area exemplars of both the processes and products of landform evolution.

Assessing the geoconservation significance of Lake Pedder and its contribution to Geodiversity

Analysis of landform significance may be aided by assessment at a number of levels (Kiernan 1991a, 1995, 1996, Kiernan & Eberhard 1993):

1) the systems level, or the geologic, topographic, climatic, glaciological temporal or other context within which the landform has evolved and been influenced.

2) the individual landform types ("species") and landform assemblages ("communities") present.

3) the contents of the landforms, such as the sediment sequences contained within lake basins.

4) human use and aesthetic issues, including past, present and possible future use.

Lake Pedder emerges as a significant feature at each of these levels of analysis.

The Systems Level

Landslides and mass movement down valley sides not uncommonly form lakes by damming the stream in the main valley (Adams 1981), one Australian example being Lake Tarli Karng, the deepest lake in Victoria (Bayly & Williams 1973). However, lakes formed in this topographic position by glacigenic sedimentation from valley sides appear far more unusual. Numerous examples of moraine-dammed lakes occur in Tasmania, but all have been formed behind end moraines or are perched upon lateral moraines formed by a glacier that flowed down the valley in which the lake formed. Lake Pedder differed significantly from all these in having been formed in a trunk valley as a result of glacial activity in a tributary valley. Moreover, Lake Pedder was of relatively large size. As such, it has no replicate in Australia and represents the only occurrence of this species of landform in Australia. No lake basin of comparable size and origin exists in the glaciated mountain landscapes of New Zealand (Cotton 1942, Suggate 1973, Adams 1981, Soons & Selby 1982). Neither does there appear to be any equivalent in South America (Caldenius 1932, Mercer 1976, 1984, Paskoff 1977, Clapperton 1993). These are the only areas in which terrestrial glaciation has occurred in southern temperate latitudes.

In these terms alone, Lake Pedder was one of a kind, akin to a biological species of which only one specimen exists. This point is emphasised in the comprehensive review of lake types by Timms (1992), who in describing lakes formed by outwash filling a valley refers to Lake Pedder as an "outstanding example". In contrast to the numerous examples he is able to cite to support his other categories, he cites only Lake Pedder within this category. Timms refers to its mode of formation as "unique" in captioning a figure on its origin (Timms 1992, p. 97).

In its final report the Lake Pedder Committee of Enquiry reproduced part of a letter by Mr B.C. Jones of RMIT:

> "The fundamental physiographic importance of Lake Pedder, as pointed out at the Enquiry hearings, lies in its origin as a glacial outwash impoundment. As such, of course, the lake is not only a spectacular example of international rank, but is the only one of its kind in Australia. Whilst the overall lineation of the Serpentine Valley is undoubtedly fossil and can be ascribed to preglacial differential erosion in rocks of contrasting lithology, the modern detailed drainage pattern has been developed by proglacial and almost certainly periglacial or nivational mass movement.
>
> From the foregoing considerations (omitted in detail here), not only is the complex and polycyclic glacial detritus and proglacial outwash above 935 feet in the Serpentine valley of scientific interest and of direct importance in the evolution of Lake Pedder: vertical sections through the periglacial sequence above and below the lake are, I believe, vital in constructing a chronology of the Pleistocene. It is extremely unlikely this opportunity exists in the glacially modified landscape of the Arthur Range, for example, because of the lower elevation, greater catchment and higher discharge of the Huon River, reflected in a different relationship between stream gradient and the slopes of the interfluves below the Scotts Peak dam" (LPCE 1974, p. 80).

The present review of the geomorphology of Lake Pedder (*this paper Part A*) resoundingly supports Jones' contention.

The Landforms Level

Components of the wider landform community are also of geoconservation significance at various levels. For example, the clear exemplar of the importance of shading and snowfence effects that is offered by the Frankland Range snowfence is significant at the national level, but the individual cirques often at no more than the state level. However, reductionist perspectives are seldom appropriate in assessing the importance of phenomena as conservation targets, as the conduct of the Commission of Inquiry into the Lemonthyme and Southern Forests (Helsham *et al.* 1988) demonstrated; they are all too easily taken to extremes such that one could perhaps argue that a species is not worth conserving in its own right since analysis suggests it is composed of the same types of atoms as are common in many other phenomena and that therefore it is not unique. It is not the worth of the individual components of the Lake Pedder landform complex that is at issue here, even though some are clearly significant in their own right. What is important is the integrated complex.

The lake margin features include littoral shelves, beaches, barriers, spits and bars, and evidence of progradation. Various small glacial lakes in Tasmania contain sandy bottoms or small sandy shoreline sand pockets, but none are on anywhere near the scale of those at Lake Pedder. The beach systems of Lake Pedder are more extensively developed than in any other comparable freshwater system in Australia (Bayly *et al.* 1972). In his comprehensive text *Lake Geomorphology*, Timms (1992) singles out the beach and barrier of Lake Pedder as significant landforms. Reviewing lake beaches around the country, he concludes that "perhaps the best and certainly the most beautiful example was the famous beach at Lake Pedder". He recognises that other beaches exist at Lake St Clair, around Lake Eyre when it is full, and in some of the larger Australian dune lakes such as Lake Boomanjin on Fraser Island, but concludes that: "most other Australian lakes are too small to develop sand accumulations worthy of the title 'beach' ".

Timms (1992) comments on the rarity in Australian lakes of barriers, or bars built offshore on shallow shelving coasts where offshore and inshore vertical circulation cells meet, such bars commonly being shaped like beaches and indeed being exposed at low water levels. He cites in his volume the "striking" example of the beach at Lake Pedder, but notes others in the very different environment of Lake Wyara in southwest Queensland, a non-glacial site and hence one not really comparable in a morphogenetic sense.

Beaches and dunes are not uncommon on glacial lakes, such as Lake Pukaki and Lake Wanaka in New Zealand, while a very much larger sand mass than that at Lake Pedder occurs on the margin of Lake Michigan in North America. In Tasmania most such dunes of any size are formed on the margin of elongate lakes impounded by moraines deposited by glaciers that flowed down the main valley. Unfortunately, the dune at Lake St Clair, the Pedder lunette's nearest and largest relative in Tasmania, has been eroded due to raising of the lake level for hydro-electric purposes. Its eroded flank has been buried under rock rip-rap, a road has been hacked along its crest and considerable volumes of sand have been quarried from its landward side (Kiernan 1987, 1991a, Dixon 1994). Indeed the condition of the Lake St Clair dune is probably worse than that of Lake Pedder, even though the latter is presently beneath the waters of the Huon-Serpentine Impoundment, while the Lake St Clair dune remains a highly visible part of a major national park and a World Heritage Area.

Lunettes are well known features around water bodies in semi-arid parts of Australia. They are uncommon in humid areas, although they may form wherever a sandy substrate is subject to essentially uni-directional winds (Timms 1992). The presence of a very large lunette in the very humid conditions of southwest Tasmania is noteworthy, and has resulted from the intriguing mechanisms that control lake level. In Tasmania, the only other substantial dune system that has formed on a glacial lake, apart from Lake Pedder, is at Lake St Clair. However, the fact that sand at Lake St. Clair has been blown against the faces of end moraines exaggerates the apparent dune size.

The fluvial geomorphology of the Serpentine River is certainly significant at the state level and probably in the humid south-eastern Australian context. Large scale channel systems elsewhere in southeastern Australia, such as those of the Riverine Plains (Schum 1968), differ in terms of their climatic setting, scale, the antiquity of their evolutionary processes and the multiphase nature of those processes. Literature search and the writers own experience indicates that nowhere else in Australia or New Zealand is there a comparable relationship between the development of such a channel system and adjacent glaciers that constrained the channel position and supplied the sediment, and there seems no published record of any parallel situation existing in the glaciated parts of South America. Hence, it is unique in the Southern Hemisphere at the very least.

Although the scope of this assessment is restricted to Lake Pedder and those landforms to which it is genetically related, it should be recognised that other sites of geoconservation significance that are not genetically related to Pedder are also present within the wider area submerged by the Huon-Serpentine Impoundment. One such is the Lake Edgar Fault, which has been intermittently active for over 500 million years. The Lake Edgar Fault scarp is also one of the best expressed fault scarp landforms in Tasmania, while Lake Edgar and its companion lake were excellent examples of sag ponds formed against the fault scarp.

The Landform Contents Level

Ferro-manganese concretions similar to Pedder Pennies have been recorded from a number of other Tasmanian lakes (Tyler 1979, Tyler & Buckney 1980). Coarser concretions occur in Lake Youl and Yates Lagoon, Lake Dove and Lake Curly. However, the northern lakes have a dark coloured dolerite nucleus rather than a lighter coloured quartzite nucleus, while those from Lake Curly are coarser than those from Lake Pedder. Though Pedder Pennies are morphologically similar to marine concretions in the Gulf of Finland, they are genetically more similar to the freshwater concretions in Canadian lakes. However, the iron oxide content is very significantly higher in the Pedder Pennies (40-50%) than in the Canadian concretions (15-40%), while the manganese content differs hugely (Pedder 0.03-0.1%, Canada 15-30%). The marine concretions from the Gulf of Finland have a similar composition to the concretions from the Canadian lakes (Tyler 1979). The concretions in Basin Lake in the West Coast Range differ significantly from those at Lake Pedder in being multiple nuclei forms, which is a rare situation in Pedder Pennies.

If Pedder Pennies were biological organisms then the differences between the Canadian and Lake Pedder examples, or between the distinctive concretions from Lake Pedder and those from Basin Lake, would probably be sufficient to warrant the recognition of separate species - species that would then attract general acceptance as appropriate targets for conservation.

The Human Use Level

Conservation significance may also derive from the value of the research results a particular area provides to the world scientific community as a whole, such as the information offered to the debate about environmental change. In this sense, Pedder derives importance from the contributions of Peterson (1969) and Davies (1967). That the Pedder area has not contributed to recent advances in Tasmanian glacial studies stems simply from the fact that the floor of the Serpentine Valley is presently inaccessible. It is axiomatic among geomorphologists that while erosional processes may produce spectacular scenery, it is the sedimentary evidence that offers the principal insight into past events. In glaciated areas each successive glacier commonly modifies or destroys the erosional legacy left by its predecessor, while the sediments deposited downvalley may survive. Just as workers have lamented the loss of access to glacial sediments due to dams in crucial localities in some other Tasmanian valleys (Colhoun 1976, Kiernan 1991c, 1996, Hannan *et al.* 1993), so too are glacial studies at Lake Pedder inhibited while the dams remain filled.

The association of a place with significant persons in the past may also contribute to its significance (AHC 1990). As science progresses, the interpretation of particular features may change. This may increase rather than decrease their worth since they may become important as examples of scientific process (Davey 1989). In such a sense, the Pedder complex derives significance from the association of the luminary of early Tasmanian glacial studies, parliamentarian and lawyer Arndell Lewis, commemorated in the Royal Society's A.N. Lewis Medal:

> "In 1922 (December) I was descending the slopes of Mt Anne, and, looking over the Huon Valley, - whether the evening light or the peculiar configuration of the Frankland Range emphasised the fact I know not - but I was struck with the absolute clearness, on the panorama there unfolded, of the evidence of two distinct and superimposed glaciations, the one responsible for the topography of the Huon Plains, the other disclosed in the tributary valleys leading down from the encircling ranges. The fact of a smaller series of valley glaciers, terminating in piedmont moraines each resting on the oldest glaciated surface of the wide Huon Valley, was too apparent to be missed. With this clear disclosure in the field, I found the key to the task of reconstructing the history of the Pleistocene glaciation in this Island."

The multiglacial model which Lewis subsequently developed, based on erosional morphology, was eventually rejected by later workers. Nevertheless, it dominated Tasmanian glacial studies for decades and influenced overseas interpretations of the palaeo-environmental history both of Tasmania and of southern temperate latitudes more generally (Lewis 1945, Flint 1957).

Summary: The Geoconservation Significance of Lake Pedder

The main grounds for which one might assert that Lake Pedder is of scientific significance may be categorised similarly to the system adopted by Davey (1989) to define the scientific value the Australian Alps.

First, Lake Pedder and its environs is a storehouse of evidence about environmental phenomena and processes. It is a resource that enables reconstruction of palaeoenvironments (and hence a capacity to understand the present and to predict and model the future) with respect to environmental disturbance and response to perturbations. It offers evidence about the origins and relationships of biota, habitats and landforms. It contributes to defining the characteristics of a region. It contributes to the explanation or analysis of wider phenomena.

Second, such special places as the Alps or Lake Pedder and its environs exhibit remarkable differences (intra-continental, inter-regional, hemispheric) of their locality from their analogues elsewhere, but also similarities in the face of other differences.

Third, Lake Pedder, like the Australian Alps, is of scientific significance through being the focus of cultural value relating to the role of individual places in the development of science (including its controversies). The landform complex of which Lake Pedder forms part has played a major role in developing the understanding of Tasmanian glacial environments, palaeoglaciology, and glacial landscape evolution.

The assessment criteria for Natural Properties adopted by the World Heritage Bureau recognise:

- outstanding sites that represent the evolutionary history of the earth including significant geomorphic or physiographic features;
- superlative natural phenomena; and
- habitat of threatened species of outstanding universal value.

On the basis of its geomorphological values alone, Lake Pedder would seem to meet at least the first two World Heritage criteria.

Integrity

The integrity provisions contained within the Operational Guidelines issued by the World Heritage Bureau (UNESCO 1984, 1987) also warrant some comment with respect to Lake

Pedder. From a geomorphological perspective alone, the integrity requirement cannot properly be met for the Tasmanian World Heritage Area for as long as Lake Pedder remains inundated and at risk of ultimate disintegration beneath the Huon-Serpentine Impoundment. The integrity conditions demand that "the sites...should contain all or most of the key inter-related and inter-dependent elements in their natural relationships; for example, an "ice age" area would be expected to include the snowfield, the glacier itself and samples of cutting patterns, deposition and colonisation (striations, moraines, pioneer stages of plant succession etc.)" (UNESCO 1987). Deglaciation is complete in the Lake Pedder area, and hence the set of features that would be required to meet the integrity conditions consists primarily of landforms rather than including active ice masses. In the case of Lake Pedder, the vast majority of the area of glaciofluvial deposition is presently beneath the Huon-Serpentine Impoundment, which probably also covers extensive areas of till. The integrity condition with respect to the glacial system is clearly not met.

The area of the Huon-Serpentine Impoundment itself was included by the World Heritage Bureau in the Tasmanian World Heritage Area in the express hope that the natural environment might be restored. However, an area need not even actually be registered on the World Heritage List to demand protection by the Commonwealth Government since Commonwealth legislation demands protection of areas of World Heritage calibre. That Lake Pedder is a place of World Heritage calibre is beyond question. That assessment can soundly be based solely on the geomorphological value of this remarkable place, quite apart from the value Lake Pedder has to other disciplines or to non-scientists.

CONCLUSIONS: A SINGULAR LANDFORM WITHIN A SINGULAR GEOMORPHIC COMMUNITY

What geomorphological phenomena are present at Lake Pedder? At the simplest level, Pedder is a glacial lake, formed by glacigenic sediment shed from the Frankland Range into the valley of the Serpentine River, impeding its flow and causing ponding in the upper valley. It is a time transgressive, possibly multiphase, landform. The extent of the glaciers that first formed Lake Pedder, the relative importance to its initial formation of glacial and glaciofluvial sedimentation, and the antiquity of the first Lake Pedder, all remain unclear. What is certain is that Pedder has no parallel in Australia or New Zealand. Although the glacial legacy of southern temperate latitudes in South America is not fully documented, no genetically similar lake on a similar scale has been documented. Hence Pedder is probably unique in the Southern Hemisphere at least. Nor does there appear to be any other geological, topographic and palaeoclimatic setting where a counterpart of Lake Pedder, with its bed and beach of fine quartzite sand, could have evolved.

But Lake Pedder is more than just a singular landform. Pedder would not have formed but for the particular pattern of glaciation in the area, that pattern being directly determined, in turn, by the preglacial topography and by the geological structures that gave rise to it. The subsequent evolution of Lake Pedder involved a range of interacting and interdependent processes: the supply of sediment and flow regime of the Serpentine River and the evolution of an outlet that limited discharge from the lake; the evolution of striking bedforms in response to lacustrine water circulation; evolution of the aeolian landforms, tied closely to the exposure of the bar in response to discharge from the lake basin via the Serpentine, coupled with evaporative loss. More distant from Lake Pedder, but nevertheless a very distinctive feature partly drowned by the same Huon-Serpentine dams, is the ancient but recently active Lake Edgar Fault, and its fault scarp; all add to the geodiversity of the general area.

Lake Pedder is more than simply an important and unique landform site, it is a place of extraordinary complexity of interdependent processes. Living species cannot properly be understood individually and out of context with the biological community within which they have evolved. Nor can they be isolated from their physical environment if their conservation or management requirements are to be addressed adequately. Similarly, the protection of landform "species" demands that regard be paid to the wider landform "community" of which they form part. Lake Pedder forms part of a wider genetically-related landform community that comprises the surrounding mountains, and the glacial cirques, troughs, valley steps, moraines, till deposits, meltwater channels, glaciofluvial aprons and other cold climate landforms. In its broadest form, Lake Pedder is a fossil feature, the product of geomorphic processes that are no longer at play. In its detail, however, much of the Lake Pedder that was submerged by the Huon and Serpentine dams is the product of postglacial processes, that is, the processes that produced the fluvial landforms, the lacustrine bedforms, the dunes and other aeolian landforms, are essentially the product of conditions that persist in the area today. Should the dams be drained, they would again be active just as they were after the proto - Lake Pedder first formed.

While biodiversity may be a current buzz-word, the maintenance of geodiversity is just as fundamental to the conservation of environmental diversity and to any concept of nature conservation or sustainable development. The basic tenets of landform conservation are now well established at a national and state level. Lake Pedder is one of a kind, with no replicate at least in the southern hemisphere and probably on a global scale. It can therefore be likened to a biological species of which only one specimen exists. This sort of extreme rarity is commonly the stimulus to recovery programs where animal or plant species are concerned. It is just as appropriate for similar initiatives to be taken where landform species are involved.

On any rational, scientific and systematic assessment of landform significance such as those currently employed by various planning and management agencies in Australia (e.g., Rosengren & Peterson 1989, Kiernan 1990c, Sharples 1993, 1995), Lake Pedder could not help but be recognised as a quite outstanding feature that warrants the very highest level of protective management. Indeed, the geomorphological importance is such that I believe it would be professionally negligent not to advocate the recognition and management of Lake Pedder as a site of quite exceptional scientific value.

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