GEOMORPHOLOGICAL MODELLING AS A FRAMEWORK FOR UNDERSTANDING ACID SULFATE SOIL DISTRIBUTION AND HYDROLOGICAL PATHWAYS – EAST TRINITY SITE, NORTH QUEENSLAND, AUSTRALIA.

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Abstract
A 470 ha property near Cairns that had been degraded by the clearing of mangroves and salt flats, and extensive drainage works was purchased by the Queensland Government in 2000 for remediation. Previous studies on the site had identified the export of environmentally hazardous levels of acid and heavy metals associated with acid sulfate soil activation.

The present study adopted a multidisciplinary geoscience/soils approach that had been applied successfully at a number of locations during the past decade, to develop an understanding of the sites stratigraphy and evolution. This understanding has proven valuable in establishing both the three-dimensional distribution of acid sulfate soils, and relationships between soil chemistry and sediment provenance.

Strong and sometimes surprising associations between acid sulfate soil chemistry and Holocene-age sedimentary facies emerged from the study. In particular, identification of the provenance, distribution and acid sulfate soil chemistry of two distinct surficial environments, and the hydrogeological architecture of the deeper stratigraphy were successful in providing a framework within which to couch management strategies that have subsequently been implemented on site.

Additional Keywords: geomorphological modelling, hydrogeological architecture, acid sulfate, management.

Introduction
During the past decade a coalition between the disciplines of coastal geomorphology and soil science has proven beneficial in both delineating the distribution of acid sulfate soils at specific sites, and improving the overall understanding of acid sulfate soil formation (Graham and Larsen 2000a). The contribution of geoscience to this understanding has followed two streams; modelling of the stratigraphic architecture as a reflection of the provenance and environment of deposition of the sediment, and methodology. When faced with the task of assessing the acid sulfate soil status of an extensive (470 ha), poorly accessible property at East Trinity in Cairns, the Queensland Acid Sulfate Soil Investigation Team (Queensland Dept. Natural Resources and Mines) logically turned to this joint geoscience/soils approach.

The East Trinity site is located less than one kilometre from the Cairns Central Business District across Trinity Inlet (Figure 1), and was a natural, tidally-influenced plain dominated by mangrove and saltmarsh communities prior to being bunded and cleared for cane farming some 25 years ago. This disturbance caused oxidation of formerly benign acid sulfate estuarine silt clays, ("marine muds") resulting in the release of substantial quantities of sulfuric acid and associated heavy metals into the environment. As a consequence of its generally degraded environmental state the land was purchased by the Queensland State Government in 2000 for rehabilitation.

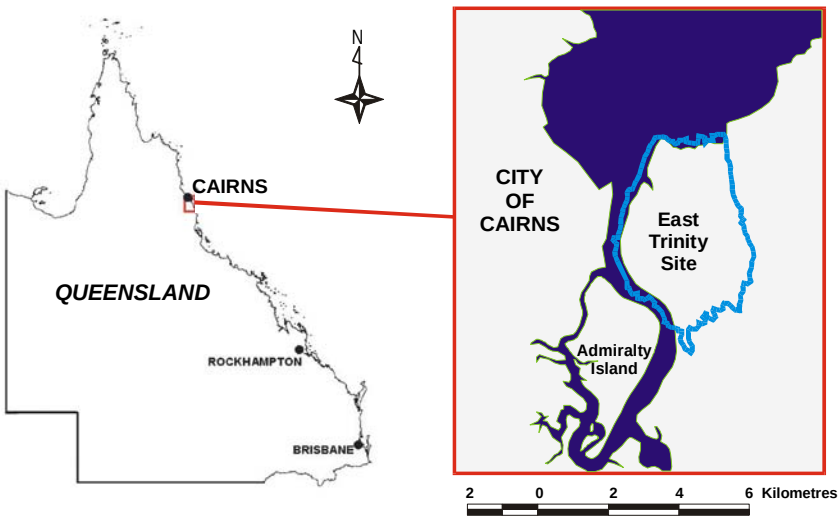

Figure 1. Locality map of the East Trinity investigation site.

Early estimates of acidification of the site based on prior research suggested enormous volumes of soil would require remediation. Therefore, rather than using the conventional approach of lime treatment, early attention was directed toward the progressive re-introduction of tidal flushing to the lowest areas in conjunction with flood control structures to allow remedial lime treatment of waters if necessary. The tidal exchange is planned to increase the water table in the acidified surface layer and ultimately halt the progress of oxidation of the sulfidic layers, thereby preventing the generation of more acid.

GeoCoastal (Australia) was commissioned to provide sampling and stratigraphic modelling of the site. This model provided an understanding of the depositional provenance of these soils, thereby supplying a framework for assessing their distribution, as well as fundamental relationships between soil chemistry and depositional environments. It also identified hydrogeological pathways that have the potential to conduct acidity and heavy metals to surface waters and groundwater.

Materials and Methods

Geomorphological methodology

Based on an initial examination of different generations of aerial photography of the site, four transects of boreholes spaced approximately 200m apart were selected to provide a representative picture of its depositional evolution. As is customary, these transects were orientated shore normal (i.e. parallel to direction of transgression and progradation of the shoreline).

The fundamental logging unit in geomorphology and sedimentology is the *facies*. Although definitions of what actually defines a facies remain somewhat nebulous (i.e. a facies may sometimes only be identified by its position within a series of associated facies, and by reference to an overall model of depositional systems within the practitioner's experience), it may be generally described as a 'mappable, areally restricted sedimentary body associated by either character or origin'. As the younger (Holocene-age) sediments within which acid sulfate soils are predominantly found generally have experienced minimal pedogenic modification (particularly beyond shallow surface layers), and consequently have preserved much of their original depositional character, they lend themselves well to a facies modelling approach.

Field Sites

The field survey, resulting in a total of 85 continuously cored drill holes, was undertaken between May and September 2001. The first 63 drill holes were positioned along the chosen transects, and as the survey progressed, a further 22 holes were strategically sited to investigate particular aspects of the stratigraphy. The deepest drill hole (site #14) was 22.3 m.

Coring was conducted with GeoCoastal's Geoprobe direct push/rapid hammer (1800 blows/min) drive rig mounted on a wide rubber tracked all-terrain-vehicle. This equipment, which is compact and exerts similar ground pressure to a person standing, provided unprecedented access to many poorly traffickable areas of the site.

Sample Treatment

Geoprobe cores were sliced open or extruded on site where they were: logged (i.e. for geomorphic and soils characteristics), field pH tested, and samples removed and refrigerated for laboratory analysis. Field pH before and after oxidation with hydrogen peroxide was measured in small samples of soil/sediment taken every 0.25m down the core by QASSIT staff. A spear-point pH electrode and field pH meter was used, and peroxide reaction characteristics were noted.

Laboratory Analysis

A total of 898 samples were selected by QASSIT staff with respect to both ASS and stratigraphic characterisation, in accordance with the standards set out in the *Guidelines for Sampling and Analysis of Lowland Acid Sulfate Soils (ASS) in Queensland* (Ahern *et al*. 1998). Samples were analysed at the Natural Resource Sciences Laboratories at DNR&M, Indooroopilly. The Chromium Reducible Sulfur (S_{CR}) method was primarily used, which gives the best approximation of pyrite content in highly organic sediments.

Sediment Grain Size Analysis

Fundamental division into three primary sediment groups silt/clay:sand:gravel was carried out by wet sieving in GeoCoastal's laboratory. This division can be quite diagnostic when interpreting geomorphic environments.

Palaeontological Analysis
One selected sediment sample was sent to Dr George Chaproniere (Australian National University, A.C.T.) for paleontological analysis. Analyses included assessment of benthic and planktonic foraminifera species and non-foraminiferal components.

Information collation
Field logs of the 85 drill holes were converted to digital logs using a software template developed by GeoCoastal (Australia).The digital logs also incorporate results of field and laboratory soil chemical analyses and sedimentary analyses. These composite digital logs are an important stage in the development of stratigraphic models.

Results and Discussion
A suite of 16 Holocene and pre-Holocene facies were discriminated underlying the East Trinity site. These are summarised in Table 1, and their typical stratigraphic geometry illustrated in Figure 2.

Table 1. Depositional facies and primary depositional association, East Trinity Inlet

Primary facies association		Facies	Description
Pre-Holocene–age substrate	1	Pleistocene substrate	Greenish grey & light olive brown, medium/heavy clay
	2	Pleistocene fluvial delta	Intercalated greenish grey clay and grey poorly sorted gravelly sands. Predominantly subangular, clear quartz
	3	Zone of Holocene infiltration into Pleistocene substrate	Bluish grey, medium/heavy clay
	4	Fluvial Channel	Grey, poorly sorted, pebbly, gravelly, sand: ranging to pebble size of 25mm, predominantly subangular to subround clear quartz, plus occasional lithic.
Holocene-age transgressive sequence	5	Transgressive sandy lag	Dark grey, muddy, shelly sand: poorly sorted, ranging fine to coarse
	6	Transgressive organic muds	Dark grey, uniform, moderately plastic, clayey silt – ultra organic with abundant wood debris and occasional shell fragments.
	7	Fluvial prodelta estuary/bay, sandy muds	Intercalated dark greenish grey, soft muds and sandy layers with occasional shell fragments
	8	Shelf-break backstepping fluvial delta deposits	Grey, gravelly sands: poorly sorted, predominantly subround clear quartz + numerous lithic grains + scattered organics throughout
	9	Backstepping fluvial delta deposits	Grey, gravelly sands: poorly sorted, ranging fine to gravel, subangular to subround, predominantly clear quartz with shelly layers
	10	Prodelta influenced estuary/bay muds and sandy delta lobes	Dark greenish grey, soft, clay/silt with very fine/fine sandy laminae & delta lobes of grey to greenish grey muddy sand: very fine/fine clear quartz + heavy minerals + lithic grains
Holocene-age progradational sequence	11	Estuary/bay marine muds	Dark greenish grey, soft plastic silt/clay
	12	Deltaic/prodeltaic laminated sandy muds	Dark greenish grey, soft plastic silt/clay with sand laminations
	13	Supratidal plain	Greenish grey to greenish brown, light/medium silty clay (commonly iron mottled)
	14	Chenier ridge	Light grey and brownish yellow, laminated finer and coarser sand layers ranging to gravel size with abundant degraded shell, coquina layers, including both Gastropods and bivalves.
Post-progradational features	15	Secondary estuarine infill organic muds	Dark greyish brown to very dark grey, very soft, poorly plastic clayey silt – ultra organic
	16	Alluvial levee and alluvial cap	Very dark brown to very dark grey, sandy silt/clay – sand ranging to very coarse in levee, fining as levee feathers – highly organic

Stratigraphic Architecture
The following discussion describes the character and deposition history of the facies identified on the East Trinity site in chronological order.

Pre-Holocene facies - The East Trinity site extends into the inlet from the mouth of a substantial valley in the eastern ranges (serviced by the primary stream - Hills Creek), and its geometry, as seen in aerial photography

immediately suggests that it has developed over an alluvial fan projecting from this valley. Consequently, sediments intersected at the rear of the plain were characteristically intercalated sand and gravel beds of pre-Holocene deltaic origin, underlying a thin veneer of younger sediment. Moving seaward, the pre-Holocene substrate was generally demarcated by more uniform mature clays within which coring was suspended because it defined the limit of both hydrological conductivity and acid sulfate soil potential that were the dual objectives of the survey. Deeper water-bore drilling has confirmed that an extensive, mature alluvial fan sequence underlies the site. There is a general declination from northeast to southwest in the pre-Holocene substrate underlying most of the site, however, the pre-Holocene substrate fell away dramatically toward its seaward margin (i.e. ~1:20 slope), marking the plunge into the palaeovalley underlying the present Trinity Inlet.

Transgressive facies - generally, the transgression was marked across the site by a ubiquitous blanket of highly organic, soft clay/silt sediments. Where this facies overlaid a generally low relief surface it appears to have been deposited to a thickness of approximately 1-4m, but achieved thicknesses of greater than 9m where it has filled valleys in the flooded landscape. These muds testify to the colonisation of the transgressing shore by mangroves in the protected proto-embayment, leading to the trapping and retention of suspension sediments

Also related to the marine transgression were sporadic deposits of gravelly sand directly overlying the mangrove muds. These sediments, which identify the retreat of stream mouth deltas landward, formed very substantial deposits at the major break-of-slope marking the plunge into the palaeo-valley underlying Trinity Inlet.

Progradational facies -Sea level ceased rising in the region between 6,500 and 6,000 year ago (Chappell 1983; Thom and Roy 1985). As discussed in the previous section a blanket of sedimentation had tracked sea level inland, however, as is often the case this sedimentation was unable to fill the accommodation created by rising sea level.

Following the cessation of sea level rise there is a requirement for the nearshore wedge of aquatic accommodation to fill, so that intertidal environments may prograde to form a coastal plain. At the East Trinity site this nearshore fill is composed of a uniform, soft, plastic silt clay with a distinctive green colour (Munsell 4/5GY). Field pH testing of this facies indicated that it had an extraordinary buffering capacity, leading to further tests on-site with diluted acid. From this it was concluded the sediment contained a high proportion of fine carbonate, and a sample was forwarded for palaeontological assessment which revealed that the sediment contained a low diversity, totally calcitic foramineral assemblage, dominated by the species *Ammonia breccarii* (Chaproniere 2002). This report quotes Murray (1973) as identifying this faunal assemblage with hypersaline, lagoonal or estuarine environments. The environment of deposition of this facies is subtidal and largely in open-exchange with marine conditions. It was generally observed to have a low percentage of organic material.

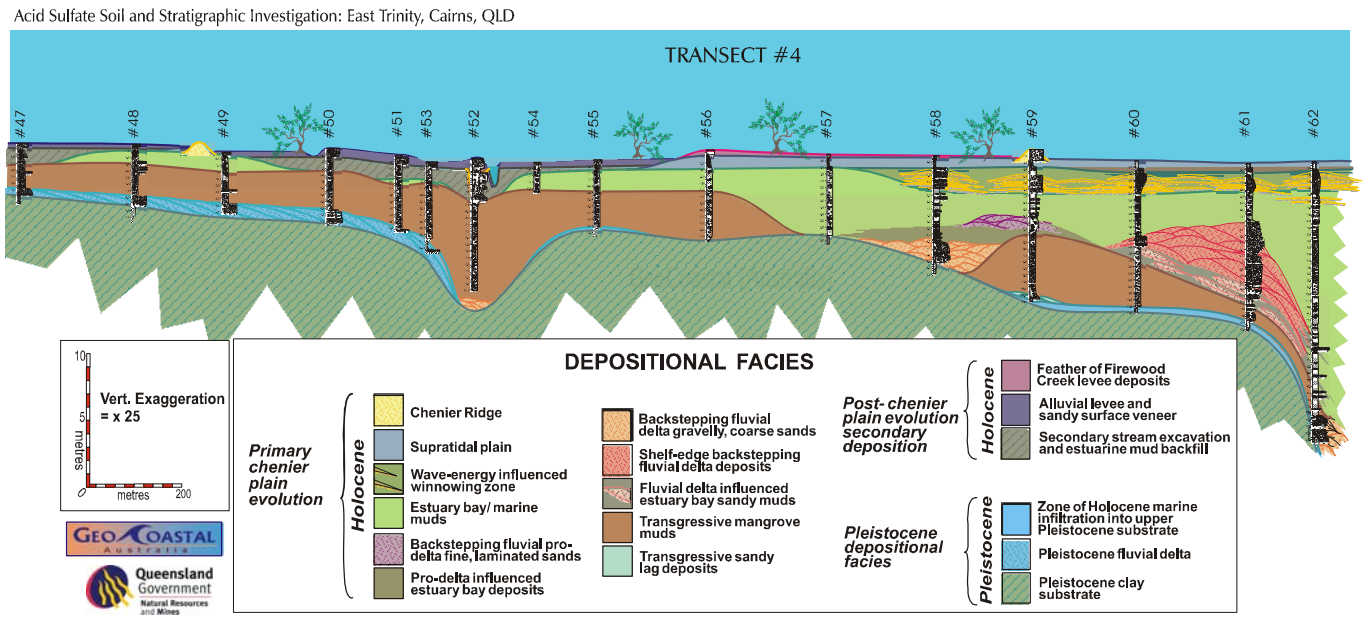

Figure 2. Stratigraphic facies associated with Transect 4 across the East Trinity site.

This systematic infill of the nearshore platform provided a foundation for the final progradation of inter-tidal environments to the present shoreline. Shoreline progradation would have been assisted by a relative sea level fall of approximately 1m resulting from hydroisostatic uplift of the Cairns coast (Chappell et al. 1982; Hopley 1982). This final phase of the site's progradational history was dominated by chenier-plain deposition. The pattern identified here appears to be of periodic stabilisation of deltas, probably in response to a dry period leading to a reduction in suspension muds and the consequent development of strandline cheniers. During alternate phases, when the suspension sediment source is again turned-on, general mudflat deposition and delta progradation is favoured. A supratidal sheet of medium clay formed a final cap on the newly developed coastal plain, elevating it into the range where halophytic plants such as samphire begin to colonise.

Post-progradational facies- changes in stream courses following the final phase of chenier plain deposition have had a substantial impact on the East Trinity coastal plain. The most significant of these is a past major diversion of the primary stream, Hills Creek, to the southeast resulting in the creation of the stream presently identified as Firewood Creek. The relict course of this channel can be easily distinguished on the 1952 aerial photograph. Allied with this relict course are low levee features which are superimposed on the original floodplain surface. Drillhole survey around Firewood Creek found that meanders were superposed into the pre-existing plain. Where meandering had scoured a swathe through the plain, secondary deposition of highly organic, laminated, very soft clay/silts was recorded. These sediments commonly have abundant jarosite and iron mottling. Once established these stream courses are preserved by tidal incursion. Similar secondary organic swamp deposition has also occurred in around Magazine Creek and in areas where the present Hills Creek has abandoned meanders. Again these sediments were highly jarositic.

Facies/Acid Sulfate Soil relationships

Pre-Holocene facies - across the site the pre-Holocene deposits were generally found to be mature, heavy clays which were intercalated with sand/gravel layers in the alluvial fan deposits toward the rear of the plain. It can generally be assumed that this old landscape had some 120,000 years of subaerial exposure during the Late-Pleistocene sea level lowstands, and consequently had exhausted any acid sulfate potential. In general the chemistry in these heavy clays supported this assumption, however, a distinctive 'blue' zone in the upper 0.2-0.4m of these substrate clays did show moderate to high levels of potential. This is a phenomenon that has now been widely observed at a number of sites in Queensland (pers. obs.), and may be the result of either transgressive mixing, or some secondary inheritance of sulfidic potential by near surface exchange with overlying highly sulfidic Holocene-age sediments. The very high values probably relate to the former explanation, however, the absence of Holocene-age accessories in many cases points to the latter.

Transgressive facies – this mangrove-rich, silt/clay sediment developed either *in situ*, or in close proximity to a densely vegetated shoreline which is a classic environment for the development of highly sulfidic soils. Consistent with this, analyses revealed levels of oxidisable sulfur commonly exceeding 2%. This facies tracks the underlying substrate, and is generally deeply buried across the site, but shallows to within 1.5m of the surface toward the rear of the plain. There is a consistent sulfidic peak just above the interface with pre-Holocene sediments associated with the initial transgression. This has been noted previously (Graham and Larsen 2000b), and may be related to selective entrainment of pyrite by reworking in this environment. Field pH_{fox} testing of transgression-related backstepping fluvial-delta sands and gravels revealed dramatic falls. However, as is often the case with sandy sediments, this did not translate to high levels of sulfidity when tested in the laboratory.

Progradational facies – a significant finding of this study was the discovery that, while the sub-tidal estuary/bay sediments that form the bulk of the shallow sediments underlying the site have significant levels of sulfides (commonly greater than 1%), they also contain sufficient available carbonate to provide total self-buffering.

The dominant source of this carbonate is the foraminifera *Ammonia beccarii*. This species has been observed in estuarine basin sediments previously (e.g. the Clarence Valley, northern N.S.W., Chappell 1991), but apparently not in the abundance observed at this site. This facies is common to many sequences in north Queensland, and further research may reveal a phenomenon whereby this species of foraminifera provides a biological counter-balance to the added levels of bacterial activity that occur in these higher temperature climates.

As discussed earlier, the environment of deposition of this sediment was in direct marine exchange, and had a relatively low carbon content; conditions which would have moderated the level biological sulfate conversion.

This relationship may break down in places toward the top of the progradational facies where upper intertidal deposits have incorporated seaward tracking mangrove shorelines, or are experiencing higher energy and can be expected to have not received the foraminiferal rain that buffers the underlying sediments.

As may be expected, the supratidal environments; cheniers and clay capping layers do not have significant sulfide levels.

Post-progradational facies - The most significant levels of existing acidity were encountered in organic swamp silt/clay deposits. These sediments were deposited as secondary infill in abandoned channels created by migrations of the stream channels since the initial phase of coastal plain deposition. These environments are typically stagnant swamps with restricted tidal ingress/egress, and are therefore very conducive to the development of sulfidic conditions. On the East Trinity site these swamps occur primarily around Firewood Creek (abandoned Hills Creek channel), and Magazine Creek, and areas adjacent to the present course of Hills Creek where abandoned meanders occur.

Hydrogeology

Three possible avenues of acid sulfate soil leachate were investigated:

1. infiltration into deep alluvial fan deposits from which groundwater is extracted locally – it was established that sufficient depth of heavy clays provided a continuous aquiclude membrane underlying the Holocene sequence
2. backstepping fluvial deposits – these sediments by their provenance often provide stratigraphic conduits, and connectivity between modern streams and the large shelf-edge, sandy delta deposits identified in the stratigraphy on this site are likely. However, it was established that these shelf-edge reservoirs are totally encapsulated by low-transmissivity marine muds, minimizing the threat of groundwater export to inlet waters
3. relict meander tracts – although the volume and connectivity of transmissive stream deposits in these relict corridors are low, they represent the most significant conduits because they are directly in contact with the most active acid sulfate soils. Fortunately, most of these conduits issue into waters that are presently being targeted by lime neutralization.

Conclusions

Geomorphological modelling of the East Trinity site proved an ideal framework within which to couch an understanding of the relationship between the sulfidic state of sediments and their progenitive environments. Importantly, the multidiscipline approach used on the project was able to both identify, and three-dimensionally delineate, sulfidic provinces with a high degree of confidence. As a result it was demonstrated that, while a substantial acid sulfate problem remains, original estimates of total site acidity were based on data from a zone of secondary deposition that is atypical of much of the site, and were therefore substantially overestimated. This understanding has provided for more targeted management strategies.

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