Provenance and sediment characteristics of contemporary gravel deposits at Sellicks Beach, eastern shore of Gulf St Vincent, South Australia

J. H. CANN1*, C. S. LOWER1,2 AND J. B. JAGO1

1 School of Natural and Built Environments and the Barbara Hardy Institute, University of South Australia, Mawson Lakes, South Australia 5095, Australia.
2 BHP Billiton, 55 Grenfell Street, Adelaide, South Australia 5000, Australia.

Sellicks Beach, located on the eastern shore of Gulf St Vincent, South Australia, is subject to wave-dominated processes and northward longshore transport. During winter, when wave energy is typically vigorous, gravel deposits are exposed across most of the beach, and three step-like berms are well developed. Sand is restricted to a narrow strip that is exposed only at low tide. In contrast, during summer, when wave energy is generally moderate to low, much of the gravel is covered by a thin veneer of sand and only the high berm, on the landward edge of the beach, remains as an obvious feature. Steeply dipping Neoproterozoic to Cambrian strata that outcrop strongly across Sellicks Hill are the original source rocks for the beach gravel; distinctive sedimentary textures, structures and fossils in the cobble-size clasts can be confidently matched with those of the provenance rocks. Much of the sediment entered the modern beach environment as a consequence of coastal erosion of transitional alluvial fan sediments. The oldest alluvial fan sediments are of late Pliocene to earliest Pleistocene age. Mount Terrible Gully provides a conduit for the input of fluvial sediment at the mouth of Cactus Canyon, where clasts as large as boulders accumulate across the beach. Sellicks Beach gravels are subject to longshore transport northwards. Relatively softer clasts, such as those derived from the Heatherdale Shale, are rare beyond Cactus Canyon. In contrast, quartzite clasts are more abundant towards the north. This lithological differentiation is attributed to preferential survivorship of clasts that are physically harder and chemically less reactive. The change in the shapes of clasts northwards, from predominately shingle-like ‘very platy’ and ‘very bladed’ at Cactus Canyon, to more ‘compact’ towards the boat ramp, is in accord with the more massive fabric of the surviving quartzite clasts. At Sellicks Beach, preservation of uplifted, coarse gravels, with entire and comminuted marine molluscan shells, of last interglacial age, provides evidence of neotectonism. At the landward margin of the beach, imbricated gravels in which pore spaces have been infilled with mud, and which show no evidence of modern coastal erosion, may provide evidence of continuing uplift during the recent Holocene. The geological setting, geomorphic framework and modern sedimentary regime at Sellicks Beach combine to provide an exceptionally useful outdoor laboratory for education in field geology.

KEYWORDS: coastal processes, beach morphology, gravel clasts, alluvial fan, Quaternary, Cambrian, education.

INTRODUCTION

The highly urbanised population of Australia has long shown a preference for living in close proximity to the coast. Given their economic and social importance, it is not surprising that sand beaches have received much attention in sedimentary research, with limited recognition of other types of beaches on wave-dominated coasts; e.g. beaches of gravel in which pebbles and/or cobbles are substantial components. In the Northern Hemisphere, gravel beaches are reported to be widespread on wave-dominated coastlines of northern Europe and North America, and New Zealand and South America in the Southern Hemisphere (Buscombe & Masselink 2006). Gravel beaches are less common in Australia, particularly on the coast of Gulf St Vincent (Figure 1).

For any given lithology, factors that influence clast size and shape include: the gross fabric of the pre-existing parent rock at the time of erosion, such as the dimensions of joint and cleavage patterns; the wave energy regime; the duration of exposure to beach processes; and any earlier processes that were effective in delivering sediment to the beach, such as transport by glacial meltwater. For example, at Hallett Cove, a southern coastal suburb of metropolitan Adelaide, Permian sediments of fluvio-glacial origin are exposed along the shore at low tide. The matrix of these sediments is poorly lithified...
mud to sand in which are embedded numerous larger, rounded clasts varying in size from pebbles to boulders; the degree of rounding reflects an earlier history as components of glacial melt-water sediment. Coastal erosion has released these larger clasts into the modern environment where they are redistributed as poorly sorted beach gravel. While the provenance of some clasts has been easy to establish, e.g. granite from the southern Fleurieu Peninsula, other lithologies are not so easily matched to their origins; the mixture of rock types is in keeping with their former Permian glacial environment.
In this paper, we report on gravel deposits at Sellicks Beach, on the eastern shore of Gulf St Vincent (Figure 1), which we believe to be a particularly useful, but under-utilised, outdoor laboratory for education in field geology. We consider first the parental rocks, outcropping on Sellicks Hill, from which the gravel clasts were derived, and the initial but somewhat temporary storage of these materials as alluvial fan sediments. Second, we describe the redistribution of the alluvial fan sediments into the beach environment by fluvial transport via Cactus Canyon and by in situ erosion of coastal cliff exposures. Finally, we describe our observations of seasonal changes in beach morphology and evaluate the impact of sedimentary processes in influencing the distribution, textures and compositions of the beach gravel.

**METHODS AND OBSERVATIONS**

**Geological setting of clast source hinterland**

**Neoproterozoic and Cambrian Rocks. Sellicks Hill**

Sellicks Hill is part of the uplifted block of the northeastern trending Willunga Fault. Outcropping Cambrian rocks comprise a succession of lithologically distinctive strata, which unconformably overlie the Neoproterozoic Wilpena Group (Figure 1). Interpretations of the stratigraphic relations of the steeply dipping and partly overturned strata are facilitated by bold outcrop along strike, essentially parallel to the Willunga Fault, and by exposures in several steeply incised valleys and in roadside cuttings along the original unsurfaced South Road to Myponga, now closed to vehicular traffic.

**Neoproterozoic Wilpena Group**

The oldest rocks exposed in the Sellicks Hill section of the Willunga Fault scarp are red–brown mudstones of the Brachina Formation, in the Neoproterozoic Wilpena Group (Figure 2a, b). In road-side outcrops near the top of Sellicks Hill, these rocks are steeply dipping, deeply weathered and faded in colour. Overlying the Brachina Formation are interbedded siltstones and orthoquartzites that are equivalent to the ABC Range Quartzite of the Flinders Ranges (Jago et al. 1986). The nearly vertical, grey, cross-bedded orthoquartzite beds (Figure 2c) outcrop strongly, and in the road-side exposures, the rock has fractured across the grains, forming blocky angular fragments. Microscopic examination of a thin-section (Figure 2d) reveals that the rock is composed almost entirely of well-sorted quartz sand, 0.2–0.4 mm, with pronounced authigenic quartz overgrowths, and minor feldspar. Authigenic quartz also infills pore spaces. Because of their resistance to weathering, the quartzite beds outcrop prominently along strike.

**Cambrian Succession**

**Mount Terrible Formation**

The basal unit of the Cambrian succession, the Mount Terrible Formation (Daily 1963), unconformably overlies the Wilpena Group with a thin basal conglomerate resting on an irregular, nearly vertical erosional surface. Gravestock et al. (2001) described three members: a 15 m-thick basal cross-bedded arkose with thin siltstone layers towards the top; a middle siltstone member about 60 m thick; and a top cavernous, weathered, ferruginous sandstone member about 20 m thick. Microscopic thin-section examination of the bottom member (Figure 2e) reveals bimodal sorting, a textural feature that is also evident in hand specimens. The larger, less common clasts are of quartz and microcline up to 0.5 mm in size; the bulk of the rock comprises smaller clasts, from ~0.1 mm to 0.25 mm, predominately of quartz, with authigenic overgrowths, and with a significant amount of microcline. The middle member is a grey siltstone when fresh but weathers to a brown siltstone that is strongly cleaved. The top member is a cavernous, weathered, ferruginous sandstone and siltstone; the cavernous weathering is due to the presence of small, bedding-parallel, carbonate-rich lenses.

The upper part of the basal member of the Mount Terrible Formation is bioturbated, and shelly fossils are preserved towards the base of the middle member; these include hyolithids, the mollusc Watsonella, chancellorids and sabelliditid tubes. There is a similar fauna in the top member with the addition of the mollusc Bemella (Jago et al. 1986; Gravestock et al. 2001).

**Wangkonda Formation**

The Wangkonda Formation, which conformably overlies the Mount Terrible Formation, is about 110 m thick; it comprises intraclastic, stromatolitic, fenestral, pale grey, micritic limestone at the base passing up into silty limestone, with at least one horizon of poorly sorted, coarse, calcareous sandstone. Ooid grainstones are present at some levels. A carbonate-dominated, intertidal to supratidal depositional environment was suggested for this formation (Daily et al. 1978; Gravestock & Gatehouse 1995). A thin-section (Figure 2f) shows a rock comprising entirely interlocking calcite crystals up to 0.25 mm in size. The larger grains, many of which exhibit well-defined, typical calcite twinning, lie within a matrix of smaller, poorly defined, crystalline calcite grains.

**Sellick Hill Formation**

The Sellick Hill Formation (see Explanatory Note #1) is a silty limestone (Figure 3a, b) that conformably overlies the Wangkonda Formation in the Sellicks Hill succession (Daily 1963, 1969). A sandy facies, which occurs at the bottom of the formation in the Myponga Beach area, about 6 km southwest of the study area, is absent at Sellicks Hill. Alexander & Gravestock (1990) described the Sellick Hill Formation in detail; it is about 210 m thick. Unweathered outcrops in quarries and road cuttings reveal a distinctive pattern of evenly spaced pale grey and darker grey beds, ~2 cm thick. Some exposures exhibit various degrees of post-depositional disruption of bedding, varying from boudinage structures to a motiled mix of the lighter and darker components. Some collapse breccias are evident. There are several prominent horizons of edgewise conglomerates in the lower part of the formation. Small archaeocyathid-bearing bioherms
Figure 2 Major lithologies of the Neoproterozoic–Cambrian succession at Sellicks Hill. (a) Brachina Formation: weathered yellow appearance with barely discernible bedding. (b) Brachina Formation: unweathered purple appearance with well-defined bedding. (c) Unnamed Neoproterozoic orthoquartzite: typical appearance in outcrop; small veins of mobilised quartz. (d) Unnamed Neoproterozoic orthoquartzite: thin-section, crossed polars, showing authigenic quartz overgrowths and infilling quartz cement. (e) Mount Terrible Formation: thin-section, crossed polars, showing a subrounded grain of microcline in a matrix of smaller grains of predominantly quartz. (f) Wangkonda Formation: thin-section, crossed polars, showing interlocking, twinned calcite.
Figure 3 (a) Sellick Hill Formation: typical appearance of unweathered rock, Sellicks Hill. (b) Sellick Hill Formation: typical appearance of moderately weathered rock, Sellicks Beach. (c) Sellick Hill Formation: thin-section of the pale grey limestone lithology, plane polarised light, showing ‘clean’ mosaic of sparry calcite. (d) Sellick Hill Formation: thin-section of the darker, partly clastic lithology, plane polarised light, showing euhedral dolomite. (e) Fork Tree Limestone: outcrop of limestone with fossil archaeocyathids and stylolites, Sellicks Hill. (f) Fork Tree Limestone: thin-section of the limestone, plane polarised light, showing a fossil archaeocyathid infilled with sparry calcite and a stylolite.
occur towards the top of the formation. Where the bedding is intact, small cross-beds and scour structures may be present in the darker layers. In contrast, the lighter layers lack evidence of a clastic component. In weathered outcrops, it is evident that the lighter grey limestone has been more prone to solution and is preferentially dissolved, leaving the alternating, more resistant layers standing out, thus producing a serrated weathering pattern. Microscopic examination of a thin-section reveals that the distinctive bedding exhibited in outcrop and hand specimens is associated with different carbonate minerals. In the darker layers, dolomite occurs as euhedral, zoned crystals, up to 0.25 mm across, in a matrix of smaller, subhedral dolomite crystals (Figure 3d). Thin films of insoluble minerals occur at the dolomite crystal boundaries, giving these layers a dark-brown colour in plane polarised, transmitted light. The mineral composition of the lighter layers is almost exclusively calcite, which occurs as transparent, well-defined subhedral to euhedral interlocking crystals up to 0.13 mm in size, in a matrix of smaller crystals (Figure 3c). There is no evidence of the insoluble minerals that were observed in the dolomitic layers.

**Fork Tree Limestone**

The Fork Tree Limestone, which conformably overlies the Sellick Hill Formation, comprises two members (Daily 1963). The lower member is a massive, grey, clean, archaeocyathid-rich limestone comprising coalesced bioherms, lacking evidence of bedding or siliciclastic components, about 160 m thick. It is susceptible to solution weathering, outcrop is generally poor and small-scale karst features are evident. Weathered outcrops display etched archaeocyathid fossils and pressure-solution features as brown–yellow stylolites of insoluble minerals (Figure 3e). These features are also apparent in thin-section. Spaces within the archaeocyathid skeleton are filled with clear, sparce, authigenic calcite (Figure 3f); stylolites appear as opaque dark red–brown structures. The mottled upper member is about 25 m thick. It is similar in appearance to the serrated weathering pattern of much of the Sellick Hill Formation.

**Heatherdale Shale**

The Heatherdale Shale, which conformably overlies the Fork Tree Limestone, is the youngest member of the Cambrian succession at Sellicks Hill. Here it comprises a lower calcareous member, ∼35 m thick, that is gradational with the Fork Tree Limestone, and an upper member comprising very dark grey to purplish black shale and siltstone, generally lacking in carbonate (Abele & McGowran 1959; Jago et al. 2006). The top of the Heatherdale Shale is not exposed in the Sellicks Hill area, where it is truncated by the Willunga Fault (Figure 1). In outcrop, the shale weathers to a buff colour (the weathering rim can be up to 5 cm thick), in marked contrast to the much darker colour of the unweathered rock. The shale parts easily along bedding, cleavage planes and joints, forming fragments that are typically elongate and flat in shape. The shales contain small, black, bedding-parallel phosphatic nodules that are particularly conspicuous on pale weathered surfaces (Figure 4a). A microscopic thin-section reveals that the nodules contain phosphatic fragments, which could be the remains of incompletely digested food items such as trilobite and other arthropod carapaces. Thus, the nodules are interpreted as invertebrate coprolites (faecal pellets). Thin-section examination also revealed an extremely fine grainsize, with

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**Figure 4** (a) Heatherdale Shale: black phosphatic nodules are conspicuous on the pale weathered surface; Sellicks Beach. (b) Heatherdale Shale: thin-section, crossed polars, showing phosphatic nodule.
abundant muscovite clasts and incipient foliation (Figure 4b).

**Willunga Fault and Miocene Port Willunga Formation**

The Willunga Fault (Figure 1) is one of several north–south-trending faults that were activated or reactivated during separation of Australia and Antarctica. It defines the landward margin of the Willunga Embayment in which, during and following separation of the two landmasses, a succession of Cenozoic sediments, including the Port Willunga Formation, was deposited (Cooper 1979; Primary Industry and Resources, South Australia 2011). The Port Willunga Formation at Sellicks Beach comprises bioclastic calcarenites of Miocene age and outcrops as low cliffs and broad rock platforms, which are exposed at low tide and upon which the beach sediments are deposited. North of Cactus Canyon the Miocene strata are nearly horizontal. At the southern end of the beach, where they unconformably overlie the Cambrian strata, they are upturned adjacent to the Willunga Fault.

**Alluvial fan—conduit to the coastal zone**

Erosion of the Neoproterozoic and Cambrian rocks from the succession outcropping on Sellicks Hill has generated poorly sorted sediments that comprise a substantial alluvial fan on the downthrown side of the Willunga Fault. The term ‘alluvial fan’ refers to a fan-shaped outline of sediments that have been deposited where a stream emerges from a topographically elevated area to a lowland area, most commonly, as in this case, across a fault.

At the proximal end of a typical alluvial fan, where an alluvial fan has maximum thickness, sediments are coarse, angular and poorly sorted. At the arcuate distal margin, sediments consist of thin deposits of fine sand and mud. The surface of the fan slopes steadily away from the proximal end at the fault towards the distal margin, the relatively gentle slope, in this case, contrasting with the steeper surface topography of Sellicks Hill, approximately five times the gradient. Mount Terrible Gully is the main stream course, which somewhat counter intuitively, follows the crest of the fan. Alluvial fan sediments are typically porus and permeable. At times of heavy surface water runoff from Sellicks Hill across the Willunga Fault into the discharge channel, water soaks rapidly into the previously deposited, underlying alluvial sediments, stranding the most recent sediment within the channel. Thus, channels become clogged with sediment, followed by avulsion, erosion and formation of new channels. Some stream channels appear to have no precise beginning and no definite end. Alluvial sediment aggradation occurs preferentially towards the median line and proximal end of the fan. The coarser channel deposits are commonly lens-like in section and consist of cobble-size, subangular sediments, with more flattish fragments stacked together tile-like (imbricated), in response to the runoff water flow. Finer sediments may represent over-bank deposits of sand and mud. Because of the changing directions of the fan distributaries, some horizons of these sediments have been exposed for substantial periods of time before the following episode of sedimentation, long enough for soil horizons to form.

**AGE OF THE ALLUVIAL FAN**

The alluvial fan at Sellicks Beach originated in late Pliocene—early Pleistocene times (Figure 5). Basal sediments of the Seafood Formation disconformably overlie Miocene bioclastic limestone of the Port Willunga Formation (Lindsay & Alley 1995; McGowran & Alley 2008). Ward (1966) inferred a Pliocene age for the non-marine Seafood Formation. However, May & Bourman (1984) described a bed of rubbly limestone, within and close to the base of the Seafood Formation, which they recognised to be an exposure of Burnham Limestone (Firman 1976). On the evidence of the fossil occurrence of the marine pelagic gastropod *Hartungia denannantia chausan* (Ladbrook 1978, 1983, figure 3h–j), the Burnham Limestone at Sellicks Beach has an early Pleistocene age (May & Bourman 1984). However, as the Burnham Limestone interfingers with the Seafood Formation near its base, the alluvial fan may have originated in the late Pliocene.

Supporting evidence for an early Pleistocene age for the bulk of the Seafood Formation was provided by Pillans & Bourman (1996), who investigated the paleomagnetic properties of weathering features within the alluvial fan sediments in cliff exposures at Sellicks Beach (Figure 5). The Ngaltlinga Clay and the upper third of the underlying Ochre Cove Formation have normal polarity (i.e. in accord with Earth’s present magnetism); polarity is reversed in the middle third of the Ochre Cove Formation. The lower third of this unit has normal polarity and was correlated with the Jaramillo Subchron, and the change in polarity between the upper and middle thirds was recognised as the Brunhes/Matuyama boundary, 0.78 Ma (Pillans & Bourman 1996).

The distal margin of the alluvial fan at Sellicks Beach once extended further seawards at a time (or times) when the sea-level was much lower. Hill et al. (2009, figure 3) provide an impressive image of the exposed continental shelf (Lacepede Shelf) during glacial low stands of sea-level. The time frame for alluvial fan sedimentation, dating back to early Pleistocene, established by May & Bourman (1984) and Pillans & Bourman (1996) (Figure 5), encompasses multiple global glacial/interglacial climatic events and consequent changes of sea-level. For example, in deep sea sediment recovered in equatorial Pacific core V28-238, Shackleton & Opdyke (1973) recorded 19 Marine Oxygen Isotope stages above the Brunhes/Matuyama boundary (0.78 Ma), many of which signify major glacial events and thus low stands of sea-level. Similarly, in southeastern South Australia, many changes in sea-level have been inferred from stranded Pleistocene coastal barriers, prior to the change at 0.78 Ma from Matuyama reversed polarity to Brunhes normal polarity (Cook et al. 1977; Murray-Wallace et al. 2001).

**EROSION OF THE ALLUVIAL FAN AND SEDIMENT SUPPLY TO SELLICKS BEACH**

The modern cliffs exposing Quaternary alluvial fan sediments at Sellicks Beach are an outcome of marine
erosion following the postglacial marine transgression and the continuing present high stand of sea-level. Marine erosion has removed the distal portion of the fan, which may at times have extended several kilometres across the exposed floor of Gulf St Vincent during low stands of sea-level. Undercutting of coastal cliffs by wave action, followed by slumping of the unsupported rock mass above the wave-cut notch, provides a credible explanation for coastal erosion and landward retreat of the cliff line. In this context, the poorly consolidated sediments of the alluvial fan would have been particularly vulnerable to erosion, if not for the underlying limestone of the Port Willunga Formation (Figure 6a). Although these rocks are not particularly resistant to erosion, they outcrop at sea-level and form low cliffs, which provide some support and protection for the overlying, relatively unconsolidated alluvial fan sediments.

Retreat of the cliff face may be attributed to several ongoing and seasonal processes that weaken the muddy matrix. Alternating wetting and dehydration of clay minerals, particularly in the context of the prevailing Mediterranean climate, causes expansion, shrinking and cracking. Aerosol salt from sea spray crystallises in cracks and pore spaces, wedging grains apart. Rainfall generates gully erosion, preferentially removing the finer matrix materials and thus releasing the larger clasts to move down slope towards the beach (Figure 6b). Ultimately it would be expected that a degree of equilibrium might be established, the colluvium forming an apron of piedmont fans (Figure 6c) at the base of the cliffs, in part stabilised by vegetation. The features illustrated in Figure 6 confirm that erosion of the alluvial fan sediments is a dynamic process that ensures continuing input of coarse gravel-size clasts to the beach.

However, there is good evidence to indicate that episodic slumping of the alluvial fan sediments might be a particularly significant process in the retreat of the cliffs and the transfer of those materials to the modern beach (Bourman & May 1984; May & Bourman 1984). These authors described a rotational land slump in which an estimated 300 000 m$^3$ was removed from the cliff face, and they postulated that the total volume of material was such that a frontal lobe of mobilised alluvial fan sediments flowed across the beach into the sea (Figure 7).
By way of explanation for this event, May & Bourman (1984) proposed the influence of heavy rainfall and potential slippage along smectite-rich clay layers associated with the Burnham Limestone. Furthermore, at Sellicks Beach they recognised the existence of older slumps of similar magnitude on the evidence of ‘back-tilting.’ Thus, a substantial quantity of sediment has apparently been transferred from the alluvial fan to the near-shore marine environment by this mechanism.

The Mount Terrible Gully is an incised water course that is sourced in the Sellicks Hill Range, where the succession of Neoproterozoic and Cambrian strata outcrop (Figure 1). Erosion of these strata has generated clastic sediment, some of which, at times of high rainfall, has...
been transported downstream to the debouchment site at Cactus Canyon (Figure 8). At this locality, the sediment becomes subject to redistribution by waves and longshore transport, but many of the clasts are of boulder size and remain more or less in place, forming a delta-like deposit at the mouth of the canyon. Some of the larger clasts exhibit distinctive textures and structures that facilitate visual matching to their provenance rocks. They include: limestone with fossil archaeocyathids and stylolites, derived from the Fork Tree Limestone; banded to mottled silty limestone of the Sellick Hill Formation; and tabular fragments of shale with phosphatic nodules from the Heatherdale Shale. Thus, this site at the mouth of Cactus Canyon is also established as a major source of sediment for the gravel beach.

Sellicks Beach gravels

BEACH PROFILES

Our collective observations over a period of more than 40 years—regular field trips with undergraduate students and dedicated research studies—have discerned a seasonal pattern in the exposure of surficial sediments on Sellicks Beach. In summer, when wave energy is generally low, the gravels are at least partly covered by a thin veneer of sand (Figure 9a). Conversely, in winter, when more energetic wave action normally prevails, gravels are exposed across the broad expanse of the beach leaving just a narrow strip of sand exposed along the shore at low tide (Figure 9b). At the extreme landward edge of the beach, the gravels comprise a berm in which a large proportion of cobble-size, tabular clasts have a distinctive imbricate fabric (Figure 9c). Seaward of the gravel at the top of the beach (Figure 9c, d) there are two other berms that stepwise, are inferred to represent high tide storm activity (the middle berm) and normal high tide wave activity (the low berm) (Figure 9e).

IMBRICATION OF CLASTS

The preferential sorting and imbricate fabric of gravel comprising the high berm can be attributed to a slower rate of settling of tabular clasts (compared with more spherical clasts of similar weight) from the transporting waves. Deposition of this gravel facies, with its distinctive fabric, is inferred to have been the outcome of extreme storm events. However, in some places it is evident that this shingle-like gravel comprising the berm at

Figure 8  Mouth of Cactus Canyon showing outwash gravel comprising boulders and large cobble-size clasts; the composition of many of these clasts can be visually matched to the Neoproterozoic and Cambrian strata that outcrop on Sellicks Hill. Person, at far right of image, for scale.
the top of the beach has been unaffected by wave action in very recent time; outwash mud from the alluvial fan has filled pore spaces providing a matrix for the imbricated clasts (Figure 9d).

In this context, the possibility of a relative fall in sea-level cannot be dismissed; a mid-Holocene eustatic fall in sea-level is favoured by some researchers. However, recent uplift along the Willunga Fault is another factor...
to be considered. South of Cactus Canyon, relict beach gravels of last interglacial age (125 ka, Marine Isotope Substage 5e, Glanville Formation; Cann 1978), dated by amino acid racemisation of preserved molluscan shells, are elevated > 5 m above present-day equivalent sediment (Murray-Wallace & Bourman 2002). Assuming a last interglacial sea-level of C 2 m (Murray-Wallace & Belperio 1991), these elevated gravels signify uplift of ~3 m since deposition. At Normanville, just ~20 km south of the study area, last interglacial sediments are elevated by up to 12 m compared with the estimated global +2 m sea-level, providing further evidence of neotectonic uplift of the Fleurieu Peninsula (Bourman et al. 1999).

Gravel clasts—composition, sizes, shapes and distribution

Here we report on the changes in clast size, shape and composition from four stations along the beach, from Cactus Canyon northwards to the boat ramp, a distance of approximately 1 km (Figure 10), and on differences between the gravels comprising the high, middle and low berms. At each location 27 clasts were sampled from surficial gravel deposits for analysis. These clasts were selected by placing a horizontal wooden stake to define a line of transect perpendicular to the trend of the beach berms and selecting and marking nine contiguous surface clasts from gravel from each of the three berm levels (Figures 10, 11). See Explanatory Note #2.

COMPOSITION OF CLASTS

The lithology of each clast was generally easy to visually match with the provenance rock; some clasts were taken for preparation of petrological thin-sections and microscopic examination (Figures 2d–f, 3c, d, f, 4b). The distribution of lithologies for each of the low, middle and high berms, at each of the four sites, was recorded (Supplementary Papers Tables 1–4).

CLAST SIZES AND SHAPES

Electronic callipers were used on site to measure each of the orthogonal axes: longest a-axis; intermediate b-axis, and shortest c-axis (Figure 12). When conducting these measurements: a straight line along the longest segment of each clast was determined to be the a-axis; the intermediate b-axis exists within the same plane, but orientated at 90° to the long a-axis; the b-axis is shorter than the a-axis but longer than the c-axis; the shortest c-axis is perpendicular to the plane formed by the long and intermediate axes. The three orthogonal axes measurements obtained can be interpreted to represent an ellipsoid.

Measurements of the three orthogonal axes of each clast from the gravel berms were graphically represented on Folk diagrams, first presented by Sneed & Folk (1958). While similar to ternary diagrams, the Folk diagrams have only two axes but are still represented on
a triangle. The vertical axis (left side of the triangle) represents the ratio of the short axis to the long axis \((c/a)\). The horizontal axis (base of triangle) is a ratio of the difference between the long \(a\)-axis and the intermediate \(b\)-axis to the difference between the long \(a\)-axis and the short \(c\)-axis \((a-b)/a-c\) (Figure 13; Supplementary Papers Tables 1–4). The Folk diagrams were electronically tabulated using an Excel based program called Tri-plot (Graham 2006). Data for each berm level at each of the four sites were plotted on individual Folk diagrams. A detailed discussion on the use of Folk diagrams can be found in Graham & Midgley (2000) and Le Roux (2004).

RESULTS OF ANALYSIS OF GRAVEL CLASTS

The relative abundances of the recognised lithologies as gravel clasts are shown as histograms for the low, middle and high berms at each of the four sites (Figure 14). The classification of the shapes of gravel clasts are shown as Folk diagrams for the low, middle and high berms at each of the four sites (Figure 15).

DISCUSSION OF DISTRIBUTION OF GRAVEL CLASTS

Two clasts of Heatherdale Shale were recorded from the high berm at Site #3, but otherwise clasts of this lithology are confined to Site #4 at the mouth of Cactus Canyon; clasts of Heatherdale Shale are evidently a substantial component of the sediment delivered to Site #4 via the Mount Terrible Gully. North of Site #4, the absence of shale clasts in the low berm gravels, where systematic longshore transport can be expected, may be attributed to preferential attrition of the shale in company with physically harder clasts such as quartzites of the Wilpena Group and the Mount Terrible Formation.

Field experiments provide quantitative evidence for longshore transport on gravel beaches. For example, Matthews (1980) seeded beach gravel at the entrance to Wellington Harbour, New Zealand with chips of ‘double-baked, brick roofing tiles’ and derived estimates of rates of longshore transport. It was established that the tracer material moved along the beach within the swash zone at 0.42 km per year and that transport was active primarily during storm events. Rapid initial rounding of the tracer chips in the first 20 days was followed by a more gradual increase in roundness over the course of the study (200 days). In a subsequent investigation, of beach pebble attrition in Pallister Bay, New Zealand, Matthews (1983) recorded a weight loss of 41% per year for limestone tracer pebbles at the most exposed site, and 15% and 7% loss at two less exposed sites.

At Sellicks Beach, absence of shale clasts from even the high berm at Site #1 (boat ramp) and Site #2 is evidence that there is little input of this lithology to the beach via erosion of the alluvial fan. Not surprisingly, robust quartzite clasts derived from rocks of the Wilpena Group are resilient and increase in abundance
Figure 14 Distribution of lithologies in the beach gravel at Sellicks Beach, as noted for the selected clasts at Sites #4 (Cactus Canyon) through to #1 (boat ramp), and for the high, middle and low berms at those sites. Longshore transport is northwards from Site #4 to Site #1. Clasts of Heatherdale Shale are present across the expanse of gravel at Cactus Canyon, but further to the north this lithology is present only in the high berm of Site #3. In contrast, clasts of quartzite, attributed to the Wilpena Group and Mount Terrible Formation, are poorly represented at Cactus Canyon, but are particularly abundant in the gravels at the boat ramp.
Figure 15. Application of the Folk grain-shape diagram to the same selected clasts referred to in Figure 14. Colour coding of lithologies is the same as that in Figure 14. Across the beach, there is a general trend from clasts of flattish shape (P-VP/B-VB) in the high berm to those of more equate dimensions in the low berm. Clasts of flattish shape are most abundant in the gravels at Site #4, generally giving way to more compact clasts at Site #1. Clasts classified as VP/VB (e.g. Site #4) were derived mostly from the Heatherdale Shale and the Brachina Formation; more compact clasts of quartzite were mostly derived from the Wilpena Group and the Mount Terrible Formation.
northwards, with concomitant reduction in clasts of Bra-ncina Formation. Limestone clasts derived from the Wangkonda Formation were recorded from low berm gravels at sites #1 and #2, but only a single clast of lime-
stone from the Sellick Hill Formation was identified in the systematic observations (Site #4); clasts of the dis-
tinctive Fork Tree Limestone (archaeoeciths and sty-
olites) were not recorded. The relative hardness ($H = 3$) and potential for dissolution of limestone are factors unfavourable for survival of carbonate clasts.

At Site #4, clasts in all three berms are predomi-
nantly ‘very platy’ to ‘very bladed’ in shape. While this sorting according to shape is maintained in the high berm north to Site #3, clasts of more ‘compact’ to ‘bladed’ shape become more abundant northwards; e.g. in the low berm gravel at Site #1. Gravels of the low berm are those subject to more persistent wave action, and thus more active longshore transport, better sorting and enhanced rounding of clasts. The surficial gravel of the low berm at site #1 exhibits better sorting of clasts by shape than the gravels analysed on the middle and high berms.

This observed zonation of gravels comprising differ-
cent clast shapes has been previously recognised else-
where (Buscombe & Masselink 2006 and references therein). For example, Bluck (1967) described beach gravel in South Wales that was derived from deposits of (glacial) boulder clay, noting that ‘particle size and shape vary systematically across the beach’ and that ‘the most oblate discs are found in areas least worked on by the sea.’ From these observations, it was inferred that ‘disc and blade-shaped particles’ had been ‘preferentially transported upslope, acting like a hydrodynamic wing’ while ‘spherical and roller shapes’ were transported downslope (cited in Buscombe & Masselink 2006). Osborne (2005) records similar observations and interpre-
tations for clasts comprising a gravel shoreline in Washington State, USA.

CONCLUSIONS

(1) Sellicks Beach provides a rare example of beach gravel sedimentation within Gulf St Vincent, South Australia. Observations over a period of more than 40 years have revealed a pronounced seasonal cycle of surficial sedimentation and berm development. During winter, when wave energy is typically vigi-
rous, gravel deposits are exposed across most of the beach and step-like berms are well developed. Surficial sand is restricted to a narrow strip that is exposed at low tide. In contrast, during summer, when wave energy is generally moderate to low, much of the gravel is hidden by a thin covering of sand and only the high berm remains as an obvious feature. The preferential sorting of relatively large, flattish clasts comprising the high berm, and their imbricate fabric, is attributed to maximum wave energy at high tide.

(2) The provenance of the gravel clasts comprising the Sellicks Beach sediments has been established; the clasts were derived from the Neoproterozoic/Cam-
brian succession that outcrops at nearby Sellicks Hill. Much of the gravel entered the modern beach environment as a consequence of coastal erosion of transitional alluvial fan sediments. The oldest alluv-
ial fan sediments are of late Pliocene to earliest Pleisto-
tocene age. The Mount Terrible Gully provides a conduit for the input of fluvial sediment at the mouth of Cactus Canyon.

(3) Sellicks Beach gravels are subject to longshore trans-
port northwards. Relatively softer clasts, such as those derived from the Heatherdale Shale, are rare beyond the Cactus Canyon. In contrast, quartzite clasts are more abundant towards the north. This lithologi-
cal differentiation is attributed to preferential survi-
vorship of clasts that are physically harder and chemically less reactive.

(4) The change in shapes of clasts northwards, from pre-
dominately ‘very platy’ and ‘very bladed’ at Cactus Canyon, to more ‘compact’ towards the boat ramp, is in accord with the more massive fabric of the surviv-
ing quartzite clasts.

(5) Preservation of uplifted last interglacial gravels at Sellicks Beach provides evidence of neotectonism. At the landward margin of the beach, imbricated gravels in which pore space has been infilled with mud, and which show no evidence of modern coastal erosion, may provide evidence of continuing uplift during the recent Holocene.

(6) The geological setting, geomorphic framework and modern sedimentary regime at Sellicks Beach com-
bine to provide an exceptionally useful outdoor labor-
atory for education in field geology. In that context, the established time frames for the construction of the alluvial fan and late Quaternary sea-level changes are particularly significant.

(7) The results of the pilot study of clast measurements and interpretations are credible and encourage fur-
ther investigation that might generate more statisti-
cally robust findings.

EXPLANATORY NOTES

(1) When the Sellick Hill Formation was stratigraphi-
cally defined (Abele & McGowran 1959), there was apparently some confusion concerning the geo-
graphic name; ‘Sellick, ’ ‘Sellic’s’ and ‘Sellics’ were all place names in common usage. Elimination of possessive terms for locality names favoured use of ‘Sellick’ Hill as the preferred geographic name for the stratigraphic unit. However, the place name ‘Sell-
icks’ has prevailed as the official geographic name for Sellicks Hill and Sellicks Beach.

(2) In the early planning of the quantitative pilot study of the Sellicks Beach gravels, it was assumed (albeit incorrectly) that adjacent clasts of a small, selected area would be of similar sizes. Originally it was intended that a manual statistical procedure invol-
ving the square root of the number of measured clasts would be used. The number nine ($\sqrt{9} = 3$) was adopted for convenience. Subsequently the clast measurements were processed using the methods described above.
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SUPPLEMENTAL DATA

Table 1 Numerical data for selected clasts at Site #4, Cactus Canyon, Sellicks Beach. GPS 35°20'29.64"S, 138°26'16.41"E.

Table 2 Numerical data for selected clasts at Site #3, Sellicks Beach. GPS 35°20'19.56"S, 138°26'21.34"E.

Table 3 Numerical data for selected clasts at Site #2, Sellicks Beach. GPS 35°20'10.33"S, 138°26'14.14"E.

Table 4 Numerical data for selected clasts at Site #1, Boat ramp, Sellicks Beach. GPS 35°19'48.63"S, 138°26'29.98"E.

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