THE GEOMORPHOLOGY OF THE PERTH REGION, WESTERN AUSTRALIA

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ABSTRACT

An overview of the geomorphology of the wider Perth region is presented in the context of issues relevant to geotechnical engineering. The region is divided into the erosional terrains of the Darling Scarp and the Cenozoic depositional landforms of the coastal plain. Attention is drawn to claims of possible neotectonic activity associated with the Darling Fault, and the likely geomorphological expression of recent events. The soil, geomorphological and stratigraphic divisions of the Cenozoic coastal deposits are discussed, and the importance of the Tamala Limestone is stressed. The stratigraphic and geomorphological details of the coastal sequences are provided and evaluated in the context of global Late Cenozoic sea-level events. The alluvial deposits of the coastal plain are described and an overview of the controls on deposition and the resultant alluvial architecture is provided. The stratigraphic architecture of both the coastal and alluvial deposits has important implications for hydrogeology and contaminant movement. In closing, the paper draws attention to specific geomorphological events and processes of direct relevance to geotechnical engineering, which may not have received sufficient attention.

1 INTRODUCTION

The major elements of the geomorphological framework of the Perth region are relatively straightforward and well known. Less known are the details of the processes that are active in the various geomorphological settings and the likely significance that these processes, and more general geomorphological considerations, may hold for geotechnical engineering.

The regional-scale geomorphology of the Perth region is dominated by the Darling Fault and its associated escarpment that bounds the eastern margin of the Perth Basin and delimits the depositional coastal and alluvial terrains which constitute the coastal plain, from the deeply weathered and erosional landscapes of the Yilgarn Craton. Of interest are: (i) the morphotectonics of the Darling Fault and the related geomorphological issues that occur in the area of the scarp and (ii) the details of the morphostratigraphy and associated wider considerations of the coastal and fluvial events which constitute the geomorphology of the coastal plain.

In providing an outline of the general geomorphology of the Perth region, the discussion, in part, draws on the geological framework developed by Commander (this volume) and places this into a geomorphological context. The paper first provides an overview of the morphotectonic controls of the regional geomorphology; this is followed by discussion of the details of the geomorphology and surficial geology of the coastal plain; a final section of the papers outlines selected aspects of process geomorphology. Figures common with other papers in this volume are indicated in the text as ‘Key Figure’.

2 THE MORPHOTECTONICS OF THE PERTH REGION

The Perth region provides a very distinctive morphotectonic setting, with the geomorphology of the coastal plain providing a sharp contrast to the Darling Plateau. The escarpment that forms the margin between the two is a direct reflection of the Darling Fault that separates the largely erosional and deeply weathered terrains of the Yilgarn Craton from the Late Cenozoic depositional environments of the Perth Basin. The Darling Fault is the major morphotectonics feature of the western margin of the Australian continent and extends for some 1000 km along strike. It is a planar normal fault that has a long and complex history, extending back some 2.5 Ga (Harris, 1994; Middleton et al., 1993). It is likely that the proto-Darling Fault formed a plate/terrane boundary involving significant strike-slip movement (Dentith et al., 1993). In the immediate Perth region the complex structural geology which accompanies the Darling Fault (Playford et al., 1976) has no topographic/geomorphological expression – with the escarpment having retreated some 2 km from the fault line, due to erosion.

The Phanerozoic uplift history and geomorphological development of the escarpment is incompletely known. An issue is the age of the last significant uplift and whether tectonic activity associated with the fault has extended into the Late

Cenozoic, and if this can be inferred from the geomorphology. It is clear that the Darling Fault was active at various times during the Phanerozoic and most recently during continental break-up in the Early Cretaceous.

It is to be expected that its present geomorphological expression is related to that event. It is difficult to establish the end of significant movement along the Darling Fault. In the offshore parts of the Perth Basin the younger limit of normal faulting is provided by the Neocomian break-up unconformity (Song and Cawood, 2000) and it has been claimed that no major movement of the Darling Fault has occurred since then (Davidson, 1995).

Stratigraphic evidence supports the suggestion that the Darling Scarp existed as a well defined topographic feature during the deposition of the Leederville Fomation. The evidence is provided by ‘granitic’ scree boulders in the Wanneroo Member – Barremian (Davidson, 1995) and from other subsurface information in the Wagerup area. In cores obtained from the Wagerup area, the Cretaceous sediments (Leederville equivalent) are characterised by a series of strongly organic silts and sands indicative of near-shore coastal plain, alluvial and deltaic settings. Coarse sands and clast horizons are conspicuous in parts of the succession. The clasts are largely granite and gneisses and many are unweathered (Figure 1).

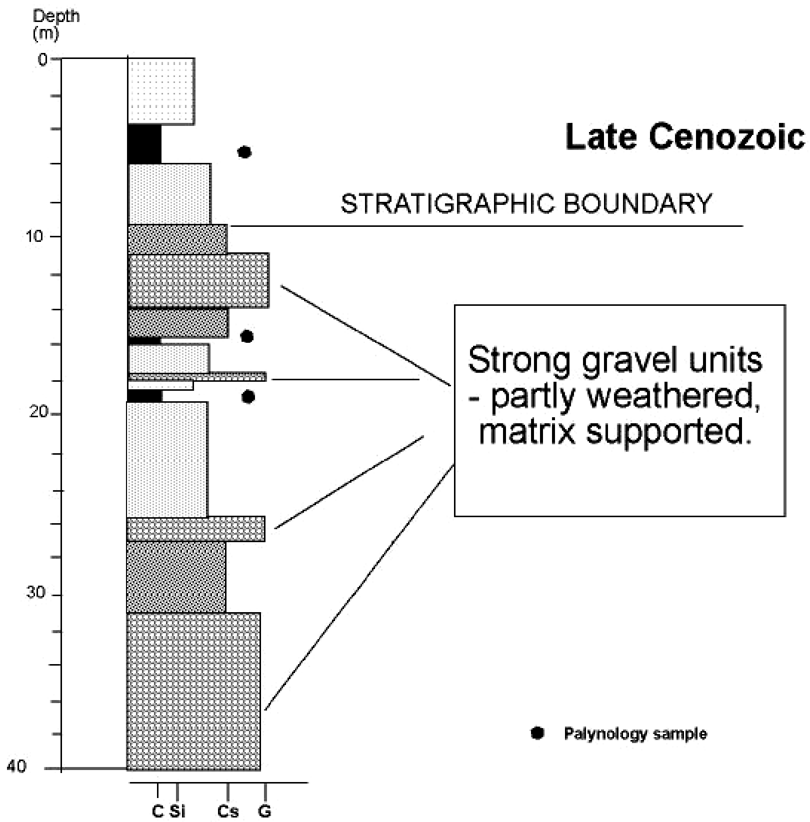

Figure 1: Details of stratigraphic log from the Wagerup area showing the presence of coarse clast units possibly indicative of uplift of the Darling scarp.

An erosional unconformity indicated by a weathering horizon/paleosol marks the top of the Cretaceous. A gneiss-granite gravel unit that partly forms a lag (?) on the erosional unconformity separates the strongly-organic Leederville from the overlying Late Ceonozoic succession. In cores taken in the vicinity of the escarpment the gravels become prominent. In one core the basal 10 m consists of a gravel unit in which clasts are matrix supported and set in coarse sand. Clasts remain prominent in the overlying coarse, green sands. Isolated thin organic-rich units are interbedded with these sands. A strongly weathered profile occurs from approximately 9 m to 17 m. The sediments of the upper c. 9 m are strongly overprinted by a ferricrete profile. The ferricrete has developed in a series of medium sands and associated pale clays. The sediments of the upper c. 10 m of the core are Late Cenozoic in age – possibly Pleistocene.

The absence of palynological material in the lower section of this core, makes the age of these sediments uncertain. It is tentatively proposed that the coarse gravel dominated units of the lower part of the core may postdate the Leederville and correlate with the thin gravel beds common in cores recovered further to the west. In these cores gravel clasts are present on the weathering profile that has developed on the Leederville, but may (?) also be a feature of the upper parts of the Leederville Formation. The gravels indicate that an escarpment existed close to its present location and it seems likely that the gravels reflect an erosional response to regional uplift.

The question of possible significant uplift during the late Cretaceous and Cenozoic is still open. The general claim has been made that only relatively minor movement has continued into the Cenozoic (Playford et al., 1976). There is evidence along various parts of the Darling escarpment of gravel deposits well above present stream courses. A prominent outcrop is associated with the Canning River at Roleystone. The outcrop contains well-rounded clasts that clearly indicate a fluvial environment of deposition (Figure 2). The age of the deposits is not known. The outcrop is restricted but it appears (?) that the deposits are incorporated into the deep weathering profile. Rather than representing uplifted stream gravels, it seems more likely that the deposits record incision of the escarpment after uplift (Commander pers. comm.). If the age of these deposits could be established they would provide some constraints on the timing of uplift events along the Darling escarpment.

Figure 2: Large well rounded gravel clasts in a deeply weathered profile in the Canning Valley at Roleystone - Contour Road.

Playford et al. (1976) summarise the known occurrence of conglomerates, clays and sandstones in valleys cut into the Darling Scarp at localities between Walyunga and the Donnelly River. Because of the location of their type section, the deposits were named the 'Harvey Beds'. The Roleystone deposits could be included in this and they may well be of significance in placing some limits on the age of uplift along the scarp. However, the details of their geomorphological position and sediment characteristics are so poorly known that few conclusions can be drawn.

There have been a number of claims that the Darling Fault has geomorphological attributes that suggest 'recent' uplift. Vening–Meinesz (1948) suggested that the Perth Basin is out of isostatic equilibrium and should be undergoing uplift. This prompted Lambeck (1987) to develop a loading-unloading model coupled with a regional compressive stress field that implies isostatic rebound of the Perth Basin. He suggested that the shore parallel arrangements of the Late Cenozoic marine deposits (see below), which increase in height towards the east, may be the result of uplift. Other evidence for movement along the scarp during the Late Cenozoic comes from the suggestion of 'warping' of some heavy-mineral strandlines (Playford et al., 1976). Furthermore, from directional changes in stream courses Gordon (1972) has claimed that there has been relatively recent movement along the Darling Fault.

Other suggestions that may have some bearing on the issue of tectonic events in the Perth Basin during the Quaternary are the claims of Playford (1988) who invokes tectonic uplift to partly explain Holocene sea-level events at Rottnest Island. Similarly, Semeniuk and Searle (1986a) have argued for Holocene tectonic uplift in the region south of Perth (Rockingham to Bunbury). Of importance in this context is the essentially planar, west sloping unconformity surface at the base of the Late Cenozoic deposits. This would appear to indicate little significant deformation in the last c. 2 Ma (Commander, pers. comm.)

From the evidence that is presently available it is difficult to draw any conclusion as to whether there has been significant movement along the Darling Scarp over Late Cenozoic time-scales. The suggestions are that if there has been any displacement this would have been relatively minor and that the Darling Scarp, as a morphotectonic structure, finds its origin in the Cretaceous, with relatively little change since then.

3 DEVELOPMENT OF THE CENOZOIC SURFICIAL GEOLOGY AND THE ASSOCIATED GEMORPHOLOGICAL TERRAINS

Over Late Mesozoic and Cenozoic time-scales the Swan Coastal Plain has acted as a depositional environment registering: (i) the sediment inputs from the immediate escarpment and adjacent Darling Plateau and (ii) the marine transgressions which have characterised global and regional sea level changes over that time. Consequently, the general geomorphology of the coastal plain of the Perth region is the result of coastal and fluvial depositional events and hence a mirror of the surficial geology. McArthur and Bettenay (1960) outlined the major geomorphological and surficial geological divisions (Key Figure 2 and 3). They related these to the major soil divisions of the Swan Coastal Plain. In the Perth region their scheme recognises the dominance of a series of essentially scarp-parallel soil/geomorphological divisions – the Ridge Hill Shelf, which is the easternmost unit immediately associated with the Darling Scarp, the Bassendean Dunes, the Spearwood Dunes and the Quindalup Dunes located at the present coastline.

The major dune systems separated by McArthur and Bettenay (op. cit.) equate with the geological divisions of the Bassendean Sand, Tamala Limestone (Spearwood Dunes), Becher Sand (see below, Section 3.3) and Safety Bay Sand (Quindalup Dunes). This highlights a limitation of the terminology adopted by McArthur and Bettenay, in that it does not emphasise sufficiently the fundamental difference that exists between the dominantly siliciclastic terrains of the Bassendean Sand and the carbonate lithology and karst terrain characteristics of the Tamala Limestone (Spearwood Dunes). In this respect the adoption of the term Tamala Limestone or Tamala System – a term linking the geomorphology with the distinctive lithology – would have been more useful than Spearwood Dunes. While both the Bassendean and Spearwood systems largely relate to dune topographies (which in parts are strongly degraded), their differences are fundamental and deserve to be emphasised in the terminology adopted.

The Bassendean, Spearwood and Quindalup Dunes are evident over much of the coastal plain of the Perth Basin and constitute a series of former coastal dune and associated marine members that relate to Cenozoic global sea-level fluctuations. The Ridge Hill Shelf has a limited spatial extent and subdued geomorphological expression, with its significance and age least understood. Prider (1948) first documented the occurrence of a ferricreted sand/gravel deposit and named it the Ridge Hill Shelf. The deposit has been interpreted as representing a shoreline of essentially unknown age – although Prider speculated that it may be Cretaceous in age. The Ridge Hill Shelf may have some significance in assessing the uplift history of the Darling Scarp but as no recent work has been undertaken, its present significance remains uncertain

In addition to the major gemorphological divisions striking north–south parallel to the coast, more minor colluvial and alluvial footslope deposits and minor alluvial fills occur in the piedmont zone of the Darling Scarp, with the materials sourced from the immediate area of the scarp. Of fundamental importance in the geology and surficial geology of the Perth region are the extensive areas of alluvial deposition, such as those associated with the Canning and Helena Rivers, and especially those associated with the Swan River. From a geological perspective the alluvial deposits of the Swan River have been seen as constituting the Guildford Formation. In the McArthur and Bettenay scheme these alluvial associations constitute the Pinjarra Plain.

3.1 THE YOGANUP – ASCOT-BASSENDEAN TERRAINS AND FORMATIONS

As Commander (this volume) notes, the erosion of the Mesozoic rocks during the Tertiary created a planar unconformity on which, during the Late Cenozoic, the surficial formations which constitute the geomorphology of the coastal plain, were deposited. The oldest of these are the Pliocene – Pleistocene marine sequences which characterise the eastern margins of the Swan Coastal Plain. These are strongly siliciclastic and are represented by the Yoganup Formation and Bassendean Sand. It is not clear how the two formations relate to each other stratigraphically, with the solution to this problem being hindered by poor exposure and the apparent absence of datable material. In the Perth area the Yoganup Formation occurs in only isolated locations, where the deposits abut the escarpment, giving rise to a gentle, mounded step to the base of the escarpment. The formation becomes a more prominent element of the geomorphology south of Perth. Here it represents a complex of shoreline features, forming a geomorphologically much modified nearshore marine–dune association. The name is derived from the type section at Yoganup, south of Perth. The age of the formation remains unknown and it is not clear how realistic it is to correlate the deposits in the various parts of the Perth Basin. It has to be recognised that the deposits are stratigraphically complex and clearly integrate a number of sea-level events extending over a significant height range.

The potential stratigraphic details and complexities that exist in this formation have been well demonstrated in areas south of Perth where the sediments have been mined for heavy minerals (Baxter, 1977; Collins et al., 1986). It is possible that the Yoganup Formation relates to the sea-level highstands of the early-middle Pliocene, which was a time during which global sea-levels experienced high stands (see summary discussions in PRISM Project Members, 1995 and Kennett, 1995). If this is the case it is noteworthy that the Darling escarpment has shown little modification since that time, with the suggestion of relatively minor scarp retreat. South of Perth the Yoganup Formation appears to give some indication of uplift associated with the Jarrahwood Axis (Cope 1975).

The Bassendean Sand was originally ascribed to the area of remnant dune morphology characterised by siliciclastic sands. It is only in its western parts, in the areas termed the Gnangara Dunes, that the Bassendean still exhibits a dune expression (Bastian, 1996). It was originally thought that these sands had a carbonate origin and that there was a loss of carbonate through time. The view was subsequently revised and it is now generally recognised that the sands had largely a primary siliciclastic origin (Kendrick et al., 1991).

The Bassendean Sand and associated terrain characteristics are associated with its marine equivalent - the Ascot Formation. The Ascot Formation occurs in the shallow subsurface and has been divided into a 'Younger' and 'Older' member with distinctive biostratigraphic signatures. The older Ascot assemblage has a distinct Pliocene affinity, while the younger Ascot indicates an Early Pleistocene age. Kendrick et al. (1991) interpret the Bassendean Sand as representing the regressive dune facies of the Ascot Formation, with some reworking and additions during the later Pleistocene. This interpretation runs counter to the claims that the Bassendean Sand exhibits morphologies of 'star dunes' indicative of a desert aeolian origin with the sediments transported from the east (Semeniuk and Glassford, 1987; Semeniuk and Semeniuk, 2001) The latter interpretation does not appear to accord with the stratigraphic setting and context of the Bassendean terrains. Commander considers (pers. comm.) the claim that the Bassendean Sand can be related to the Ascot Formation as problematic. He views the Bassendean Sand as stratigraphically more closely related to the Guildford Formation.

The sediments and stratigraphy of the Bassendean/Ascot association provides an important consideration for groundwater movement and possible contaminant transport in the shallow subsurface. Work south of Perth (Wyrwoll, unpublished) shows that the Ascot Formation has a complex and variable stratigraphy – even at a very local scale. Because of the marine depositional environment, a general north-south arrangement of the major sediment bodies is to be expected – which in general is the case. In addition, considerable stratigraphic and sediment heterogeneity is also present, and some of this can be related to transgressive/regressive events and associated facies migration but it also results from the presence of likely fluvial members in the succession. Davidson (1995) recognises a similar stratigraphic complexity associated with the Bassendean Sand. This is emphasised by the Gnangara Sand, which occurs only in the subsurface below the Bassendean Sand in much of the central Perth region (Davidson, 1995 – see Key Figure 5). The sediments of the Gnangara Sand are thought to be primarily fluvial in origin with some possible estuarine component.

The apparent straightforward geomorphological expression of the Bassendean Dunes gives a misleading indication of the geomorphological history and associated stratigraphy of the surficial geology of this part of the coastal plain. The Bassendean/Ascot association represents both marine and fluvial geomorphological events. However, even where interpreted as a marine facies, it seems likely that the Ascot Formation is more complex than its recognised division into an "Older' and 'Younger' member. It may well be a register of a complex of transgressive-regressive events. The associated fluvial facies are clearly expressed but are often laterally discontinuous. The stratigraphic architecture has the potential of being spatially quite variable and complex and some way removed from a straightforward layer-cake stratigraphy. It may be better approximated by a combination of the 'Layer Cake' and 'Jigsaw Puzzle' stratigraphic arrangements discussed by Galloway and Sharp (1998a). Whatever the details of the geomorphological history and the resultant stratigraphy of the Bassendean/Ascot association, it is realistic to expect significant variation in the hydraulic attributes of these terrains.

Associated with the Bassendean Sand is a series of shallow lakes that contain organic rich sediments. These lakes have a restricted sediment accumulation when compared with lakes further to the west that are associated with the Tamala Limestone. The lakes located in the Bassendean terrains are prone to drying phases, during which acidification can occur - acidification being due to the oxidation of sulphate minerals associated with the organic sediment accumulations.

3.2 TAMALA LIMESTONE – KARST TERRAINS

Much of the Swan Coastal Plain is characterised by the carbonate terrain associated with the Tamala Limestone. The formation is dominated by dune sequences and subordinate near-shore marine members that are essentially arranged as a number of coastal barrier complexes, divided by groundwater fed lakes. The dunes represent carbonate aeolianites, consisting of generally well sorted, large-scale cross-stratified sands, comprising carbonate grains of marine skeletal material and an associated but variable siliciclastic component. The Tamala Limestone has quite different lithological, diagenetic and weathering characteristics from those usually associated with limestones, and these differences have important repercussions for the geomorphology associated with it.

The Tamala Limestone represents a striking change in sedimentation style from the siliciclastic of the Bassendean Sand to the strong carbonate sediments that continue to be deposited to the present day. The ‘switch’ to carbonate deposition was the single most important event in the Quaternary geomorphological evolution of the Swan Coastal Plain, as it completely changed the direction of the future geomorphological development of the area.

The development of the coastal plain through coastal progradation during the Pliocene–Pleistocene, and the consequent progressive trapping of terrestrial sourced sediment, may in itself have been a factor in changing the style of sedimentation. An alternative explanation for this change in sediment style is that it is a response to higher carbonate productivity in the offshore marine environment, possibly linked with Leeuwin Current activity. There is clear evidence in the molluscan fauna of middle Pleistocene marine units for the onset of higher sea surface temperatures at that time, and this may have prompted increased carbonate productivity (Kendrick et al., 1991). The strong subtropical and tropical affinity of molluscan assemblages is a likely indicator of Leeuwin Current activity. From this evidence an active Leeuwin Current has been inferred for the Middle Pleistocene. Similarly, the weak presence of subtropical and tropical elements in the older Plio-Pleistocene units has been taken to indicate that the Leeuwin Current was not active, or of lesser importance at that time. It seems possible that the events that ultimately resulted in a very distinctive change in the geomorphological development of the Swan Coastal Plain were in part driven by large scale oceanographic changes.

Strong carbonate deposition continued throughout the Middle-Late Quaternary (Hewgill et al., 1983; Murray-Wallace and Kimber, 1989; Price et al., 2001) with large volumes of marine and dune sediments deposited during that time. Prominent in the geomorphology of the western part of the Swan Coastal Plain are depositional sequences of the Last Interglacial. The associated sea-level high-stand is thought to have lasted along the Western Australian coast from c. 130 000 to 117 000 years ago (Zhu et al., 1993). During this time sea-level reached a height of the order of +4 m above its present position. The Last Interglacial deposits dominate much of the immediate coastal areas of the Perth region. The marine members associated with the Last Interglacial sea-level high are well exposed in the lower part of the Swan Estuary and are especially prominent at Minim Cove. On Rottnest Island the corresponding Last Interglacial unit constitutes Fairbridge Bluff (Szabo, 1979), where a strong coral unit is suggestive of a more active Leeuwin Current at that time.

The Tamala Limestone forms a series of ‘belts’ essentially paralleling the present coast. These represent a series of former coastal barriers, related to respective marine transgressions, separated by inter-barrier areas, which in part are occupied by lakes. However, the details are much more complex than a simple barrier structure and the overlapping structure of successive units makes it difficult to separate the geomorphology into distinct barrier forms.

Bastian (1996) undertook a comprehensive study of the heavy mineral assemblages and their weathering characteristics to establish the age structure of the dune expression of the Tamala Limestone. His work is a major contribution which clarified the geomorphological succession of events (Figure 3). He divided the Tamala Limestone into five dune belts – the Trigg, Karrinyup, Gwelup, Balcatta and Yokine dunes. In addition, he distinguished the Gnangara dunes – which mark the western margins of the Bassendean Sand and, unlike much of the rest of the Bassendean, has retained a dune-form expression. The various geomorphological divisions cannot be recognised everywhere in the Perth region due to the complexities of barrier structure and associated dune morphologies and the on-lapping stratigraphic relationships.

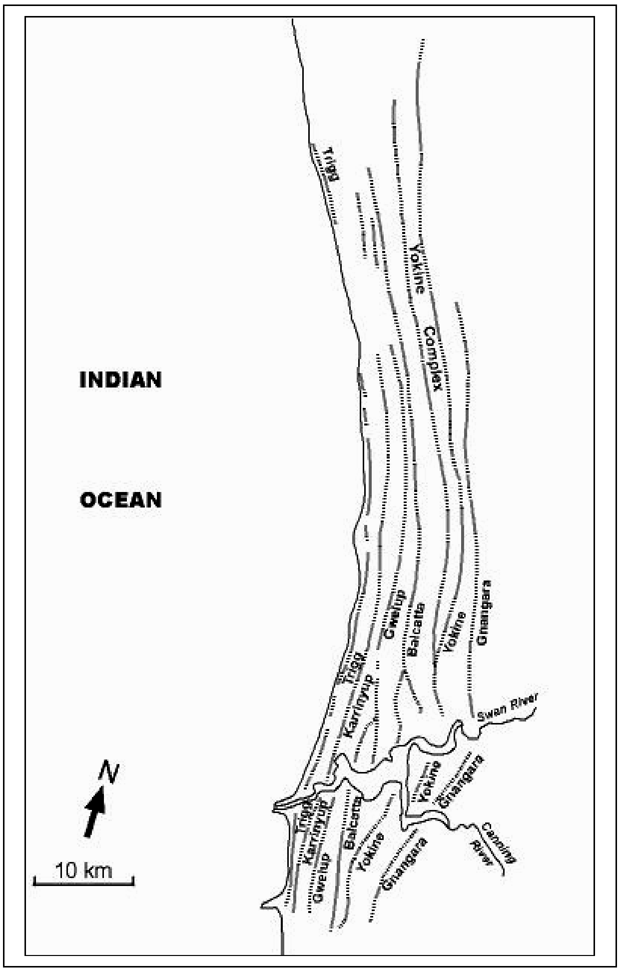

Figure 3: Barrier Complex morphostratigraphy of the Tamala Limestone and western margins of the Bassendean Sand (after Tapsell et al., 2003).

It is still not possible to provide an absolute chronology for all the major Pleistocene dune building events in the Perth region. The general stratigraphic position and their relationship with marine members suggest that the Trigg Dunes relate in parts, to the sea-level high events of the Last Interglacial. In addition, from global sea-level considerations and some preliminary dates (Price at al., 2001), this association also contains later dune additions related to sea-level stands during the last 100 000 years. In attributing the Karrinyup Dunes to an earlier interglacial at c. 240 000 years ago, Bastian follows the suggestion of Kendrick et al. (1991). The older dune units must similarly relate to other Pleistocene high sea-level events. It would seem likely from Bastian's results that the Tamala Limestone may prove to contain a more comprehensive record of Pleistocene sea-level events than previously envisaged (c.f. Kendrick et al., 1991)

The weathering of the Tamala Limestone has given rise to the characteristic karst expression of these terrains. In its surface expression the degree of karst development is related to the age of the host unit. However, the degree of dissolution is also related to position in the landscape and associated hydrological controls. Pinnacle forms are the most striking surface karst forms and are evident throughout much of the Perth area. Their prominence and degree of development increases to the east – reflecting an age zonation. Associated with this is a siliciclastic yellow sand cover in which these pinnacles are often set. As with the pinnacle arrangement, the yellow sands become aerially more pervasive and prominent away from the coast. On slopes vegetation plays an important role in stabilising the yellow sand 'cover' and when removed can trigger a hillslope response, as recently demonstrated by the slope failure at King's Park (Figure 4).

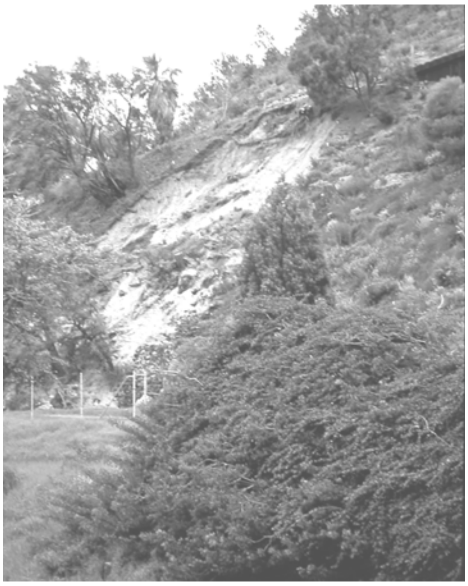

Figure 4: Shallow slope failure in yellow sand over Tamala Limestone at Kings Park.

The yellow sand constitutes the Spearwood association of McArthur and Bettenay (1960). They considered the sands to be a weathering product of the Tamala Limestone – which follows the earlier conclusion of Prider (1948). In a series of papers (e.g. Glassford and Killigrew, 1976; Semeniuk and Glassford, 1987) the suggestion has been made that the sand is an aeolian sediment associated with an extension of the arid zone into the coastal regions. This proposal has never attempted to address the objections that have been raised in the literature (Lowry, 1977; Wyrwoll and King, 1984; Kendrick et al., 1991). The early criticisms have been considerably strengthened by the more recent findings of Bastian (1996) and Tapsell et al. (2003) and it is difficult to see how the view of a desert aeolian origin for the yellow sands can be sustained.

The details of the karst geomorphology for the Perth region have been poorly documented in the available literature – except as a landform/landscape feature. It is clear that in the Perth region karst development is extensive, variable and of considerable importance in the engineering and the wider environmental issues that it poses. Atkinson (1986) and Ford and Williams (1989) provide good overviews of the engineering and hydrological problems associated with karst terrains. A systematic evaluation of these issues for the Perth region are not available in the ‘open’ scientific literature. In many ways this is surprising given the importance that has been placed on groundwater resources and contaminant migration in shallow aquifers. It would be helpful if such work was available, as it would overcome the need for individual firms/consultancies to address these issues in an on-going piecemeal fashion.

The modelling of contaminants transport in groundwater in the Tamala Limestone would need to take note of the hydraulics of flow through karst conduits and fissures (Figure 5). Their degree of development and network arrangements would be related to the age of the unit. Consequently, given the age structure of the Tamala Limestone and its variable weathering/dissolution characteristics, considerable variation can be expected. In explaining these characteristics some attention may need to be given to the likely influence that climate and sea-level changes have had on karst development and structure. Given the Ghyben-Herzberg relationship, that describes the position of the saltwater-freshwater interface, and the controls that the vadose/phreatic boundary and fresh water–salt water interface have on karst formation, past changes in sea-level can be an important consideration for some groundwater/contaminant studies in explaining the nature of hydraulic pathways (Ford and Willams, 1989). At present our understanding of climate change in southwestern Australia over Quaternary time-scales is too limited (Pickett, 1997; Wyrwoll et al., 2000) to evaluate the likely impact that this may have had on karst development.

Figure 5: Dissolution fabrics in a core section (depth of c. 37 m) of Tamala Limestone - Middle Pleistocene.

3.3 HOLOCENE COASTAL UNITS

The immediate coastal zone of the Perth region is comprised of a series of dunes and shore line features associated with the most recent marine transgression, during which sea-level along the coast of Western Australia increased from some –130 m at circa 20 000 years ago to a sea-level high of some +2 m which occurred at c. 6 000 years ago –Figure 6 (Eisenhauer et al., 1993; Wyrwoll et al., 1995).

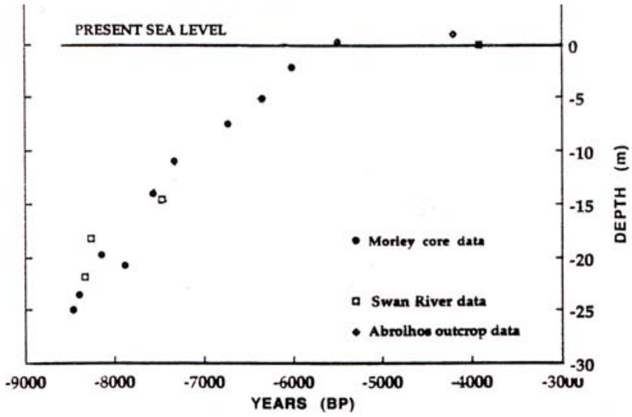

Figure 6: Sea level along the Western Australian coast over the last 9000 years (after Wyrwoll et al., 1995).

Of the more recent work, the most comprehensive reconstruction of the late Holocene sea-level history in the Perth region comes from Searle and Woods (1986). Their record was obtained from the Rockingham area where a prograding beach ridge plain provides the opportunity of a relatively complete record of sea-level history over the last c. 6 500 14-C years. When this record is combined with other data from the region (see Wyrwoll et al., 1995) a sea-level record emerges which shows that sea-level was still significantly below –25 m by 10 000 years ago. It must have reached a height of at least –20m by c. 8 000 14-C years ago. It has been generally thought that after reaching its maximum height of c. +2 m at c. 6000 years ago, there has been a progressive fall of sea-level to its present position. The changes in sea-level since the Holocene highstand have been related to hydro-isostatic adjustment (Lambeck and Nakada, 1990). Claims that there may be a tectonic element in the record (Playford, 1988; Semeniuk and Searle, 1986) have proven difficult to substantiate. However, it is clear from the known record of Holocene sea-level events along the Western Australian coast that the hydro-isostatic model which has been proposed (Lambeck and Nakada, 1990) appears not to coincide with the field evidence (Wyrwoll et al., 1995) in the regions south of Perth, and this may well relate to a tectonic imprint.

The geomorphology associated with the Holocene transgression is characterised by extensive tracts of rocky coastlines, with interspersed pocket beaches, some accretional areas and associated coastal dunes. A great deal of general descriptive material is available which provides a guide to the Holocene coastal geomorphology, but what is largely missing is a comprehensive outline of the dynamics of the present coastal zone.

The Holocene dune sequences encompass the Quindalup Dunes of McArthur and Bettenay (1960). While much has changed as the result of urban development since they provided their guide, the dunes remain as basic elements of the coastal geomorphology of the Perth region. The Safety Bay Sand of Passmore (1967) has traditionally been equated to the Quindalup Dunes (see Playford et al., 1976). The Safety Bay Sand, as originally defined, is a carbonate dominant sand of both marine and eolian origin. Semeniuk and Searle (1985) have divided the Safety Bay Sand into: (i): the Becher Sand – an association of near-shore marine sands and (ii) Safety Bay Sand (Passmore 1967, 1970) – largely aeolian (equivalent to the Quindalup Dunes – see Davidson, 1995). The Becher Sand attains a thickness of the order of c. 20 m, and consists of loose sands exhibiting high permeabilities. The unit overlies the Tamala Limestone with the unconformity marked by a distinct hydraulic boundary. The Becher Sand is clearly an important element in the hydrogeology of the area and is of significance in understanding the potential of infiltration and transmission of contaminants associated with industrial activity.

Significant Holocene prograding and accretionary coastal elements in the Rockingham beach ridge plain have been extensively described and dated. The plain extends over some 10 km and since first described is now extensively covered by residential development. The Whitford Cusp provides an additional example of an accretional element in the coastal geomorphology (Semeniuk and Searle, 1986). It represents a cuspate foreland consisting of a complex of beachridges and dunes and has formed in the lee of an island-rocky reef area.

3.4 ALLUVIAL TERRAINS – THE GUILFORD FORMATION

There has been extensive alluvial deposition associated with the larger streams which exit the Darling Scarp. The alluvial sediments have been taken to constitute the Guildford Formation. McArthur and Bettenay have incorporated these areas into their Pinjarra Plain division. The dominant alluvial bodies are associated with the Swan, Helena, Serpentine and Canning Rivers. The smaller streams emanating from drainage basins set in the immediate area of the Darling escarpment also exhibit significant alluvial accumulations.

The Swan River exits the Darling Scarp through an incised and confined valley. Downstream of this it develops a broad alluvial plain with well defined terrace forms (Aurousseau and Budge, 1921 – also Figure 7). Given the change in slope and the opportunity for channel adjustment in this area, alluvial deposition is to be expected. The lack of confinements promotes channel migration and hence widespread deposition. This depositional pattern can be described through a simple random walk model (Wyrwoll, 1988) and the broad alluvial zone of deposition which can give rise to a complex stratigraphy and alluvial architecture.

Little is known of the alluvial stratigraphy of the Swan River deposits or the age structure of the alluvial sequences. The possible relationship between the alluvial build-up and baselevel changes or variations in the sediment load/transport capacity of the river, which may have controlled the aggradation – degradation events, remains unknown. One of the few published numerical dates on alluvial deposits comes from the Upper Swan archaeological site where an age of 38 000 14-C years has been obtained from an alluvial fill forming the surface of a terrace (Pearce and Barbetti, 1981). As the 14-C date obtained lies at the upper limit of detection a thermoluminescence date was also obtained for the terrace-fill (Wyrwoll, unpublished), which essentially confirms the 14-C date.

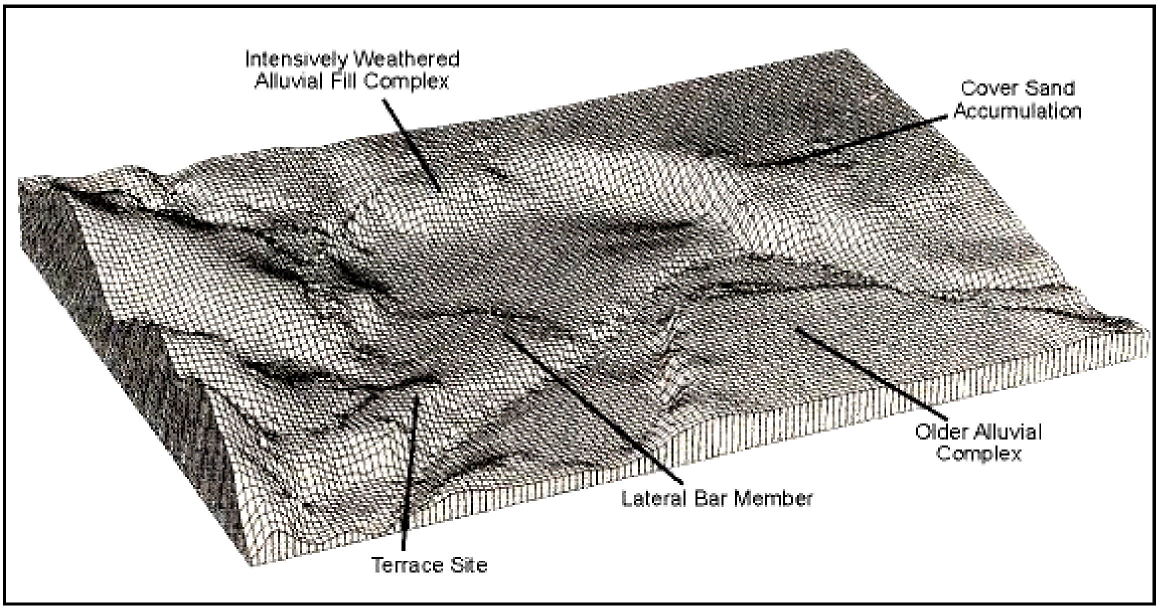

Figure 7: The relief expression of the terrace fills of the Upper Swan area (after Wyrwoll, 1988).

The complexity that is a feature of the alluvial architecture was displayed in a large clay-pit in the immediate area where the Swan enters the coastal plain. In this area the alluvial build-up is expressed topographically as two terrace forms. This simple structure is misleading and hides the complex details of the alluvial stratigraphy. In the excavation five major sediment bodies were evident (Figure 8). They consisted of a heavily weathered unit at the base with a number of overlying and cross-cutting channel fills. The basal unit has been strongly altered and has a dominant 'clay texture', but from general variations in the sediments' characteristics it is evident that the unit is a composite arrangement of channel and overbank bodies that have been strongly altered, making further division difficult. The overlying units show considerable variation in texture and, combined with their general architecture, give the units a range of hydraulic characteristics, aquifer potential and a defined flow anisotropy at the alluvial architecture scale.

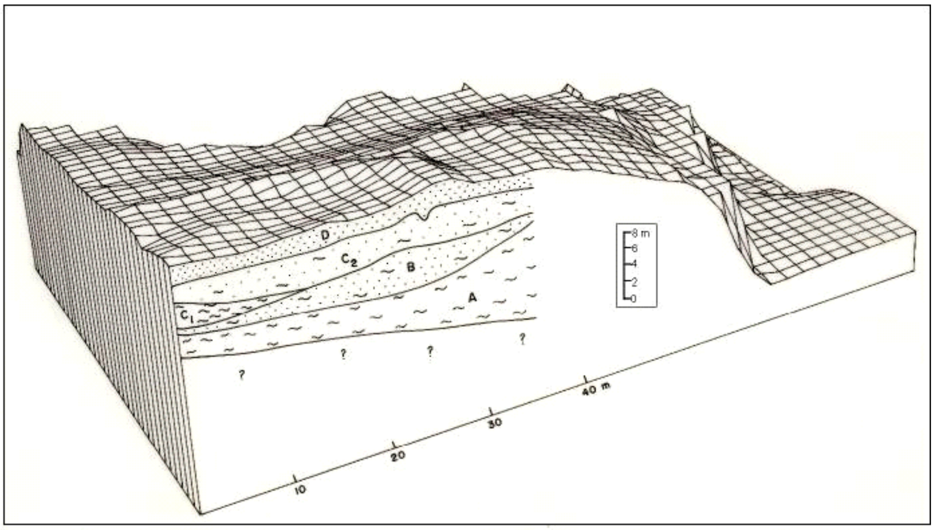

Figure 8: Stratigraphic detail of the 'Older Alluvial Complex' of the Swan River in the Millendon area (after Wyrwoll 1988).

Similar stratigraphic complexities can be expected throughout the alluvial sequences, with estuarine components becoming prominent downstream. The anticipated stratigraphic complexity is important in understanding shallow groundwater potential and movement and for predicting contaminant movement. Galloway and Sharp (1998) provide a guide to likely alluvial architectures of different stream types and outline the associated fluvial aquifer characteristics. Because of the strong contrast in systems of permeable, transmissive facies (channel fill) and confining facies (flood basin), flow patterns are controlled by channel-belt connectivity. There are at present no stratigraphic data for the Swan River alluvial deposits which could be used to address this issue.

An additional consideration in determining the hydraulic characteristics and pathways of the alluvial sediments is the influence that syn- and post-depositional alteration processes can have. In this respect the occurrence of paleosols or groundwater alterations associated with redox–front migration, reflected in part in groundwater ferricretes, or the strong alteration and weathering of sediments to give rise to neoformed clays, are important considerations.

4 GEOMORPHOLOGICAL PROCESS CONSIDERATIONS AND ENGINEERING GEOMORPHOLOGY ISSUES

While information is available on the geomorphological framework of the Perth region the details of the geomorphological processes are largely lacking. Three issues are highlighted:

(i) Hillslope processes of the Darling Scarp

The regolith cover over the escarpment is quite variable with both transport and weathering–limited settings prominent. Deeply weathered profiles with strong duricrust development are a feature of parts of the escarpment. Variations in regolith characteristics are tied to bedrock differences, with the role of dolerites being prominent. In terms of their engineering implications there are two significant issues: (i) identifying areas of potential hillslope failure and (ii) hazards posed by runoff processes. In some areas of the scarp, hillslope mass failure has occurred and other areas affected by failure must exist. Failure has occurred in areas of thick regolith development. Rates of weathering and regolith development are greatest in areas of convergent groundwater flow, such as slope embayments or small valley heads. In such slope positions a transport limited erosional regime is established, with regolith thicknesses considerably greater than on other slope settings. The development of a thick regolith cover coupled with convergent groundwater flow makes such slope embayments/valley head locations conducive to the development of high pore water pressures. These factors combined can create conditions suitable for slope mass failure – and especially so, if associated with mafic lithologies which have higher weathering potentials and yield smectites on weathering (Figure 9).

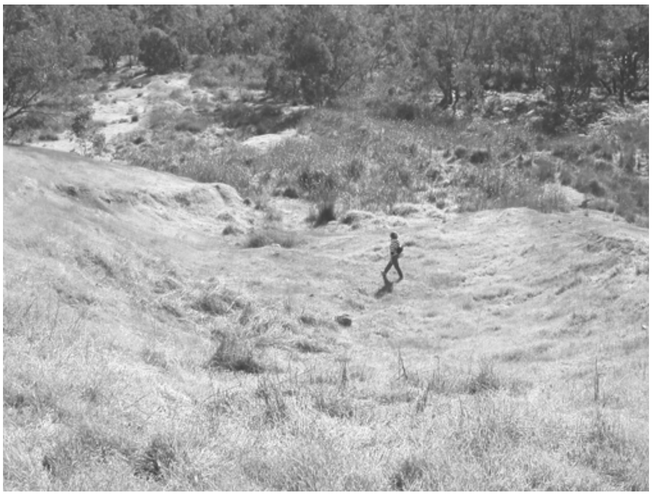

Figure 9: Shallow rotational slide at the margins of a large debris flow - Canning Valley, Roleystone.

While some slope failures have been identified on the 1: 50 000 Environmental Geology Series (Geological Survey of Western Australia, 1984), there has been no attempt to systematically identify areas along the Darling Scarp which may be susceptible to hillslope failure. This may not be an issue for many areas in the scarp, but, where it does occur, it can potentially pose a significant problem. An example of an area where hillslopes have undergone failure and where adjacent hillslopes may be susceptible to failure occurs in the lower Canning Valley at Roleystone. Here complex rotational-flow failure has occurred, with the failed mass extending for some distance down slope. In this case buildings are not affected but there may well be other instances where hillslope failure, whether potential or even after the event, if not recognised, can lead to serious consequences. In the Gingin area, which lies well north of Perth, the outcrops of Cretaceous sediments in this area have undergone very extensive hillslope failure, with other areas also susceptible to failure. With further residential development in this region the extent of the area affected needs to be identified and the potential hazard posed assessed - outcrops of Cretaceous sediments occur to the south of Bullsbrook (Wilde and Low, 1978).

Associated with the issues of potential hillslope failure is the role of vegetation. The relationship between vegetation and slope stability has long been recognised (Kuruppuarachchi and Wyrwoll, 1992, provide a Western Australian example). Its role centres on both hydrological (infiltration, pore water pressures) and mechanical (e.g. surcharge and reinforcement) mechanisms (Greenway, 1987). These considerations have been incorporated in routine slope stability models (e.g. LISA , see Hammond et al., 1992). Given the vegetation cover that is present over the areas of the Darling Scarp, vegetation clearing and its likely affect on slope stability is an obvious consideration. The issue is clearly demonstrated by the occurrence of extensive areas of hillslope failure in the Harvey region south of Perth, which is directly linked to vegetation clearing (Wyrwoll, unpublished).

Hillslope stability assessment is part of a wider geomorphological hazard assessment that needs to be undertaken for areas in the Darling Scarp. An additional problem is posed by runoff events and the capacity of stream networks in the context of land use changes. An understanding of the magnitude and frequency of precipitation-runoff events is required. This issue was highlighted by a precipitation event which occurred on February 8 and 9, 1992. For parts of the wider Perth region the storm provides the highest rainfall on record for durations between 3 and 24 hours (Davies and Ruprecht, 1996). During this event some 150 mm of rain fell in 24 hours in the Roleystone area (Davies and Associates, 1992), generating large volumes of runoff and leading to small streams experiencing discharges greatly in excess of bankfull. The result was that extensive erosional damage occurred in the area. For both the 24 hour and 72 hour precipitation duration, the event is thought to have an annual recurrence interval of in excess of 100 years. However, given the limited length of the rainfall record, any recurrence estimate has to be treated with caution. Little is known of the relationship that exists in the Darling Scarp between runoff events, the likely hazards these pose and the magnitude of precipitation events. It seems likely that events with a recurrence interval higher than those of February 1992 are capable of having a significant geomorphological impact. That this may be the case is suggested by clast sizes in some low order streams in the Roleystone area, which appear to point to discharges well in excess of 'average' events, as being quite regular in occurrence.

(ii) Fluvial Geomorphology of the Swan River and extreme floods

In the context of its present geomorphological function and hydrology, the Swan River offers the potential opportunity to establish the magnitude of extreme discharge events. While 'average' flood levels have been relatively well defined along the Swan River, no attention has been given to establishing the possibility and magnitude of extreme floods.

Paleoflood studies have become prominent elements of fluvial geomorphology and their use in establishing the possibility of extreme events has become a routine design tool (see for example the recent compilation of work by House et al. (2001). The basic geomorphological requirement for this work is a confined bedrock canyon/gorge setting, so that stage increases can be ascertained from deposits located along the valley sides and in tributary junctions. These so called ‘slack water’ deposits are dated using 14-C techniques, or possibly other short lived isotopes such as 210-Pb. Of the 14-C techniques, the now standard accelerator mass spectrometer method requires small amounts of material and has the potential of providing high resolution ages. The confined nature of the Swan River in the area of the Darling Scarp would appear to offer the possibility of using this approach to reconstruct and establish the magnitude of extreme flood events.

The other element of the fluvial geomorphology of the Swan River that requires consideration is the sediment transport regime. The available suspended sediment data are not suitable for developing a suspended sediment rating curve, so estimates of loads cannot be derived. It is commonly thought that the agricultural region of the Swan-Avon is the major source of suspended sediment, but it may be the case that a major supply of suspended sediment is provided by the high relief and dissected terrain between Toodyay and Perth. A related, but more long-term question, is whether the large volumes of bedload that were liberated by past channel ‘training’ in the Toodyay area will eventually be injected into the upper reaches of the Swan Estuary. So far, the sediment ‘slugs’ have led only to aggradation of channel reaches and the infilling of former channel pools downstream from Toodyay.

(iii) Issues of coastal stability

The coastal zone issues relate to sediments and the coastal sediment transport regime. The Perth region represents a micro-tidal (maximum spring tide range 0.6m), wave-dominated coastline. The offshore, now drowned former coastal barriers, represented by the Garden Island Ridge and Five Fathom Bank, greatly attenuate the offshore wave and energy conditions. Summer sea-breeze activity and the passage of winter frontal systems are the main drivers of near-shore processes (Eliot and Clarke, 1986). A major control of sediment transport paths and beach accretion/erosion are the engineering structures present along the coast. Of these, the North Mole breakwater and associated harbour facilities are the most prominent and are also the most effective in interrupting littoral drift. But even smaller groyne structures, such as at City-Floreat beach, influence sediment transport paths and pose problems. An early study by Silvester (1961) proposed a general north (summer) - south (winter) reversal in the near-shore sediment transport paths with a general northerly resultant. This inference has been questioned by Masselink and Pattiaratchi (2001).

Clarke and Eliot (1983) demonstrated a seasonal cycle in beach width at Scarborough, amounting to some 10 m, with maximum beach width occurring at the end of summer and minimum width attained at the end of winter. However, it has been claimed that this annual cycle is not a consistent feature of all beaches and a more complex accretion/erosion pattern applies (Masselink and Pattiaratchi, 2001), with different parts of the Perth coastline exhibiting distinctive seasonal changes in beach width. But it needs to be noted that the study of Masselink and Pattiaratchi, only extended over the period November 1995 to October 1997, while that of Clark and Eliot encompassed a period of 16 years. Hence, the shorter study could simply be seen as capturing the inevitable ‘noise’ that would be a feature of any long-term time series.

Eliot and Clarke (1986) describe the impact of a winter frontal system on near-shore processes and the resultant beach morphology. Their work emphasises the fundamental role that such synoptic events play in issues of coastal stability. The frequency and magnitude of frontal systems are clearly an important consideration in understanding coastal morphodynamics. Given the changes which have occurred in the synoptic climatology of southwestern Australia over the last c. 30 years – with a general decrease in winter storms (Indian Ocean Climate Initiative, 2002) - it may well be that issues of coastal stability and change have been quite different from those of the earlier part of the last century. It follows that anticipated future climatic conditions will impact on coastal processes, especially when linked to global-scale considerations of future sea-level changes.

Associated with questions of coastal change are questions of dune stability and management but, while this is an issue, the understanding of eolian processes is now so advanced that the management of such issues is relatively straightforward. The difficulties which exist in adopting the necessary strategies are those of available resources and societal acceptance and compliance.

5 CONCLUDING COMMENTS

The general geomorphology of the Perth region is relatively straightforward but it is difficult to decipher the details of the geomorphology as much of the necessary evidence is in the subsurface and not easily accessible. The general absence of absolute age control for many of the events makes any discussion of the geomorphological evolution of the Perth region incomplete. Some of the more immediate outstanding problems of importance for engineering considerations are:

(i) Possible seismicity associated with the Darling Fault, which remains an open question. There is more scope for study of the geomorphology to establish whether claims of relatively recent activity along the fault can be substantiated. It is clear that this issue requires a systematic evaluation of the available geomorphological evidence and that it should be undertaken at a regional scale with defined study sections along the entire fault structure. The recent summaries by McCalpin (1996) and Burbank and Anderson (2001) outline the directions such a study should follow and the evidence which can be utilised and provide guidance in terms of the geomorphological context of the issue. Central to the study would be the need to develop a convincing age structure of geomorphological events. A starting point would be a better understanding of the geomorphological context and provenance of the deposits constituting the Harvey Beds. In this respect the cosmogenic isotopes 10-Be, 26-Al and 36-Cl, as well as focused fission-track work (see Burbank and Anderson 2001), may prove useful in obtaining a chronological framework. A wider geomorphological evaluation of the Darling Scarp and associated stream networks and channels must also be undertaken and linked to likely geophysical constraints.

(ii) Associated with the Darling Scarp are questions of the geomorphological hazards posed by hillslope stability and runoff related issues. The regional assessment of the potential of hillslope failure can now be readily undertaken. Well tried GIS-based systems are available for such studies, such as for example SINMAP (Pack et al., 1998).

(iii) The recognition of the stratigraphic complexities that are inherent in the Ascot/Bassendean association and the alluvial sequences and the importance that this may hold for an understanding of shallow groundwater movement and possible contaminant migration.

(iv) The karst terrains of the Tamala Limestone and the potential environmental and engineering problems which are inherent to them is an issue which deserves to receive much more attention.

(v) Coastal stability in the context of changes in the synoptic climatology of southwestern Australia and projected global sea-level changes under developing 'Greenhouse' conditions pose issues of concern. The effect that atmospheric circulation changes have on hydrology, and hence stream flow and sediment transport-channel dynamics, should not be overlooked. From a more general scientific perspective, the marine succession of the coastal plain may well hold the key to an understanding of global sea-level events, and through this provide a guide to global-scale climate events over Cenozoic time-scales. However, before these deposits can fulfil this role an absolute age structure of the succession has to be obtained.

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