WHY ARE THERE SEASHELLS IN MY ALLUVIAL VALLEY? – THE COASTAL GEOLOGIST'S PERSPECTIVE OF VALLEY-FILL SEQUENCES.

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ABSTRACT

For engineers tasked with placing infrastructure across alluvial valleys in eastern Australia the *mélange* of unconsolidated sand and silt/clay deposits encountered beneath modern floodplains must often appear baffling, particularly the juxtaposition of river derived and marine influenced deposits. However, it is this apparent anomaly that immediately alerts coastal geologists, for whom modelling these valley-fill sequences is their stock and trade, that they are dealing with an ancient 'drowned-valley estuarine' depositional environment.

Valleys that ultimately connect to the coast have experienced numerous cycles of erosion and deposition as a consequence of major sea level fluctuations through geological time. The last major phase of fill has occurred in response to marine inundation of coastal valleys by rising sea level which stabilized at approximately its present level some 6,500 years ago.

With the exception of the alluvial capping layer that supports human habitation of these valleys, the greater proportion of silt/clay sediments deposited during this last phase have remained beyond the influence of pedogenic processes and are therefore 'unripe'. This immaturity provides a number of challenging geomechanical and environmental aspects to working with these sediments.

Although local complexity may occur, stratigraphic models of 'drowned-valley estuarine' deposition provide a good general framework for understanding the distribution of both geomechanical and environmental properties of the valley-fill sequences.

1 INTRODUCTION

To engineers investigating the properties of unconsolidated sedimentary sequences in alluvial valleys, the presence of 'marine clays' must appear incongruous – 'alluvial' sedimentation having been generated by fluvial processes, while the 'marine clays', often bearing shells, exhibit an obvious connection with the sea. This mystery deepens when the subject valley-fill sequence is encountered many tens of kilometres from the coast. However, to a coastal geologist the very presence of sediments bearing the signature of both landward and seaward influences, immediately suggests that we are in an ancient estuarine environment.

In fact, drive across the level plain of any valley that is ultimately connected to the coast, and you can be reasonably certain that you are transecting an alluvial cap over an old 'drowned–valley estuarine' sequence. Coastal geologists have studied the genesis of these sequences extensively and, although there can be considerable complexity at the second and third order of investigation, general models of their evolution can bring some rhyme and reason to the stratigraphic architecture of these valley fills.

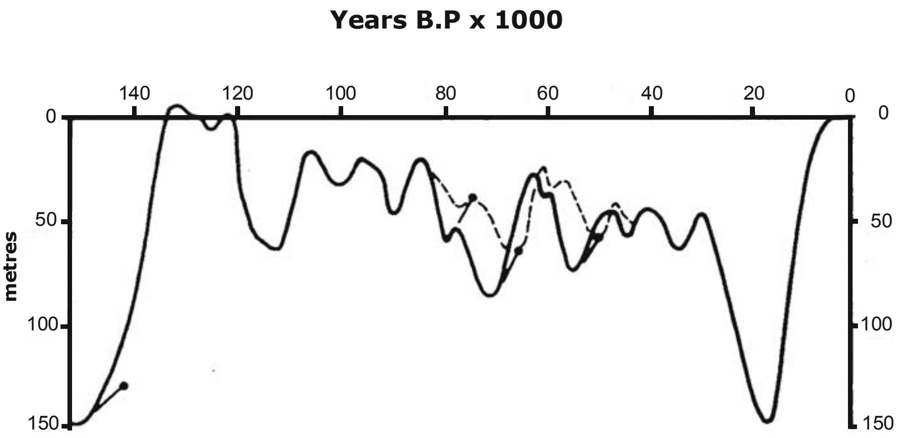
2 THE EVOLUTION OF [##]HOLOCENE DROWNED-VALLEY ESTUARIES

2.1 SEA LEVEL CHANGE

Fundamental to understanding the evolution of coastal environments is an appreciation of how coasts have responded to sea level change through geological time. Within geological timeframes sea level has been shown to fluctuate quite dramatically in response to water from the world's oceans becoming locked into large bodies of land-based ice during ice-age (or 'glacial') periods. While major sea level fluctuations have been numerous in the geological record, we generally need only concern ourselves with the changes that have occurred during the past 125,000 years when interpreting modern coastal plain evolution.

Changes in sea level during this period are illustrated in Figure 1.

[##] Holocene transgression – *Holocene* is the name of a geological time period (or 'epoch') commencing ~10,000 years ago and extending to present. *Transgression* is the term used to describe the progressive marine incursion of the land surface as sea level rises.



An age-height graph to show sea level change over the last 150 000 years in the Australian region, interpreted from the New Guinea shoreline record with modifications according to comparisons with the deep ocean isotopic cores (Chappell, 1982; Chappell and Shackleton, 1986). Small bars, solid circles and the dashed lines show modifications by Chappell and Shackleton (1986).

Figure 1: Age-height graph of sea level change (Chappell and Shackleton, 1986).

Approximately 125,000 years ago the world was experiencing a warm period between ice ages, similar to present. A number of studies have shown that sea level was higher than present at this time. In southeast Queensland, Pickett *et al.* (1985) reported evidence from old coral reefs on North Stradbroke Island of sea levels 1 m to 3 m above present. Originally, an age of 105,000 yrs ago was attributed to these corals, however they have since been reassessed as being in the range 120,000 to 130,000 (Chappell, 1987). During this period sediments were deposited at, or slightly above, the level of present coastal deposits and remnants of these older sequences are still found interspersed among younger deposits on present coastal lowlands.

2.2 GLACIAL LOW SEA LEVELS

As ice age conditions returned and sea level fell, the shoreline retreated seaward across the present continental shelf. Figure 1 shows several rises and falls of sea level during the period 125,000 to 30,000 years ago, however, none that resulted in the shoreline returning to the area we presently identify as the coast. Approximately 30,000 years ago sea level began to plummet, finally reaching a level some 130+ metres lower than present along the Queensland/NSW margin at the peak of the last ice-age (*circa* 18,000 years ago; Chappell, 1974). From this depth rapid sea level rise followed, which in its later stages, as it travelled landward across the present continental shelf, was termed the 'Holocene transgression'.

During the approximate 120,000 year interval where sea level remained below present, the processes of fluvial erosion were geared to a much lower base level and the valleys we presently comprehend as coastal were part of the more aggressive upper fluvial system. Consequently, they were extensively deepened by erosion (e.g. in larger coastal rivers of northern NSW and southeast Queensland these valleys achieved depths in excess of 40 m).

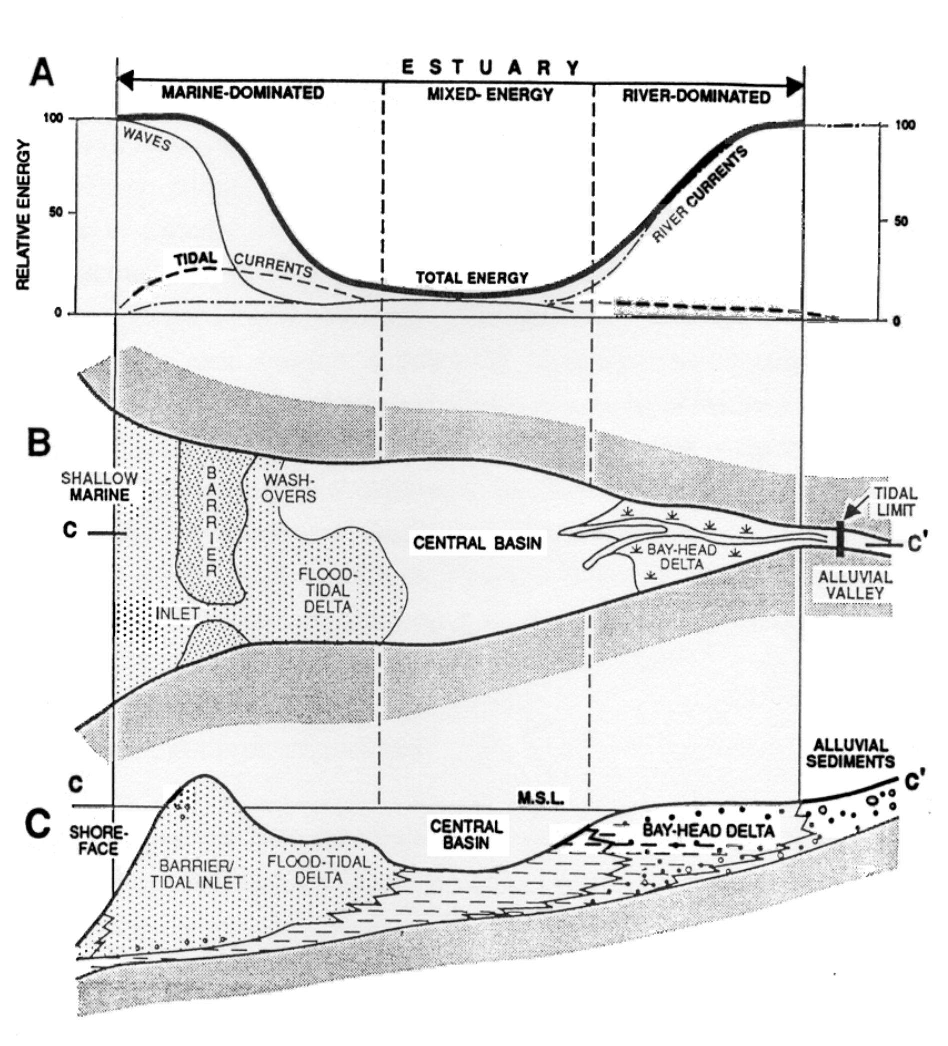
As had occurred cyclically through geological history, the setting of an erosionally-carved valley with some surviving remnants of previous coastal deposition, now formed the template for the next cycle of deposition.

2.3 THE HOLOCENE TRANSGRESSION

Aspects of sea level rise across a landscape can be understood by imagining slowly rising flood waters gradually enveloping an exposed land surface. However, the essential difference is that with sea level rise comes the translation of the dynamic shoreline systems and an associated array of shoreline environments. The rate of sea level rise is governed by the melting of major ice sheets, and the final extent of transgressive penetration of the sea across the land is determined by the completion of this melting. When sea level stabilised, a series of irregular embayments resulting from the flooding of old valley systems became the new template within which coastal and floodplain environments developed. As with floodwaters, the water first penetrated along the deeper river valleys, finally overtopping the confines of these deeper features and spreading across the landscape as a widespread sheet of water. Generally, the rate of sea level rise far outstripped the ability of coastal processes to fill these newly flooded valleys. The resultant large tidal coastal water bodies became estuaries and much of our understanding of modern coastal evolution is based on models of estuarine sedimentary processes.

2.4 STILLSTAND AND DROWNED-VALLEY ESTUARINE SEDIMENTATION

Following the Holocene rise, sea level stabilised around its present level some 6,500 yrs ago (Thom and Roy, 1985), a condition termed stillstand. As sea level slowed and finally halted sedimentary processes were finally able to keep pace with, and ultimately outstrip, the production of new sub-aqueous space. The geological evolution of coastal floodplains can be explained within the broader framework of the infilling of this sub-aqueous 'accommodation' or 'drowned-valley estuary'. For many of us our image of an estuary is that of an areally-limited, near-coastal water body, however, in geological terms they are often very extensive features of which these small coastal waterbodies are only a final remnant. A fundamental model for the development of an estuary is illustrated in Figure 2.



Distribution of A) energy types, B) morphological components in plan view, and C) sedimentary facies in longitudinal section with an idealized wave-dominated estuary. Note that the shape of the estuary is schematic. The barrier/sand plug is shown here as headland attached, but on low-gradient coasts it may not be connected to the local interfluves and is separated from the mainland by a lagoon. The section in C represents the onset of estuary filling following a period of transgression.

Figure 2: Lateral association of estuarine facies (Dalrymple, Zaitlin and Boyd, 1992).

3 HOLOCENE DROWNED-VALLEY ESTUARINE DEPOSITION

The following summary identifies the sequential stages of ‘drowned-valley estuary’ evolution, the sedimentary ‘[Φ]facies’ that may be expected to be deposited, and some geomechanical attributes of these sediments.

3.1 STAGE 1- LOW SEA LEVEL (‘GLACIAL’) PERIOD

The shoreline retreated a considerable distance offshore relative to its present location. Consequently, the area now occupied by modern coastal floodplains was transformed to a river headwaters environment, characterised by an eroded, river-dissected landscape similar to that seen in present river catchment areas.

3.1.1 Resultant sedimentary facies

If the very thalweg of this antecedent valley is intersected by drilling, then a boulder stream bed may be intersected, however, far more commonly, a mature substrate clay that has developed in either residual parent material or in remnant former valley deposition, is encountered. These clays have experienced a minimum of ~120,000 years of pedogenic maturity, and consequently exhibit good compressive strength (e.g. in the order of 130+ kPa). Another relict Pleistocene-age deposit that may be encountered (particularly behind the present coast) is a degraded dune barrier, often easily identified by its distinctive humic B-horizon (‘coffee’ layer). These sands are generally well sorted, with an upper fine to lower medium grainsize, and are dense. The B-horizon of these low fertility soils may take the ‘coffee’ route where organic colloids have been present, which can vary between weakly cemented to strongly indurated hardpan (generally where iron is present), or alternatively be strengthened by a small percentage of mature clay matrix. The presence of a ‘coffee’ layer generally indicates that a water table has been maintained throughout the period of lowered sea level landscape exposure, and consequently Pleistocene-age acid sulfate soil (ASS) is commonly preserved at depth in these sands.

3.2 STAGE 2 – MARINE TRANSGRESSION

When rising sea level flooded a coastal river valley in this older landscape, it forced the retreat of the river mouth a substantial distance inland (e.g. in northern NSW the Clarence River mouth retreated some 60+ km inland).

3.2.1 Resultant sedimentary facies

There are three distinct facies types that may occur at the base of the valley-fill sequence as a result of the passage of the marine transgression:

i. toward the centre of the antecedent valley, a fining upward fluvial sand sedimentary sequence may be encountered representing the forced landward retreat (‘backstepping’) of the fluvial delta. These sands may be expected to be loose, and increase in sorting up-sequence as the site becomes more distal from the energy of the river mouth.

ii. away from the direct influence of the fluvial delta the passing of the transgression is often recognised by a thin sandy layer (often containing shells and/or organics) overlying the mature clay substrate. Although the transgression is preceded by the progressive creation of a series of familiar coastal environments such as dune, beach and backswamp environments, these are in turn generally cannibalised by the passage of shore processes, leaving little sedimentary evidence of its passing. A number of studies by the author have established that where these thin sandy lags are present, they often have a very high acid sulfate potential. Although the mechanism responsible for this elevated ASS potential is not entirely clear, it is thought that it may be due to the selective winnowing of pyrite (or its chemical antecedents) during the reworking of coastal sediments. Occasionally a thicker, more coarse-grained sand deposit will testify to the preservation of pockets of washover sands

iii. at casual scrutiny the third type, ‘transgressive mangrove silt/clays’, can be difficult to distinguish from the overlying ‘marine clays’ described in the following stage. These sediments deposit on low angle and/or protected locations (eg. embayments) where silt/clay accretion is able to support mangrove mantled shorelines. In more obvious examples mangrove debris may be present, however, where the sediments are deposited within nearshore proximity to mangroves they may contain a high percentage of very fine organics and appear to meld seamlessly into the overlying clays. Attributes of this depositional environment, such as

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[Φ] Coastal sedimentary facies may be described as a ‘mappable, areally restricted sedimentary body associated by either character or origin’.

anaerobic conditions, a constant interchange of sulfate and bicarbonate and substantial organic presence, provide ideal conditions for the bacteria that accelerate acid sulfate soil formation.

3.3 STAGE 3 – LATE MARINE TRANSGRESSION/SEA LEVEL STILLSTAND

During this phase a coastal sand barrier generally developed which substantially blocks the lower, or seaward end of the flooded valley creating essentially an extensive coastal tidal lake isolated from open marine conditions.

3.3.1 Resultant sedimentary facies

As sea level rise ceases, deposition can finally out-compete the creation of new subaqueous accommodation, and the main phase of valley-estuarine fill can begin. From the landward end filling occurs by stream sediments building a delta (i.e. a 'fluvial delta' or 'bay-head delta'). The rapid dissipation of energy as the fluvial discharge enters this estuarine 'lake' limits the extent to which sand size sediments can be transported. Similarly, from the seaward end the tidally transported marine sands invade through the passage to the sea building a 'flood-tide delta', but, again, the extent of this sand transport is curtailed by the dissipation of energy.

The centre of this large tidal lake, an area called the 'estuarine central basin' remains a large energy void, into which only fine suspension load sediments (i.e. fine silt and clay size sediments from fluvial sources) can be transported and settle. These sediments, commonly identified as 'marine clays' by engineers because of the shells present in them, are more correctly termed 'estuarine central-basin silt/clays'. Both the perception that these sediments are 'clays' and their apparent uniformity in appearance can be deceptive from an engineering point of view. These sediments commonly contain layers that have a high silt percentage (>50%), particularly toward the landward end of the system where they interface with the prodelta, presenting potential shear planes.

It should be noted that these deposits are not soils in the true sense, but rather virgin sediment that has not experienced pedogenesis, and consequently they have a poor compressive strength (e.g. ~20 kPa) prior to controlled loading and dewatering.

3.4 STAGE 4 – FINAL STAGES OF COASTAL FLOODPLAIN DEPOSITION

During the preceding stage estuarine deposition can be comfortably separated into three broad depositional entities (bayhead or fluvial delta, central basin, and flood tide delta). As the central basin area fills and the water body shallows, a platform is created for fluvial deposition to project itself across, creating the series of more complex fluvial and alluvial environments that support human occupation.

3.4.1 Resultant sedimentary facies

Simplistically, the model for this final phase of deposition can be seen as the main river passing centrally through the valley, developing levees which produce an alluvial wedge feathering toward the valley margins. Commonly swamps along these valley margins identify little or no alluvial cover over the old estuarine surface. Consequently, the draining of these swamps to extend grazing in many coastal valleys has generated a substantial acid sulfate soil problem. The initial return of the fluvial delta is generally signalled in the sedimentary sequence by occasional thin fine sandy layers in the upper estuarine basin clay deposits representing higher energy intrusions into the normally silt/clay dominated pro-delta facies. The arrival of the delta proper is often marked by a distinct boundary to sand dominated deposition. In a Doppler like analogy, this sand will generally coarsen up sequence as the fluvial energy source overtakes the site. As with the underlying central-basin silt/clay facies, this fluvial sand deposit is generally pedogenically immature, loose and flowing.

Commonly however, the stratigraphy of floodplain surface environments is considerably more complex than this simple model, due to factors such as river meandering and division of the primary channel into anabranches. Additionally, whereas the stages of estuarine development presented above provides a reasonable model for the main valley, there is often a series of subsidiary basins referred to as 'floodbasins' representing former tributary catchments in the drowned-valley system. These floodbasin environments exhibit a further set of characteristic sedimentary depositional environments. The Clarence Valley in northern NSW presents an ideal example of this with a series of 'floodbasins' at various stages of maturity.

The model for drowned-valley estuary evolution outlined above has good application in the large coastal rivers of NSW, but progressively loses application moving into Queensland where the southeast is influenced by large tidal basin estuaries developed behind an offshore sand barrier, and onward to northern Queensland where barrier reefs occupy broad continental shelves. Some of these differences are summarised in Table 1.

Table 1: Summary of the main differences in coastal lowland development between southern Australian states and northern Australian states.

S.E. QUEENSLAND + N.S.W. + VICTORIA	NORTHERN AUSTRALIA
narrow and steeper continental shelf = exposed high energy coastline	wider shallow continental shelf – major reef provinces = protected low energy coastline
deep sandy coastal barriers	vast [γ]chenier plains incorporating mangrove mud flats or low beach ridge plains with subtidal nearshore mud (possibly incl. mangroves) buried beneath.
generally estuaries still filling – very little fluvial discharge of sand size sediment into the marine environment	estuaries generally filled – large seasonal discharge of sediment into the marine environment
deep, extensive Holocene-age coastal estuaries buried beneath coastal lowlands	shallower, extensive Holocene estuaries buried beneath coastal lowlands and occupying large north facing embayments
largely temperate climate = less biological and chemical activity ∴ reduced acid sulfate soil intensity	warm wet tropical climate = greater biological and chemical activity ∴ increased acids sulfate soil intensity

4 CONCLUSION

The wealth of knowledge of coastal processes and depositional sequences accumulated within the discipline of coastal geology has a great deal to contribute to understanding the genesis and distribution of unconsolidated valley-fill sequences. Application of stratigraphic modelling and mapping can provide a practical framework within which to couch an understanding of engineering and environmental parameters.

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[γ] chenier - discrete, elongated sand and/or shell bodies stranded on a coastal mudflat or marsh.