Department of **Environment** and **Resource Management**

Acid Sulfate Soils of Cairns
North Queensland

Queensland Government

Acid Sulfate Soils of Cairns, North Queensland

Volume 1

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Front cover photo taken from the north bank of the Barron River delta. Mount Whitfield pictured in background.

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Volume 2

(The appendices and supplements sections are presented as "Acid sulfate Soils of Cairns, North Queensland Volume 2 and are recorded on the DVD which accompanies this report.)

Summary

This survey of acid sulfate soils was funded by the Commonwealth Government as part of the Natural Heritage Trust Extension, Coastal Catchment Initiative. The survey involves an area of some 14337 ha around Cairns, North Queensland and contributes to a statewide program to identify acid sulfate soil (ASS) hazard areas.

The survey area is centred on Cairns city and extends from Palm Cove in the north to Trinity Inlet in the south. Mapping was undertaken at a 1:50 000 scale intensity.

Within the survey area 262 boreholes were sampled. Borehole depths ranged from 0.9 m to 16.8 m (average depth of 4.5m) with all soil profiles described according to national standards (McDonald et al. 1990) and field pH tests carried out at 0.25 m intervals according to Sampling Guidelines (Ahern et al. 1998). Collected samples were submitted for laboratory analysis using the Suspension Peroxide Oxidation Combined Acidity and Sulfur (SPOCAS) method (Ahern et al. 2004) and/or the Chromium Reducible Sulfur (SCR) method (Sullivan et al. 2004). All laboratory analyses were carried out in accordance with the Acid Sulfate Soils Laboratory Methods Guidelines (Ahern et al. 2004).

The accompanying 1:50 000 scale ASS map displays the depth to the occurrence of ASS. Map units were allocated a mapping code (S) and a depth code according to the depth at which the first potential acid sulfate soil (PASS) layer was encountered, based on laboratory data. Colours on the acid sulfate soil map display the depth and associated risk.

Of the 14 337 hectares investigated, 459 hectares were found to contain actual acid sulfate soils (AASS) with existing acidity up to 0.31%S (equivalent) at shallow depth (the top 0.5 m). Of the remaining 8847 hectares, PASS only were found, with up to 6.7 %S at various depths ranging from the surface to greater than 15m below the surface.

These results indicate the need for caution in planning and managing developments in the Cairns area to avoid costly damage to the environment, human health and local infrastructure. Additional investigation will be required prior to construction or excavation to satisfy the recommendations of the *Sampling Guidelines* (Ahern et al. 1998) and State Planning Policy 2/02.

Resulting from this survey is the identification of an ASS hot spot located near Yorkeys Knob. The hot spot is an area which is releasing acid water from the oxidation of PASS. Road construction, drainage and tidal control have all contributed to disturbance of the area. Road culverts constructed in 2004 at Yorkeys Knob Rd and planned to be replaced in 2080 are already seriously corroded by ASS drainage and are likely to need replacement in the near future. A Yorkeys Creek working group has been formed to address the remediation of the hot spot. Some surface liming has been carried out and a monitoring station has been installed to record pH and electrical conductivity (EC) in Yorkeys Creek.

This survey will inform major activities and development involving soil disturbance and drainage within the Cairns area. All development should follow the requirements of the *State Planning Policy 2/02; the Guidelines for Sampling and Analysis of Lowland Acid Sulfate Soils (ASS) in Queensland (*Ahern et al. 1998) and the *Soil Management Guidelines* (Dear et al. 2002). It should also be recognised that the scale of the mapping undertaken in this report is intended for general planning purposes only. Additional boreholes will be required for site specific future development in the study area

1 Introduction

1.1 Brief Overview of Acid Sulfate Soils

Acid sulfate soil (ASS) is the name given to naturally occurring sediments (sands, silts, or clays) that commonly occur in low-lying, poorly drained coastal land at elevations less than 5 m AHD. These sediments contain sulfides—primarily iron sulfides or pyrite (FeS_2). Excavating soil or sediment, extracting groundwater or filling land may cause disturbance of ASS resulting in the oxidation of sulfides and the subsequent production of sulfuric acid. This can have major environmental, health, and engineering impacts.

Disturbed land can release acid, aluminium, iron and heavy metals into drainage waters affecting aquatic plants and animals (Sammut et al. 1996). Concrete and steel infrastructure including pipes, foundations and bridges are susceptible to acidic corrosion leading to accelerated structural failure.

Undisturbed ASS range from grey silty sands, black high plasticity silty clays and organic peat materials with pH values close to neutral (pH 6.5–7.5). In this state they are termed potential acid sulfate soils (PASS) because they have the potential to oxidise and produce sulfuric acid. If ASS are exposed to air, the sulfides oxidise and sulfuric acid is produced (for example: one tonne of iron sulfides can produce about 1.5 tonnes of sulfuric acid when oxidised). In this state they are known as actual acid sulfate soils (AASS). AASS are very acidic (pH <4), and often contain a straw yellow coloured mineral called jarosite. The term acid sulfate soil (ASS) includes both Actual Acid Sulfate Soil (AASS) and potential acid sulfate soil (PASS).

Potential acid sulfate soils are generally located below the permanent water table and remain inert when maintained in a state of permanent saturation. If appropriate planning is in place to avoid both direct disturbance and indirect exposure via lowering of the groundwater table, harmony between the built environment and the constraints presented by PASS materials can be readily established.

Occurrence of AASS in the profile can be the result of natural processes such as prolonged drought causing lowering of the natural groundwater table. As a result AASS and PASS can be found in the same soil profile, with AASS generally overlying PASS. Consequences of these natural occurrences, whilst widespread are generally mild in effect due to the limited or thin oxidation front, slow transport of acid via groundwater and the natural buffering potential present in many soils.

1.2 Local Acid Sulfate Soil Disturbance Risks

The production of AASS can be rapidly accelerated by the way we use and modify our land and groundwater resources. In North Queensland, the largest and most extreme environmental consequences have been experienced through changes to the natural hydrology including lowering of natural groundwater tables and tidal exclusion. These effects are long lasting and may result in regular fish kills and serious deleterious impacts on water quality in highly sensitive fish nursery areas. Infrastructure that can contribute to extreme levels of environmental harm include water table drainage, tidal exclusion via floodgate culverts and levees, and linear infrastructure such as roads and rail corridors that exclude or reduce tidal influence over lands containing ASS. Disturbance to ASS through overuse of groundwater is also suspected, particularly within shallow coastal sand aquifers. Whilst these groundwater disturbances can be widespread, water in these areas is used primarily for irrigation as opposed to potable supply. As a result, the impacts from overuse of groundwater in North Queensland remain widely under reported and poorly documented.

Most urban impacts to ASS in North Queensland have occurred through lack of knowledge and consideration of ASS as a development constraint. Close consideration of site limitations should be undertaken by relevant authorities, particularly when planning or assessing development in areas containing shallow or strong ASS. The presence and transmissivity of groundwater in the aquifer and the sensitivity of the receiving environment can be major contributing factors when considering appropriateness of a particular development. Types of developments that should be closely monitored include canal and marina style developments, cut and fill developments where the fill is sourced within low-lying lands, drainage works or works in and around watercourses, sand quarrying activities and overuse of groundwater from irrigation bores or leaky "pump out" basement car parks.

Impacts from repeated ASS exposure around urban centres are cumulative and may lead to deleterious impacts on ground and surface water quality around and under our coastal towns and cities. Of considerable concern are the impacts these disturbances have on built infrastructure. Experience has shown that infrastructure most at risk include road culverts, bridge footings, building foundations and pilings, basement car parks and all buried services. The costs for early replacement of this infrastructure places heavy strains on the financial stability of local authorities, service providers and government with the ultimate financial liability borne by the general public by way of charges, taxes and rate contributions. Combined with this, are the engineering challenges faced when attempting to reinforce or replace foundations and footings under existing buildings and increasing delays to our transportation system as bridges, pipes and other buried infrastructure are replaced well short of their expected service life spans.

1.3 Policy Context

In Queensland, concern over mounting engineering and environmental costs from improper management of ASS has led to development of the *State Planning Policy 2/02, Planning and Managing Development involving Acid Sulfate Soils (SPP2/02)*. The policy targets assessable high risk development and enables case by case assessment under a framework of guidelines for best practice.

Mapping areas where there is a high risk of ASS exposure is the next pro-active level of ASS Management. Mapping offers critical information relating to the general location, depth and strength of ASS in targeted areas. The maps and associated reports and laboratory data can readily be used at all levels of government for informed strategic planning, development assessment applications and by the private sector for commercial decision making with on ground survey and management requirements. In this manner, mapping supports and encourages the preferred “avoidance” outcomes of the SPP2/02.

Within the Wet Tropics area, seven areas were identified by a Far North Queensland Water Quality Improvement Plan (WQIP) committee as requiring ASS mapping. These included the areas around the Daintree River, Port Douglas, Cairns, Russell / Mulgrave Rivers, Hull / Tully / Murray Rivers, Johnston /Moresby Rivers and the Ingham area. Of these areas, the Cairns region was prioritised for special ASS mapping by the projects’ steering committee. Reasons for mapping Cairns revolve about the city being the largest and most rapidly expanding urban centre in the region and a history of serious ASS impacts as a consequence of sugarcane expansion, as seen at East Trinity. Cairns has an overwhelming need for reliable information to effectively plan and manage urban and infrastructure growth. This coupled with the area’s environmental significance, the importance of environment-based tourism and a strong recreational fishery, led to Cairns and surrounds as the area being the highest priority district for special ASS mapping.

This report details the 1:50 000 scale ASS mapping undertaken by the Department of Environment and Resource Management in the Cairns Area (refer to attached map).

1.4 Survey Area

Cairns is situated on the northeast wet tropical coast of Queensland and experiences hot and humid summers and mild dry winters (Figure 1). The average annual rainfall is 1992 mm with the majority falling in summer between January and March. The landscape is dominated by steep rainforest covered mountain ranges extending in places to elevations in excess of 1000 metres rising dramatically from a narrow strip of coastal lowland.

Cairns CBD is situated on a low chenier plain off Holocene age for the most part between 2 and 3 metres above mean sea level. Cairns is confined by Trinity Inlet, the Murray Prior and Malbon Thompson mountain ranges to the east and the Macalister, Whitfield, Lamb and Bellenden Ker mountain ranges to the west. Areas available for urban expansion in the south include the Mulgrave Valley toward Gordonvale in the north across the more elevated parts of the Barron River delta. Growth across the Barron River delta is strictly controlled under council codes based on flooding risk.

Substantial residential growth in the south has resulted in the community of Edmonton becoming enveloped by Cairns. Productive lands (primarily sugar cane cultivation) between Edmonton and Gordonvale are now under increasing competitive pressure with urban land uses. Urban growth to the north of Cairns is concentrated on several expanding beach suburbs with the modern suburb of Smithfield as the central hub.

This survey is centred on Cairns city and extends from Palm Cove in the North to Trinity Inlet in the South. It is the intention of the survey to encompass expected urban expansion within both the Northern and Southern growth corridors as well as urban renewal within the Cairns CBD.

1.5 Mapping Scale Intensity

Mapping scale is directly related to survey intensity, that is, the number of soil profiles and associated information collected per unit area. The mapping in this report is carried out at approximately 1:50 000 scale which translates to an average of four (4) fully described and sampled soil profiles per square kilometre (one per 25 ha or every 500 m). The sites are located using free survey techniques at spacing's of 200 to 400 meters depending upon landform or at wider intervals in tidal areas where ASS are consistently present. The remaining areas are at a broader scale of mapping, that is at 1:100 000 scale which implies one borehole per square kilometre and that mapping was completed by aerial photograph interpretation.

The resultant mapping provides map boundaries that indicate the presence of both actual acid sulfate soils (AASS) and potential acid sulfate soils (PASS) at various depth intervals. Areas of disturbed land that are likely to contain ASS have also been identified but because of the difficulty of assessment, or of accessibility, limited or no field verification has been carried out. Areas of disturbed land include the central business district of Cairns city, extractive industry sites, aquaculture and marina developments.

Mapping at 1:50 000 scale provides a clearer indication of the depth at which ASS occurs; the texture or particle size of the differing layers and the concentration of sulfides present. This information is vital for strategic planning decisions relating to current or future use of subject lands. Mapping at 1:50 000 scale is not of sufficient intensity to replace any site based assessments required under the *SPP2/02 Planning and Managing Development involving Acid Sulfate Soils.*

An unpublished draft map of ASS at East Trinity was produced by Malcolm et al. 2009 and has been incorporated into the mapping area of this study.

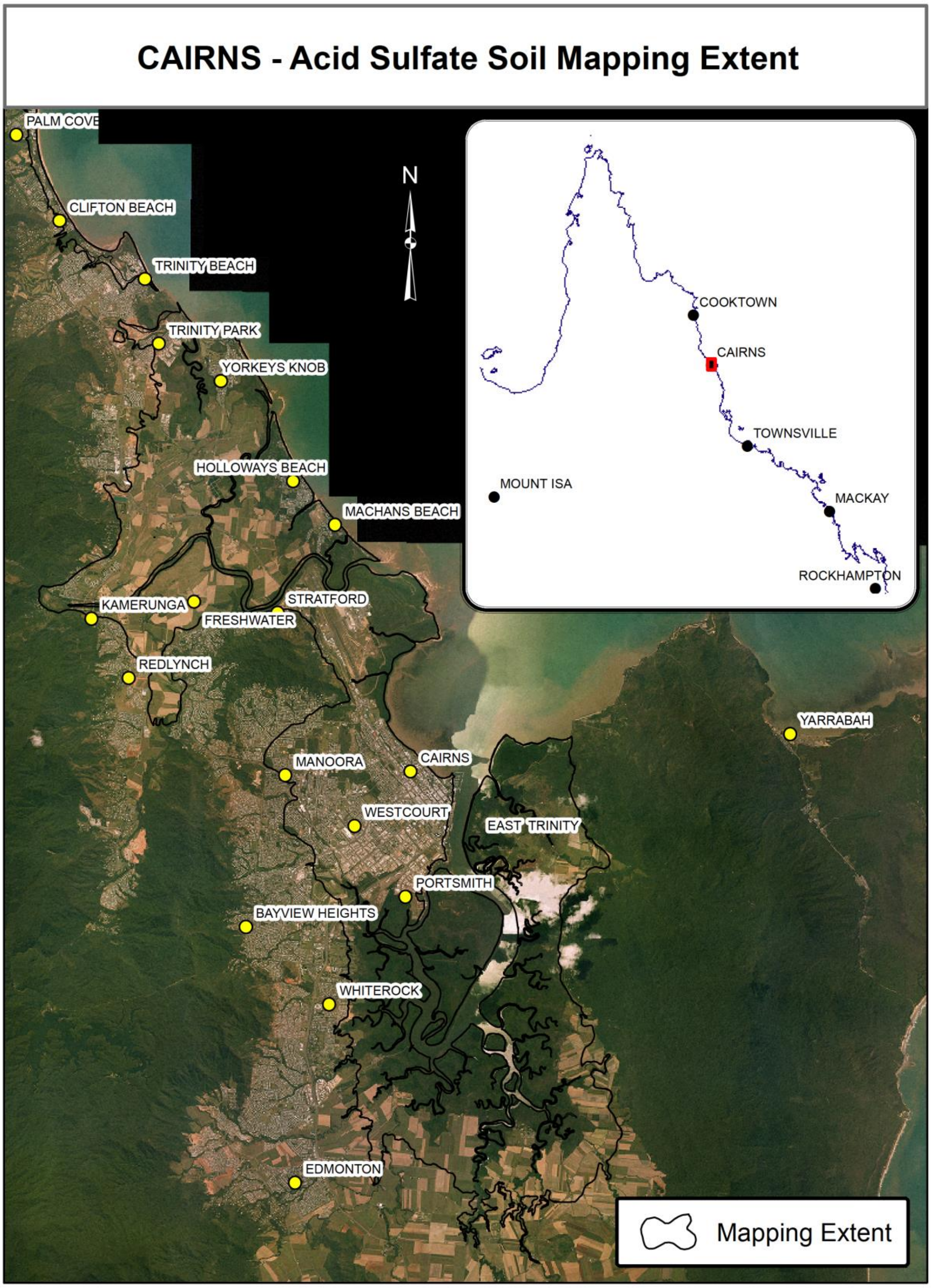

Figure 1: Extent of acid sulfate soil survey, Cairns area.

2 Brief Environmental History of the Cairns Area

Sourced from (cairns.qld.gov.au/cairns/heritage/History/Timeline)

Three indigenous tribes inhabit the area - Irukandjii, north of the inlet, Indindji, south of the inlet, and the Tja Pukai on the Kuranda range.

Captain James Cook anchored his ship, the Endeavour in a bay to the east of modern day Cairns, on the 10th June 1770. He named it Trinity Bay after Trinity Sunday, the day he sailed past the area.

Cairns was settled in 1876 as a port for the Hodgkinson goldfield. The original settlement was established along the frontal dune that formed the northern shore of Trinity Inlet. Within only weeks of arrival, Land Commissioner J. P. Sharkey called for volunteers to clear the mangroves along the beach. The first Borough Council was formed ten years later and its priorities were street formation, vegetation clearing, drainage and filling. It is likely that environmental consequences related to ASS were evident from about this time.

In March 1884, the prosperity of Cairns was secured, when the Barron Valley gorge route was chosen as the railway line from the Hodgkinson goldfields to the port of Cairns. The advantages of this railway were that all weather access could be maintained to the goldfields. The area occupied by Cairns CBD was progressively filled with between 0.5 to 4 metres of fill to bring it above most tide and flood levels. Dredge materials were used along with materials excavated during construction of the Cairns to Kuranda railway and various nearby quarries.

Malaria was a problem during much of Cairns' early history. In 1910, after two malaria-infected miners returned from Papua New Guinea, 120 cases of malaria were reported in Cairns with 24 deaths. The mosquitoes of the Cairns swamplands were believed to have taken on the malarial parasites. An extensive malaria epidemic struck the area again in 1913. A medical research unit was established in 1922 in an attempt to curb further outbreaks. During the Second World War, when about half of the civilian population had evacuated Cairns and the city was a major military base, it is reported that a malaria outbreak in 1942 resulted in every Cairns household having at least one malaria case. The Army, in conjunction with the Allied Works Council set out to systematically eradicate the mosquito breeding grounds. Consequently more wetland areas likely to contain ASS were drained and filled.

Sugar cane is the major agricultural crop of the area. The first cane was planted in 1879 and Hambledon Mill (near Edmonton) was opened in 1883. Expansion of sugarcane into marginal low-lying lands from the mid 1960s resulted in the disturbance of shallow ASS through deep drainage and tidal exclusion. One such disturbed area is the East Trinity Site (940 Ha) immediately opposite Cairns on the eastern side of Trinity Inlet. The environmental consequences of ASS exposure at East Trinity have been so severe that the land was purchased by the Queensland government in 2000 for rehabilitation purposes and to promote the green backdrop to Cairns. This area, now known as East Trinity Environmental Reserve, is being remediated using an innovative, low-cost plan devised by the Queensland Acid Sulfate Soil Investigation Team (QASSIT) from the Department of Environment and Resource Management (DERM). The plan involves controlled, lime-assisted tidal exchange and wetland creation. The ASS mapping of the East Trinity Site has been included in the map associated with this report.

The Barron River floodplain is the primary source of concrete sand and bedding fill sand for the Cairns market. Conveniently located to supply the regions booming construction industry, these sands are commonly mixed with or underlain by acid sulfate materials. As the existing pits are exhausted, sand miners are moving into other areas and can encounter quantities of acid sulfate materials. Whilst management practices have generally improved with growing awareness, significant impacts have been experienced with historical facilities. There is a growing awareness that exhausted sand pits between the Captain Cook Highway and Yorkeys Knob may be contributing to lowering groundwater pH in the area.

Dredging for navigational purposes was first initiated in Cairns in 1888. Regular dredging of the channel has been carried out since this time. Historical photographs indicate that iconic "mud flats" along the Cairns esplanade were either not present or considerably less pronounced. Excavations at the foreshore and photographs indicate the original foreshore was most likely a shelly coarse sand beach. It is surmised that sediment dumped close inshore during early dredging activities has accumulated along the foreshore with the prevailing south easterly wind. Today Cairns mudflats are conserved as a declared fish habitat and an internationally recognised migratory bird habitat. The Port of Cairns is currently permitted to dredge 500,000 m^3 per annum. Dredging and sea dumping today is carefully managed to lessen the environmental impacts and must comply with the national guidelines (Commonwealth of Australia 2002). Approval for dredging is managed by the Great Barrier Reef Marine Park Authority.

As the world heritage listed Wet Tropics rainforest and Great Barrier Reef are within day tour range from Cairns, the Cairns International Airport was established as a major centre for both domestic and international tourism. Currently Cairns International Airport is the fifth-busiest airport in Australia and the largest regional airport in the country. The airport is fully contained within and immediately overlying a large tract of ASS materials.

Sale prices for residential land have increased substantially in recent years. Achieving the prescribed minimum habitable floor levels has become increasing challenging when attempting to develop into marginal low-lying sites. Large quantities of fill are required and it is generally cheaper to source this from within the development site resulting in canals, feature lakes, bank widening and deep basement car parks.

The full long-term effect from historical ASS disturbances on the built environment is yet to be determined, but accelerated erosion of water infrastructure is a common occurrence in the city. The effect of acidified soils on infrastructure such as foundations and underground services is a large potential financial impost. As a result, it is vital that new lands proposed for development are considered carefully and with due regard to the limitations presented by the ASS hazard.

3 Geology

Sourced from (Willmot and Stephenson 1989 and Jones 1985)

Cairns' geology is located within the Palaeozoic Hodgkinson Formation which includes a suite of mostly metamorphic rocks within a large area east of the Palmerville Fault. With their origins as deep marine sediments, Hodgkinson rocks were compressed and then extruded from the ocean approximately 360 million years ago as a result of a compression in the earth's crustal plates. Rocks of the Hodgkinson Formation include interbedded argillite, slate, greywacke, quartzite, greenstone, phyllite and schist. The coastal ranges including Whitfield, Macalister, lower parts of the Lamb range to the west of Cairns are comprised of Hodgkinson type rocks.

Younger granite intrusive rocks of Palaeozoic age form the other major rock type in the Cairns district. Intrusive granitic rocks welled up underneath the older Hodgkinson formation rocks between 310 and 230 million yeas ago. Preferential weathering of Hodgkinson rocks has resulted in the underlying granite rocks becoming exposed and these now comprise many of the highest peaks including Lambs Head (1306 m), Mt Bellenden Ker (1582 m) and Bell Peak North (1026 m). Granites of the Lamb, Murray Prior, Malbon Thompson and the Bellenden Ker ranges typically contain coarse biotite and large elongate potassium feldspar crystals.

Sheering, faulting and basaltic volcanism are also a feature of the Cairns landscape. The north-northwest trending Russell Mulgrave Shear zone (248-235 million yeas ago) is a prominent feature, particularly visible about the Barron George in the North and Mulgrave valley south of Gordonvale. There have been several more recent small basaltic eruptions south of Cairns, the most obvious being Green Hill (900,000 years ago) located at the southern end of Trinity Inlet.

Erosion and depositional regimes are significant in the shaping of Cairns' coastal lowlands. Steep mountain ranges combined with high rainfall have resulted in rapid erosion and distribution of sediments across low-energy delta areas of the Barron and Mulgrave Rivers. There has been regular and pronounced migration of these rivers, particularly the Mulgrave River which migrated south leaving a remnant delta (Trinity Inlet). Much of this study is contained about and within the Barron River delta and Trinity Inlet areas.

4 Geomorphology

In general the sediments in which ASS form were laid down during periods of high sea level similar to those we know today. These high sea levels (which correlate with interglacial periods), have occurred twice in the last 150 000 years. Although it is generally recognised that the majority of ASS occur in sediments deposited in the last 10 000 years (Holocene epoch), it is useful to look further back in time to gain a better understanding of their deposition. There has been little tectonic activity along the eastern coast of Australia since ca. 130 000, which makes this region very well-suited to the study of sea-level change.

During the previous interglacial period within the Pleistocene epoch (140 000 to 120 000 BP), evidence suggests that sea levels rose several metres higher than present (Pickett et al. 1985). This caused the drowning of river valleys and low lying coastal areas. In general, shorelines and floodplains were pushed many kilometres west of where there are today and estuaries similar to those of today were formed. After this sea level high, there was climatic variability during the latter part of the Pleistocene epoch (120 000 to 20 000 BP) imposed by global warming and cooling. The sea level receded and then fluctuated between 80 m and 140 m below present (Bloom et al.1974). During this time, rivers and creeks cut deep channels through the previously deposited fluvial and estuarine sediments, removing some and isolating others. The climate from 27 000 to 10 000 BP experienced expanding semi-arid conditions with corresponding humid periods during interglacial cycles. This drier climate caused corresponding changes to flora and fauna. During this period grasslands and open woodlands dominated the area. A corresponding accumulation of sediment also resulted in the development of extensive alluvial fans such as the Mulgrave fan (Nott JF 2003).

The most recent sea level rise (the post glacial marine transgression) commenced approximately 19 000 – 18 000 years ago. At this time sea level was estimated to be 140 m lower than present with the Cairns shoreline up to 40 km east of where it is today. At the commencement of the Holocene (10 000 years ago), sea level was approximately 25 m below present and still rising (Thom 1981) with present sea level being reached around 6 500 BP (Thom and Chappell 1975). Around 4 000 BP there is evidence that a minor sea level rise occurred of approximately 1m along the southern Queensland coast, and then the sea level returned to its present position (Jones 1992). With higher tidal ranges in north Queensland, there is a significant likelihood that ASS was deposited at higher AHD levels than southeast Queensland.

The rapid rate of sea level rise during the Holocene exceeded the rates of coastal deposition and thus valleys and low lying coastal areas were drowned just as they were during the Pleistocene. Once sea level rise stabilised (termed still stand), new estuaries were formed and coastal deposition processes were able to commence filling the newly created subaqueous space.

4.1 Geomorphology of Estuaries

Understanding the coastal geomorphology of an area is an integral part of mapping ASS. The following provides a basic insight into the coastal processes that have enabled ASS formation in the mapping area.

An estuary is defined as the seaward portion of a drowned valley system which receives sediment from both fluvial and marine sources and which contains facies influenced by tide, wave and fluvial processes Dalrymple et al. (1992). The marine processes (waves and tides) decrease in intensity up the estuary while the fluvial process decrease in strength down the estuary.

According to Dalrymple et al. (1992), ideal estuaries can be divided into three energy zones (Figure 2):

(A) an outer zone dominated by marine processes i.e. waves and tidal currents;

(B) a low energy central zone where incoming marine energy is balanced by river energy; and
(C) an inner river dominated zone.

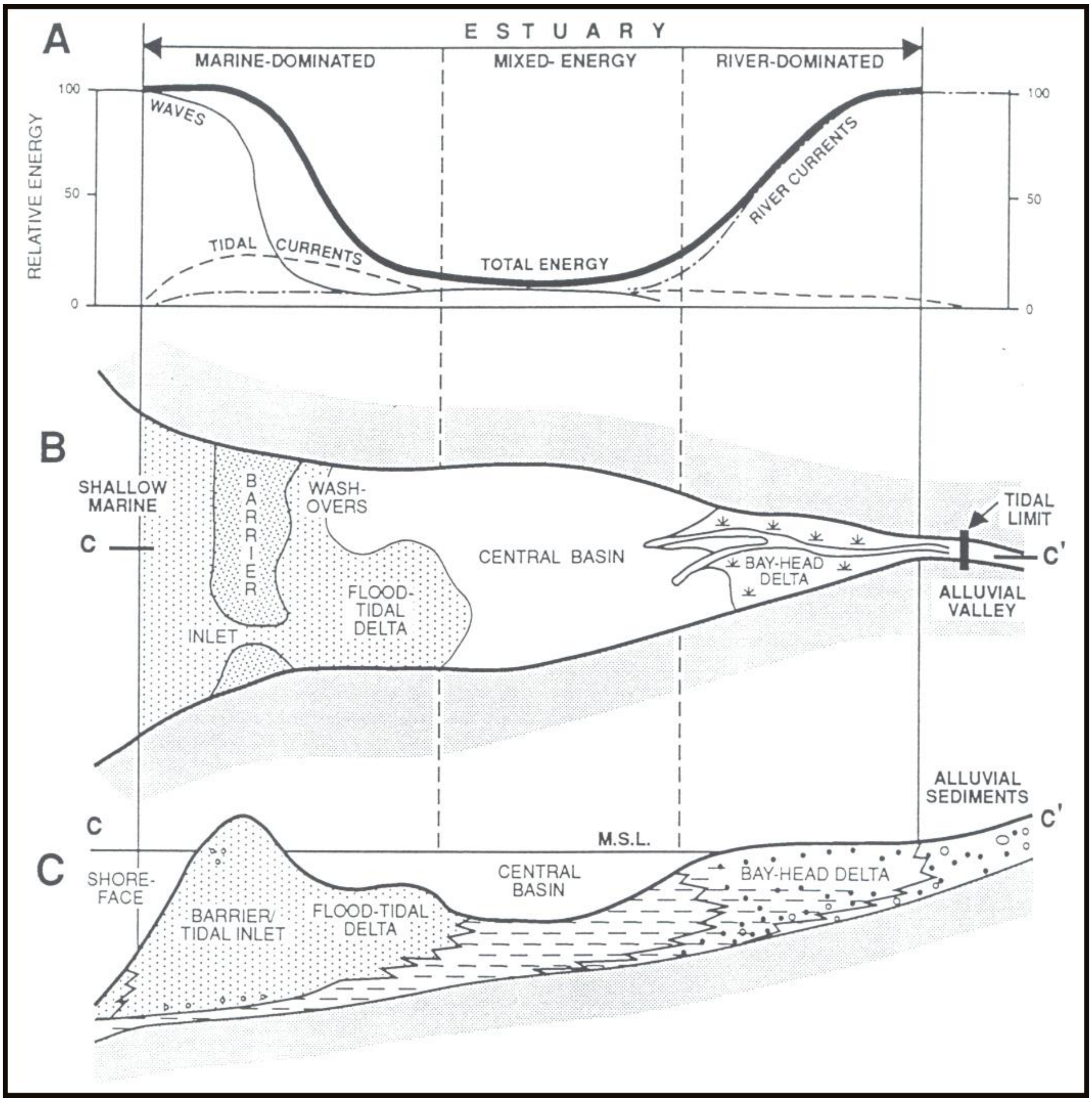

Figure 2. Estuary energy zones as described by Dalrymple et al. (1992).

4.2 Local Coastline Evolution

The coastline evolution of Trinity Bay is well documented in Beach Protection Authority (1984) and Jones (1985). The Quaternary geology of Trinity Bay can be seen in Figure 3. The coastline is discussed in more detail in the three sections that follow.

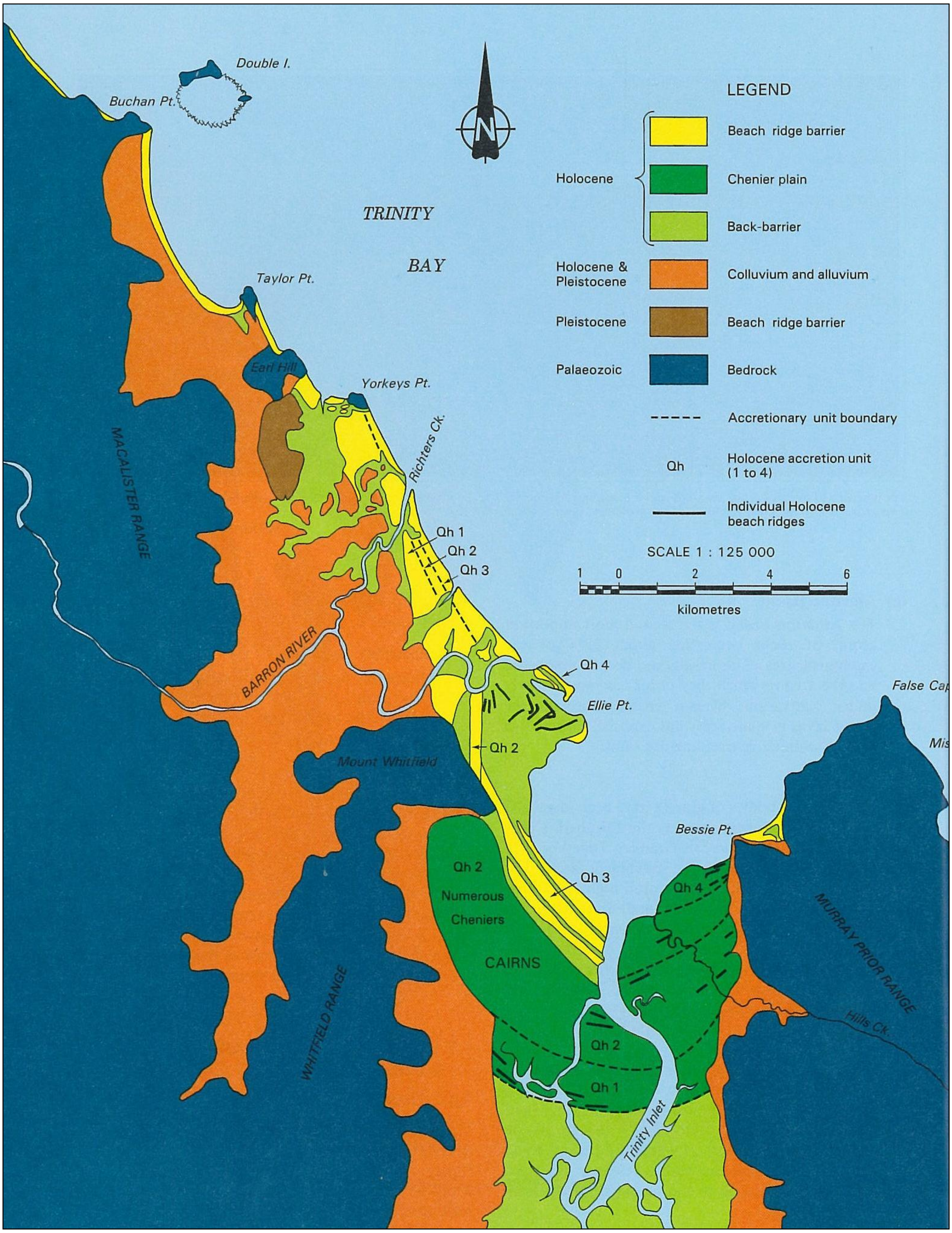

Figure 3. Quaternary Geology of the Cairns district Beach Protection Authority (1984), Jones (1985)

Buchan Point to Earl Hill
A narrow colluvial scarp exists at the base of the range between Buchan Point and Taylor Point. Holocene deposits consisting of a narrow beach barrier were deposited in front of this scarp. The beach deposits were formed by wind, wave and tidal action, from the northwards littoral drift of sand supplied from the Barron River. Smaller elements of this formation include parallel swales which dissect the beach barrier (Figure 4(a)). The swales can also include creeks that drain the foothills of the escarpment such as Sweet Creek, Deadmans Gully and Deep Creek. The creeks are often closed during the dry season and open during the heavy rain experienced in the wet season.

Earl Hill to Barron River
The Barron River delta stretches from Earl Hill in the north to Ellie point in the south and Kamerunga at the start of the delta in the west. The Barron River delta is a wave dominated delta, comprised of a river directly connected to the sea via a channel(s) that is usually flanked by low-lying vegetated floodplain and swampy areas. Entrances of wave-dominated deltas are relatively narrow due to constriction by a barrier (or sandbar) and, due to the relatively high river influence throughout the system, are rarely closed off from the ocean. The wave energy, in combination with tidal currents, causes sediment to move along shore and onshore into the mouth of the estuary where a barrier such as a spit or submerged sand bar forms. These beach barriers then prevent much of the wave energy from entering the estuary (Dalrymple et al. 1992). In general, marine sands are deposited as tidal deltas behind the barrier by incoming tides. Whilst in the upper reaches (dominated by river energy), fluvial sediments are deposited as bay head or fluvial deltas. The area of neutral energy (central basin) between the two is generally filled with finer sediment such as clays and silts. With time and a sufficient sediment supply, estuaries eventually fill with sediment and mature (Roy 1984). Once the central basins (or lagoons) are filled, river processes begin to build alluvium out over the top of the marine sediments during flood events.

The largest beach ridge barrier occurs from Mt Whitfield located south of the Barron River, northwards to Yorkeys Knob. The supply of sand via northward drift to the beaches north of Yorkeys Knob would have been disrupted by the protruding headlands (which include Yorkeys Point, Earl Hill, and Taylor Point) limiting the supply and formation of large beach ridge barriers in this area.

The migration of river channels are common place during delta developments because distributaries cannot extend indefinitely, because the gradient and the capacity of the river to flow gradually decreases towards it exit point. The river will eventually be diverted to a new higher gradient course, usually during a flood where the river breaks through its natural levee, and it develops a new course. The new course shifts the site of sedimentation to a different area, and wave and current action attack the abandoned segment of the delta. The new and active delta builds seaward, developing distributaries and splays until it also is eventually abandoned, and another site for active sedimentation is formed. The progradation of the Barron River delta has occurred by the extension of sand beach ridge barrier deposits over prodelta deposits. The area of Ellie Point consists of a series of progradation sand ridges with the intervening depressions colonised by mangroves (Figure 4(c)).

The Barron River delta channels that dissect the beach barrier include Moon River, Yorkeys Creek, Thomatis Creek, Ritchers Creek, Barr Creek and Redden Creek. Moon River and Barr Creek are currently only connected to the Barron River through overland flow.

Trinity Inlet and Cairns
It has been proposed that the Mulgrave River once entered the sea at the mouth of Trinity Inlet (Jones 1985). However, a large alluvial fan now extends from the Mulgrave River valley, northward towards Trinity Inlet. The development of the fan approximately 10 000 BP blocked the Mulgrave River from flowing northwards. When the sea level dropped around 4 000 years ago to its present level, the Mulgrave River was trapped in its present course some 30km further south. Major freshwater flows to Trinity Inlet over the Mulgrave fan (via relict streams) only occur when the Mulgrave River is in full flood. The Mulgrave fan is composed of sediments predominantly finer than medium-grained sand, with occasional pebbles and gravels. The Green Hill volcano located south of Trinity Inlet erupted some 900 ka ago while the Mulgrave River was still flowing north and had little influence in redirecting the Mulgrave River southwards (Willmott and Stephenson 1989).

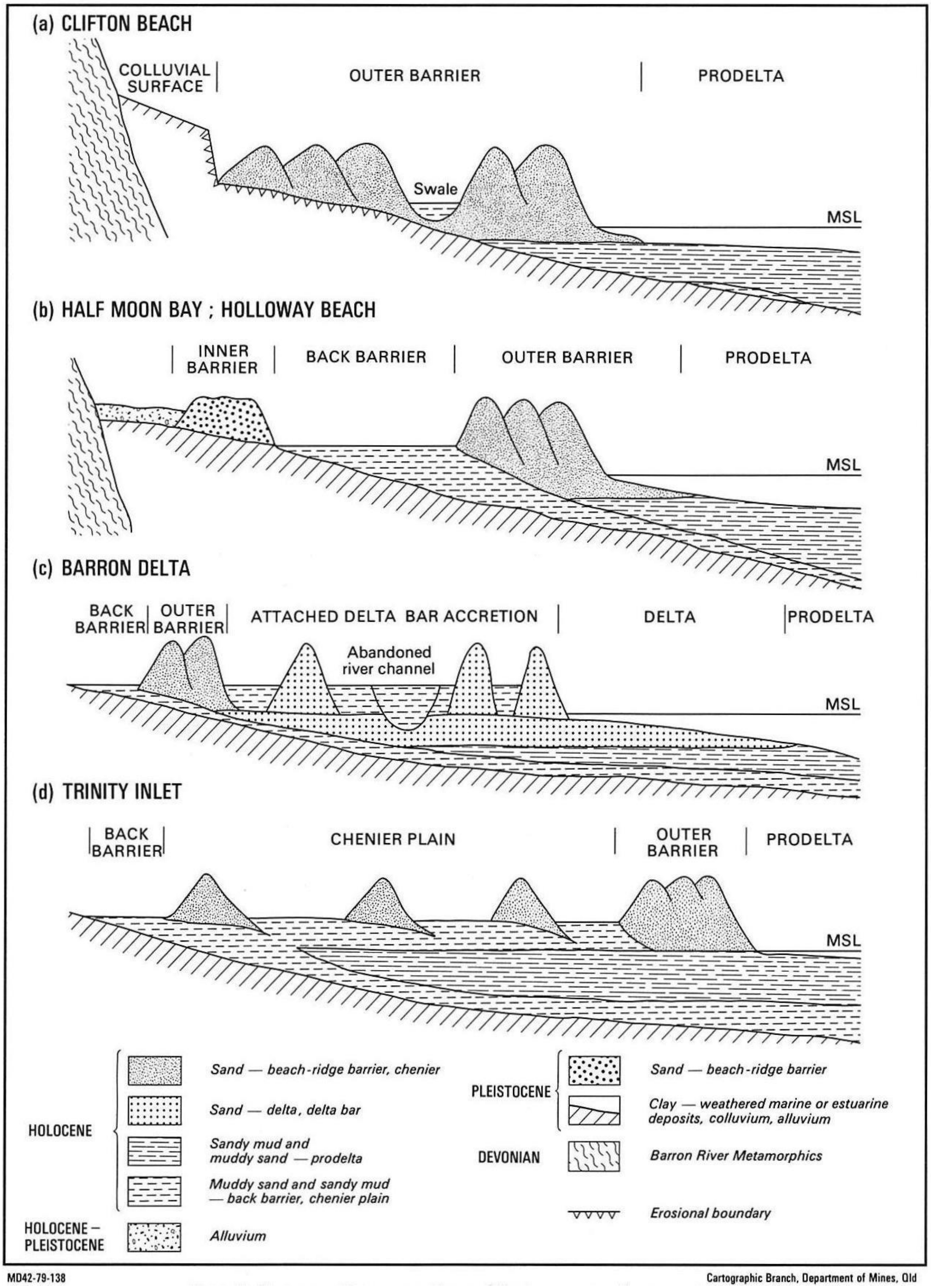

Figure 4. Diagrammatic cross-sections of Quaternary accretionary systems along the Cairns coastline. Beach Protection Authority (1984) and Jones (1985).

Three accretionary landforms occur in Trinity Inlet. These are shown in Figure 3 and diagrammatically in Figure 4(d).

- Back barrier estuarine plain
- Chenier plain in the central and eastern areas
- Beach ridge barrier in the northwest

Trinity Inlet is a tidal-dominated creek system. These systems are characterised by wide, funnel-shaped coastal waterways, and unlike deltas they have a very low freshwater input. They typically develop in low-gradient, seaward-sloping coastal flats. Estuarine back barrier sandy muds extend southwards from the most landward chenier, located at the centre of Admiralty island, to the Mulgrave fan deposits. There are numerous streams traversing the Mulgrave fan, some of these streams have incised into the Mulgrave fan allowing the deposition of ASS. Some of the streams that intersect the Mulgrave fan have their own fan development extending from the surrounding hills on top of the older Mulgrave fan.

The northern and eastern areas of Trinity Inlet and Cairns are wave-dominated chenier plains. Cheniers are long narrow sandy ridges resting on mud along a seaward-facing tidal shore with their bases near high tide mark. They differ from beach ridges which have sandy bases extending below the high tide mark. These cheniers can be formed by either erosion or deposition. The cheniers in this area are formed from storm action washing coarser sediment from offshore sources and depositing it as a ridge. The supply of sand and creation of parallel cheniers to the eastern side of Trinity Inlet is substantially less than that on the western side (Cairns city). This is either the result of the wave-sheltered eastern side of the bay or that Trinity Inlet itself restricts the amount of sand transported to East Trinity from the Barron River. Some of the sand on the eastern side of Trinity Inlet may be have been sourced from northwards littoral drift. The southern most chenier located on Admiralty Island is a continuation of the oldest cheniers on the Cairns plain.

The older cheniers in the west of Cairns are up to 3.5 meters above mean sea level. Radio carbon dating of the shelly material at the base of the oldest cheniers has yielded an age somewhere between 5530± 130 years before present i.e. 1950 (Bird 1972). The older cheniers where deposited when the sea level was higher than the younger cheniers nearer the present coastline, which have reached a height of 2 meters above mean sea level. The change from cheniers to a beach ridge barrier system (Figure 3) in the northwest corner of Trinity Inlet suggests an increase in sand supply from the Barron River. The mouth of the Barron River may have been closer and a change in climate with increased north-easterly winds may have spurred the development of the beach ridge barriers. When the Barron River diverted northwards, Cairns no longer received a sand supply to develop more sand ridges.

5 Acid Sulfate Soil Landscape Features

5.1 Bund walls, Floodgates and Watertables

Watertables in wet tropical climates are generally close to the soil surface all year round with only a limited drop in watertables (if any) over the dry season. ASS are generally not subject to significant oxidation from natural watertable fluctuations and do not produce large volumes of acid in their natural state.

Along the Queensland coast bund walls and floodgates have been used to protect land for sugarcane growing, grazing, urban development and other land uses. The construction of bund walls and floodgates keeps tidal inundation and storm surges out of low lying land while allowing for flood water to escape. The location of bund walls vary and can be located in either the intertidal, supratidal or extratidal zone. The lower in the landscape they are placed, the greater the chance for disturbance and acidification of ASS.

Most bund walls have been in place for many years and often ASS material has been used in the construction of the wall. ASS material has been obtained by either creating a large deep drain on the outside of the wall or a shallow wide depression on the inside of the wall. Vegetation often takes a long time to establish on bund walls made out of ASS material and jarosite is usually present on the surface or just below.

A drop in watertable levels as a result of bund walls and floodgates will cause the oxidation of ASS layers located close to the soil surface and consequent production of acid. This acid may be leached out of the soil during the first rainfall events of the wet season, usually thunderstorms from October to December and transported to waterways quickly where drains have been installed. The result may be environmental harm, such as fish kills and stress on vegetation such as mangroves and salt marshes. The texture of the ASS will influence the rate that acid may be leached out of the soil. Sandy soils will be exhausted more quickly than clay soils but they may contain less acid than clay soils. The high water content of ASS when soils dry out causes the elevation of the land to drop. Thereby making it impossible in some cases to remove the bund wall and floodgates. When floodgates fail due to debris or vandalism seawater can inundate the land causing loss of value to agriculturally productive areas.

Drains and creeks intersecting the floodplain allow for the draining of flood water and also act as transport corridors for the release of acid water. The water temperatures in the drains and creeks during the summer months increases causing greater levels of algal growth and microbial activity. This can lead to stagnation, low levels of dissolved oxygen and increased risk of fish kills. Water quality quickly deteriorates in drains that do not have regular tidal exchange. Floodgates that allow controlled tidal exchange will have the following desired effects:

- neutralise any existing acidity and restore neutral pH to the watertable
- higher watertable levels preventing ASS oxygenation and release of heavy metals
- decrease algae and aquatic weeds growth
- increased dissolved oxygen levels and prevention of odours from stagnant water
- increased fish passage and decrease in mosquito breading areas
- prevention of fish kills and red spot disease

5.2 Self-Neutralising Acid Sulfate Soils

The subtidal progradational sediments that form the bulk of the shallow predominately clay sediments underlying the beach ridges of the Barron River and chenier plains of Trinity Inlet and Cairns have significant levels of sulfides (commonly greater than 1%S). These sediments also have sufficient available carbonate to provide total self-neutralising capacity. The dominant source of this carbonate is from foraminifera dominated by the species *Ammonia beccarii* (Chaproniere 2002). Deposition occurs in saline subtidal environments. A PASS layer without the self-neutralising foraminifera is generally found directly above the self-neutralising layer. The PASS sediments consist of either peat, clay or sand textured, and are intertidal deposits of the gradational seaward-facing tidal shore.

From the soil profiles sampled at East Trinity and during this study the self-neutralising capacity layer is typically a soft silty clay, of (Munsell 2000) greenish grey colour (5GY4/1, 5GY5/1, 10Y4/1, 10Y5/1). Some visible large shells are present but these do not provide sufficient neutralising capacity. Field pH testing revealed a pH_F average of 8.0 and pH_{FOX} average of 6.4 (1.6Δ). The lab results from the self-neutralising capacity layer show a average net acid base accounting neutralising capacity sufficient to neutralise an additional 3% pyrite sulfur, including a safety factor of 1.5.

5.3 Pre-Holocene Deposits

When encountered the pre-Holocene surface is usually mottled heavy clay. The pre-Holocene surface in Trinity Inlet is interposed with sand/gravel layers from the Mulgrave alluvial fan deposits. During the latter part of the Pleistocene epoch 120 000 years ago, the sea level receded exposing the surface and exhausting any surface ASS. The pre-Holocene deposits have been found to have moderate to high levels of sulfide concentrations at the surface with decreasing concentrations with depth. This may be a result of transgressive mixing, or secondary inheritance of sulfidic potential by near surface exchange with highly sulfidic overlying sediments.

6 Methodology

The methodology used in the preparation of all NRW Special Acid Sulfate Soil Maps meet the following requirements:

- *State Planning Policy 2/02: Planning and Managing Development Involving Acid Sulfate Soils*
- *State Planning Policy 2/02 Guideline; Planning and Managing Development Involving Acid Sulfate Soils*
- *Guidelines for Sampling and Analysis of Lowland Acid Sulfate Soils in Queensland (Ahern et al. 1998)*
- *Acid Sulfate Soils Laboratory Methods Guidelines (Ahern et al. 2004)*
- *Australian Soil and Land Survey Field Handbook (McDonald et al. 1990)*

The survey area contains a wide variety of soil types, including difficult-to-sample waterlogged muds, monosulfide sediments, non-aggregated sands and silty soils with a massive structure. The sites also included areas which had been significantly disturbed and sites in a virtually virgin state. The following equipment was used to sample ASS.

6.1 Mechanical Sampling Equipment

Mechanical Sampling was undertaken with either a Geoprobe™ model 54DT coring machine or a trailer mounted Vacuum-Vibro Corer. The Geoprobe **(Plate 1)** is a track-mounted machine that obtains a 38 mm soil core in 1.2 m long removable clear PVC liners. Soil cores are photographed for the record before being sampled and assessed. The Geoprobe is the preferred method of mechanical sampling because it is able to sample all soil types from dry and wet sand to soft sticky mud's and also hard alluvial soils. The Geoprobe will also sample gravels but wear (damage) to the drilling equipment can occur.

Plate 1. Geoprobe model 54DT track-mounted coring machine

Mechanical Sampling using a Vacuum-Vibro Corer (VVC) based on principles used by some off-shore drilling rigs was developed and modified to more effectively sample wet sands, muds, and soft soils commonly encountered in ASS environments **(Plate 2)**. The VVC consists of a 60 mm diameter, 5 m stainless steel tube. Using both vibration and vacuum the tube is inserted into the soil to obtain a continuous, intact sample. The tube containing the sample is then winched up whilst the vacuum is maintained. A combination of compressed air and vibration is then used to extrude the sample into a clear, plastic sleeve. The sample can then be described and sampled easily. If the upper profile is hard and dry, a manual augering device may have been used until soft moist material is encountered at depth.

Mechanical sampling of soil cores are taken to a depth of 5 to 6 m where possible or until non-marine soils are encountered.

Plate 2. Core sampling employing a vacuum and vibration technique

6.2 Hand Operated Sampling Equipment

Access of mechanical equipment in mangrove areas is often impractical due to the softness of the substrate and the density of the vegetation. Hand operated sampling equipment was often used in mangrove areas where disturbance is required to be kept to a minimum.

The Jarret auger has a 100 mm (4 inch) diameter and will penetrate the soil surface approximately 200 mm before the auger head is filled. It is suitable for use on a range of soil textures in the dry and moist state but will not retrieve dry sands. Where the soil type is suitable, it may be possible to auger 5–10 metres using the Jarret auger and a series of 1-metre extension rods.

Sand augers are useful for sampling in very sandy friable soils however in our experience, the ‘Dormer No. 4 Auger’ is more versatile as it successfully recovers most moist sands and soft muds. To obtain an adequate volume of sample, a 75 mm diameter, single slot tube is commonly used. These augers penetrate to a depth of about 30 cm before filling the auger. The auger is then reinserted to obtain further samples from the same sample hole.

The tapered gouge auger is designed to take undisturbed samples from very soft material with a significant clay content. Typically, the auger is an open-faced, stainless steel tube that tapers from a diameter of 50 mm at the top, to 20 mm at the bottom. The auger is pushed into the soil, turned to cut the core and then withdrawn. It can be used at the surface or down an augered hole however re-sampling is limited due to hole collapse. The open face tube allows easy removal of soil from the auger, and the tapered end improves sample retention for wet soils. The tapered gouge auger produces a highly representative sample of the profile. Once the gouge auger has been pushed down once, it cannot be pushed down into the same hole again, as the tapering effect will lead to cross-contamination in the next soil sample.

6.3 Location of Sites, Profile Description and Sampling

The location of sample sites was based on the free survey technique (Reid 1988) with the aid of aerial photos (latest and oldest) and Light Detection and Ranging (LiDAR) elevation information or best elevation data available. Site conditions or observations made during fieldwork determined the selection of alternate or additional sites. The site location of each site was recorded in Standard Map Grid coordinates to an accuracy of no less than 3 meters using a GPS unit.

The soil profiles were described using the nomenclature of the *Australian Soil and Land Survey Field Handbook* (McDonald et al. 1990). Soil properties recorded included horizon depth, colour, field pH, field pH after oxidation with 30% hydrogen peroxide, mottles, texture and coarse fragments (eg. shell, partly decomposed plant material). Soil pH was recorded at 0.25 m intervals down the profile, firstly in a soil and water paste (pH_F), and secondly after oxidation with 30% hydrogen peroxide (pH_{FOX}). The level of effervescence produced during the pH_{FOX} test was also recorded (Volume 2 Appendix 1). A large difference (eg. 3–4 pH units) between pH_F and pH_{FOX}, together with significant effervescence is a reliable indicator of PASS.

The profile was sampled according to the *Guidelines for Sampling and Analysis of Lowland Acid Sulfate Soils in Queensland* (Ahern et al. 1998) at the following intervals (except where these crossed horizon boundaries): 0–0.1 m, 0.2–0.3 m, 0.5–0.6 m, 0.8–1.0 m and then at intervals of 0.5 m. Soil samples were collected from each of the boreholes. Samples were placed in sealed plastic bags and refrigerated immediately. Upon returning to the laboratory, samples were dried at 80°C for 48 hours and fine ground (<1 mm) before laboratory analysis.

6.4 Database Recording

All field and laboratory data were entered into the NRW Soil and Land Information (SALI) database, designed specifically for land resource surveys. Terminology and codes in SALI are consistent with the *Australian Soil and Land Survey Field Handbook* (McDonald et al. 1990). Decoded borehole descriptions can be seen in Volume 2 Appendix 3.

Laboratory analysis
Laboratory analyses were performed to quantify net acidity (ie. actual acidity plus potential acidity less any naturally occurring acid buffering capacity) with the choice of the methodology being determined by whether the soil layer in question is deemed actual or possibly potential according to field morphology. Two laboratory methods were used to determine the net acidity with all laboratory analysis carried out in accordance with the *Acid Sulfate Soils Laboratory Methods Guidelines* (Ahern et al. 2004). Refer to Glossary (Page 48) for detailed explanation of laboratory terms and acronyms.

A summarised version of the laboratory data displaying actual acidity, potential acidity, net acidity using the Suspension Peroxide Oxidation Combined Acidity and Sulfur (SPOCAS) acid base accounting methods is provided in Volume 2, Appendix 1. Full details of laboratory analyses are available in Volume 2 Appendix 2. Selected samples were analysed for full SPOCAS analysis to determine actual acidity and self neutralising capacity. The samples selected for analysis were based on the morphological data collected at the site.

The Chromium Reducible Sulfur (S_{CR}) method (Method 22B) as described by Sullivan et al. (2004) measures reduced inorganic sulfur compounds including pyrite (and other iron disulfides), acid volatile sulfides (AVS) and elemental sulfur. The method can be made specific to the iron disulfide fraction with appropriate pre-treatments to remove AVS and elemental sulfur fractions. The Chromium Reducible Sulfur method is the preferred method for low analysis sands and for highly organic or peaty soil because of its specificity to reduced forms of inorganic S, while not determining organic sulfur. While sufficient for most PASS samples the method however does not measure existing acidity.

The Suspension Peroxide Oxidation Combined Acidity and Sulfur (SPOCAS) method (Method 23) as described by Ahern et al. (2004) measures both the 'acid trail' and the 'sulfur trail' providing data on pH, retained acidity (S_{RAS}), actual acidity (TAA) and potential acidity (S_{POS}, TPA). The method also provides a measure of neutralising capacity (ANC_E, Ca_A, Mg_A).

6.5 Determination of PASS or AASS

The determination of which soil horizons constitute an ASS was based on an assessment of field morphological properties (eg. texture, soil colour, mottles and coarse fragments such as shell), field pH test results and laboratory results that met or exceeded the texture based action criteria displayed in **Table 1**.

Table 1. Texture-based action criteria (after Ahern et al,. 1998)

Soil Texture (clay content %)	Equivalent sulfur (%S)	Equivalent acidity (moles H^+/tonne soil)
Sands to loamy sands (≤ 5)	0.03	18
Loams to light clays (5 – 40)	0.06	36
Medium to heavy clays (≥ 40)	0.1	62

(PASS) were assessed using S_{CR} and S_{POS} analytical results. (AASS) were determined by the presence of jarosite, TAA results as well as field pH (pH_F) and/or laboratory (pH_{KCl}) values of 4 or less. Neutralising capacity was assessed using a combination of ANC_E, Ca_A, Mg_A, TPA, ANC_{BT} and pH. (See glossary for definitions of symbols).

7 Results

7.1 Map Units of the Study Area

The mapping process is a way of presenting extremely complex 3-Dimensional soil data in a 2 dimensional format, so that it can be input to planning or management decisions. At the 1:50 000 scale, it is possible to identify areas of high hazard. The extent of ASS present is shown in **Figure 5** and the attached acid sulfate soils map displays the map units identified in the study area.

Table 2 shows the total area of each map unit along with the percentage occupied by each unit of the 14 337 hectare total survey area. It is noted that the AASS found in the survey area (495 ha) has PASS layers below it (meaning that further disturbance has the capacity to release yet more acid and heavy metals). More importantly, approximately 88% of the area surveyed contains layers of ASS —nearly half of which is within 2 metres of the surface. This does not include developed land because a depth to ASS layer is difficult to obtain due to disturbance.

Table 2. Area of acid sulfate soils map units in the Cairns survey area

Map Unit *	Map Unit Area (ha)	Percentage of Area Assessed (%)
Actual acid sulfate soils		
A0S0	342.2	2.39
A0S1	68.4	0.48
A0S2	11.4	0.08
A0S3	2.9	0.02
A0S4	7.1	0.05
a0A1S1	4.8	0.03
A1S1	27.4	0.19
a0A2S3	1.4	0.01
A2S2	2.7	0.02
A2S3	2.1	0.01
a0A3S3	24.7	0.17
Total	**495.1**	**3.45**
Potential acid sulfate soils		
S0	4577.3	31.93
S0N	9.1	0.06
a0S1	98.2	0.68
S1	184.2	1.28
S1N	232.7	1.62
a0S2	406.6	2.84
S2	465.9	3.25
S2N	156.5	1.09
a0S3	141.4	0.99
a3S3	6.8	0.05
S3	495.9	3.46
S3N	6.0	0.04
a0S4	213.5	1.49
S4	528.8	3.69
a0S5	130.3	0.91
a3S5	9.0	0.06
S5	36.4	0.25
a0S5+	3.2	0.02
S5+	1144.9	7.99
Soil	**8846.7**	**61.71**
Acid Sulfate Soils on disturbed land		
SLA	523.7	3.65
SDL	2749.0	19.17
Low probability ASS land		
a0LP	1078.6	7.52
LP	526.6	3.67
LP5	147.2	1.03
Total Area	**14336.9**	**100**

* The soil map units areas are delineated by:

- the depth of soil at which acidity is first encountered; "A" refers to an actual acid sulfate soil layer (pH ≤4), while "S" refers to a potential acid sulfate soil layer. The numeric component of the map code refers to the depth at which these layers occur [0 = (0 to 0.5 m), 1 = (>0.5 to 1.0 m), 2 = (>1 to 2 m), 3 = (>2 to 3 m), 4 = (>3 to 4 m), 5 = (>4 to 5 m)];
- the codes can be used separately (eg. A0, S0, S1); but where a map unit contains both AASS and PASS layers, then the codes are combined (eg. A0S0, A0S1);
- additional information is provided by code "a" for areas with strongly acidic (pH >4 and ≤5) soil layers.

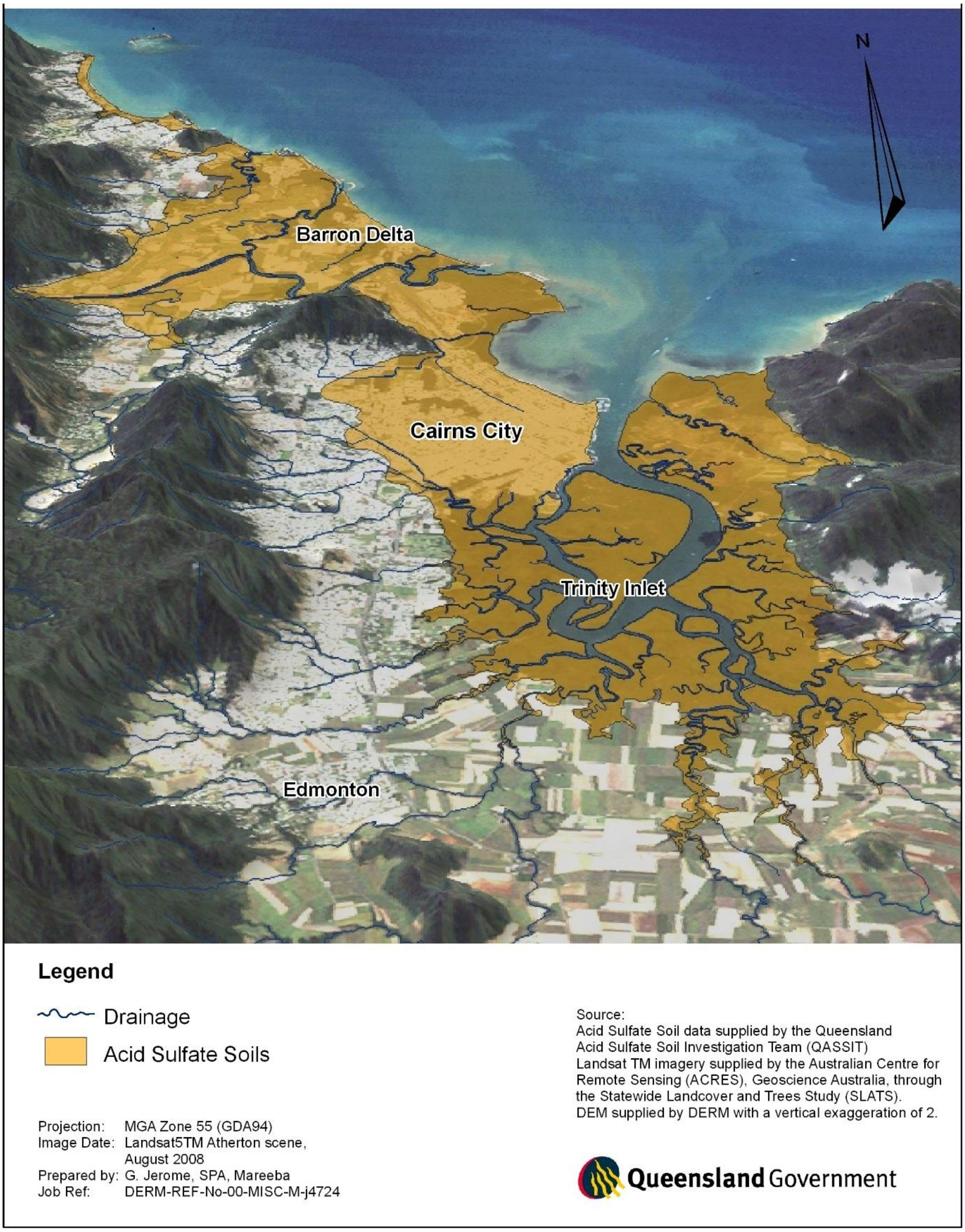

Figure 5. Extent of acid sulfate soils in the Cairns area.

7.2 Characteristics of the Mapping Area

The following selection of sites represents the different geomorphological conditions encountered in the study area. Site and profile photos are supplied for some of these. The elevation of the land above Australian Height Datum (AHD) has been estimated for each site by using LiDAR (Light Detection and Ranging) which is an optical remote sensing technology that measures properties of scattered light to find the range of a distant target. At each site the depth to the PASS layer (based upon the laboratory analysis of samples collected) can be subtracted from the LiDAR elevation to give the depth of the PASS occurrence relative to AHD.

Buchan Point to Earl Hill

The map units from Buchan Point to Earl Hill represent a total of 209 ha of PASS. The S3 mapping unit total of 109 ha represents the beach ridge barrier formation. The S0 units represent swale streams cutting across the beach ridge barrier with open mouths to the shoreline that are tidally dominated and colonized by mangroves. The S1 and S2 units represent swales not open to the ocean and are dominated by melaleucas. The 43 ha SDL unit located at Trinity Beach between Taylor Point and Earl Hill has undergone significant land form change with cut and fill activities associated with urban development. There is likely to be PASS at depth in this area however no sampling was undertaken.

Site 237 located at Clifton Beach is sited on the beach ridge barrier formation within the S3 unit **(Plate 3)**. The site has undergone significant disturbance from a previous development with fill material occurring to a depth of 1.15m **(Plate 4)**. A non-ASS sand layer containing quartz fragments occurs from the base of the fill at 1.15m to 3.4m. PASS occurs in a sand layers from 3.4m to 3.9m, and 5.15m to 6.2m. A sulfide concentration of 0.14%S occurs in the sand layer 3.4m to 3.9m. A layer of fine sandy clay loam containing shell from 6.2m to 6.9m may have some self-neutralising capacity. Below this a non-ASS pre-Holocene surface of fine sandy heavy clay starting at 6.9m to the Depth of Auger 7.2m. Due to the high energy environment of the beach ridges some sand layers do not contain sulfide concentrations higher than the action criteria of 0.03%S for sand textures.

Plate 3. Site 237, Location: Clifton Beach, Map unit: S3, LiDAR elevation: 3.6m AHD, PASS depth: 3.4m, PASS elevation 0.2m AHD.

Plate 4. Site 237 Soil Profile to 7.2m

The formation of PASS within the swales occurs at a higher elevation than within the beach ridge barrier formations. The melaleuca swamp/swale (Deadmans Gully) behind Arlington Esplanade at Clifton Beach (Site 77, Map Unit: S1, LiDAR Elevation: 1.56m, PASS Depth: 0.8m, PASS elevation: 0.76m,) has PASS layers commonly at least 0.5m higher than the surrounding beach ridges.

A site at Kerrwarra Beach situated within the mangroves recorded a sulfide concentration of up to 1.7%S with abundant organic matter in silty light clays. (Site 75, Map Unit: S1, LiDAR Elevation: 2.23m, PASS Depth: 0.3m, PASS elevation: 1.93m) This site recorded a PASS elevation of 1.93m and is one of the highest elevations recorded in the survey. This high elevation of PASS occurrence is most probably due to high tidal interchange, the presence of abundant organic matter, a low energy environment behind the beach barrier and the protection afforded behind Taylor Point from the southeast winds.

Plate 5. Narrow coastal plain from Buchan Point to Kerrwarra Beach.

Barron River Floodplain
The urban development of Yorkeys Knob, Holloways Beach and Machans Beach are all situated on the beach barrier formations which are at a higher elevations than the surrounding backplains. These units are predominately mapped as S3, S4 and S5+ units.

The Yorkeys Knob urbanised area consists of 98 ha mapped as S5+ with an elevation greater than 4m. **Site 224** at Hailing Park, Yorkeys Knob is located within the beach ridge formation and representative of the S5+ unit (**Plate 6**). The profile of site 224 (**Plate 7**) shows a soil profile dominated by a brown beach sand to 3.3m, lying over a wet non-sulfidic grey sand to 5.05m. Darker coloured loamy fine sand with a sulfide concentration of 0.07%°S occurs below 5.05m.

The PASS depositions of the Beach ridges are buried at depths unlikely to be disturbed by surficial disturbance. However the extraction of water through the use of spear pumps can lower the water table and oxidise ASS. The visual evidence of oxidation is iron is staining on built structures from water drawn from a spear pump.

Plate 6. Site 224, Location: Hailing Park, Yorkeys Knob, Map unit: S5+, LiDAR elevation: 4.8m AHD, PASS depth: 5.05m, PASS elevation: -0.25m AHD.

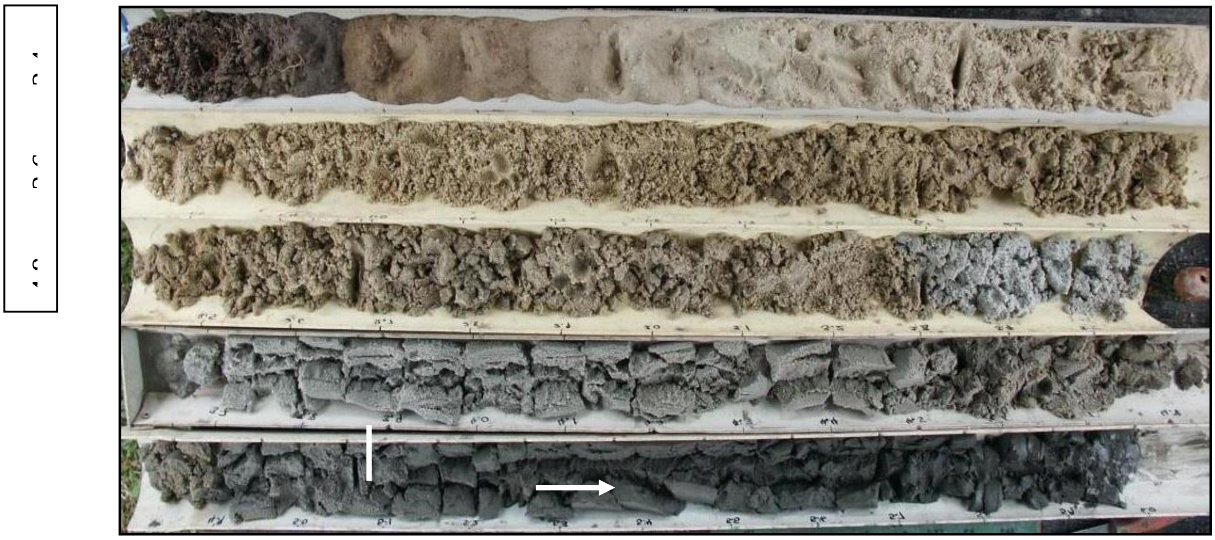

Plate 7. Site 224 Soil Profile to 6.0m (6.0m to 7.2m Not Pictured)

The Holloways Beach urbanised area consists of 129 ha mapped as S4 with a general elevation greater than 3m. Site 176 at Holloways Beach is representative of the S4 unit and ridge barrier formation. Site 176 **(Plate 8)** is very similar in profile to Site 224 located at Yorkeys Knob. The profile of site 176 **(Plate 9)** shows a profile with coloured beach sand down to 2.3m, overlying a wet grey sand becoming PASS at 3.6m with low sulfide concentration of 0.04%S. The clayey sand layer from 4.7m to 5.1m contains 0.3%S and the silty light clay layer from 5.1m to 6.0m contains 0.4%S. Both of these layers contain shell and sufficient self-neutralising capacity.

Because the beach ridge barriers are progradational they form on the high energy beach exposed to wind and wave action This high energy environment is not conducive to the conditions required for ASS formation. The PASS elevation of the beach ridge barrier formations are generally 0.0m to -0.5m with 0.4 – 0.7%S sulfide concentrations in sands. The base of the ridge barrier formation extends down to the prodelta muds, which contain shell with self-neutralising capacity.

Plate 8. Site 176, Location: Holloways Beach State School Reserve, Map unit: S4, LiDAR elevation: 3.5m AHD, PASS depth: 3.6m, PASS elevation: -0.1m AHD.

Plate 9. Site 176 Soil Profile to 6.0m

Mangrove dominated channels that dissect the beach ridge barrier on the Barron River delta include: Moon River, Yorkeys Creek, Thomatis Creek, Ritchers Creek, Barr Creek and Redden Creek. These mangrove areas are all mapped as either S0 and S1 units. Site 175 is located at Holloways Beach in a mangrove swale. A sulfide concentration of 0.29%S from 0.0m to 0.2m and 1.5%S from 0.5 to 0.6m was recorded in the loam textured surface horizon **(Plate 10)**.

Plate 10. Site 175 Location: Holloways Beach, *Rhizophora Stylosa* dominated mangrove swale, Map unit S0, LiDAR 0.9m, PASS Depth 0.0m, PASS elevation 0.9m AHD.

Site 262 is located on the Barron River delta near the intersection of Yorkeys Knob Road and Dunne Road **(Plate 11)**. Yorkeys Creek flows just to the north of the site and intersects with Moon River. Considering that Cairns has a tidal range of 3.4m, with the tide reaching approx 1.7m. Site 262 with an elevation of 0.45m should be inundated with tidal water under natural conditions. However disturbance to the natural tidal flow to this site has been restricted by road construction, drainage and tidal control gates.

The profile of site 262 **(Plate 12)** shows a soil profile with the formation of jarosite at the surface to a depth of 0.45m. A pH of 3.3 was recorded in the soil at a depth of 0.1m. PASS occurs from 0.1m to at least 4.8m. A high sulfide concentration of 2.4%S was recorded for the horizon 0.45m to 1.1m. Greenish-grey clayey coarse sand PASS layer occurs below 4.2m. This is example that PASS may not always look like the usual dark grey coloured mud or sands. The site photo of site 262 **(Plate 11)** shows a ground surfaced stained red surface from the release of iron and an absence of vegetation.

Disturbance of the A0S1 unit surrounding site 262 has caused oxidation of ASS and the release of acid water. The evidence of the acid water corroding the concert of the culvert is seen in **(Plate 13 (b))**. Road culverts constructed in 2004 at Yorkeys Knob Road and planned to be replaced in 2080 have been seriously corroded by ASS drainage in only 4 years. They are likely to need replacement in the near future **(Plate 13 (a))**. A Yorkeys Creek working group has been formed to address the remediation of the area. Some surface liming has been carried out and a monitoring station has been installed to record pH and electrical conductivity in Yorkeys Creek

Plate 11. Site 262 Location: Yorkeys Knob Road, Map unit: A0S1, LiDAR elevation: 0.45m AHD, PASS depth: 0.1m, PASS elevation 0.35m AHD.

Plate 12. Site 262 Soil Profile to 4.8m

Plate 13. (a) Yorkeys Knob Road culvert (b) Acid water has corroded concrete of culvert

The central basin deposits of the Barron River flood plain are located west of the large beach ridge barriers on the coast. Located at <3m elevations, they consist of channels or prior channels dominated by clays and loams in the profile. The remaining area of the Barron River floodplain consists of small ridges or levees >3m elevation dominated by sands in the profile and mapped as S3 and S4.

Site 228 is located at the western limit of an S2 unit on the bank of the Moore River near the Captain Cook Highway **(Plate 14)**. The profile of site 228 **(Plate 15)** consist of a non-PASS alluvial soil of mottled clay loam to medium clay to a depth of 2.05m, transitioning into a PASS clayey coarse sand from 2.0m to 2.4m with a relatively low sulfide concentration of 0.03%S. A PASS layer from 2.4m to 2.75m of coarse sandy clay loam with a sulfide concentration of 1.1%S sits above a PASS clay loam to clay horizon with a high sulfide concentration of 2.8%S from 2.75m to 6.0m. The PASS layer from 2.75m is consistent with the low energy environment that would have been encountered during central basin deposition.

Plate 14. Site 228 Location: Upper Moon River near Captain Cook Highway, Map unit: S3, LiDAR elevation: 1.8m AHD, PASS depth: 2.05m, PASS elevation -0.6m AHD.

Plate 15. Site 228 Soil Profile to 6.0m

Site 225 is located in the S2 unit close to the banks of Thomatis Creek **(Plate 16)**. The profile of Site 225 **(Plate 17)** consist of non-PASS loamy fine sand to 1.0m over a clay horizon to 2.55m. A PASS fibric clay loam layer is encountered from 2.55m to 5.25m with an average sulfide concentration of 1.45%S. The fibric layer smelt strongly of hydrogen sulfide.

Nearby sites including site 37, 38, 39, 60, 245 and 246 where found to have varying surface layers but were all characterised by the presence of a highly organic PASS layer at depth in the profile. This indicates the presence of a large swamp in this vicinity and a low energy environment.

Plate 16. Site 225, Location: East of prawn farm, Thomatis Creek. Map unit: S3, LiDAR elevation: 2.1m AHD, PASS depth: 2.55m, PASS elevation -0.45m AHD.

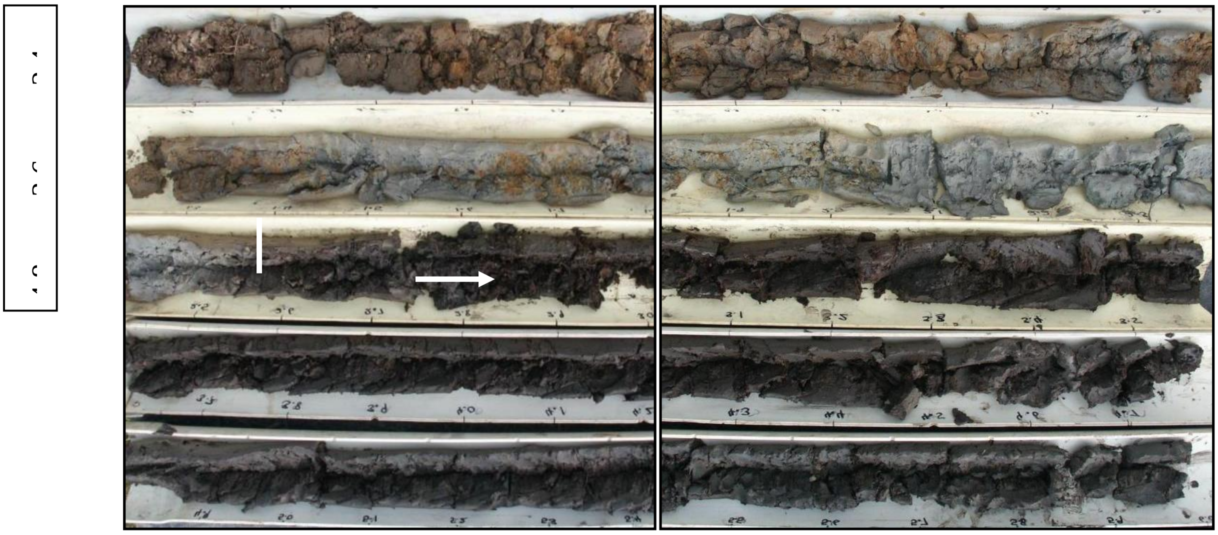

Plate 17. Site 225 Soil Profile to 6.0m

The area of the Upper Barron River is dominated by river fluvial processes. ASS occurrence in these areas tends to be random, being influenced by the high volume and power of the Barron River. This has either prevented pyritic estuarine sediment deposition in the first place because of the large volume and height of riverine alluvium, or has partially stripped out estuarine sediments as the course of the river moved laterally across the floodplain. The upper Barron River was mapped as S5+ because of these processes.

Site 210 is located on the southern side of the Barron River **(Plate 18)** in the S5+ unit. Consistent with a high energy environment, coarse sands with large quartz fragments dominate the profile **(Plate 19)**. PASS sands occur from 7.0m with sulfide concentrations of 0.12%S increasing to 0.7%S at 11.60m.

Plate 18. Site 210, Location: South of Barron River, Map unit: S5+, LiDAR elevation: 4.9m AHD, PASS Depth: 7.0m, PASS elevation: -2.1m AHD.

Plate 19. Site 210 Soil Profile to 6.0m (6.0m to 12.0m Not Pictured)

Site 203 is located near Ryan Wear Park, Kamerunga Rd in the S5+ mapping unit **(Plate 20)**. The profile of site 203 (Plate 20) shows alluvial clay loam to 2.2m. Non-PASS riverine deposits consisting of sand with small quartz fragments are evident to 6.7m. PASS layers with mostly fine sandy clay loam textures occur from 6.7m to 15.5m with an average sulfide concentration of 1.1%S. Below 15.5m to 16.8m are non-PASS coarse sands of alluvial origin with metamorphic rock coarse fragments.

Plate 20. Site 203, Location: Ryan Wear Park, Kamerunga Rd, Map unit 5+, LiDAR elevation: 5.7m AHD, PASS depth: 6.7m, PASS elevation: -1.0m AHD.

The boundary of the marine deposits up Freshwater Creek ends somewhere south of the Bill Fulton Bridge, on the Cairns Western Arterial Road. As the river energy of upstream Freshwater Creek becomes greater and the marine energy drops, the probability of marine build up of PASS material decreases. The possibility of reworking of marine deposition by migratory river changes increases.

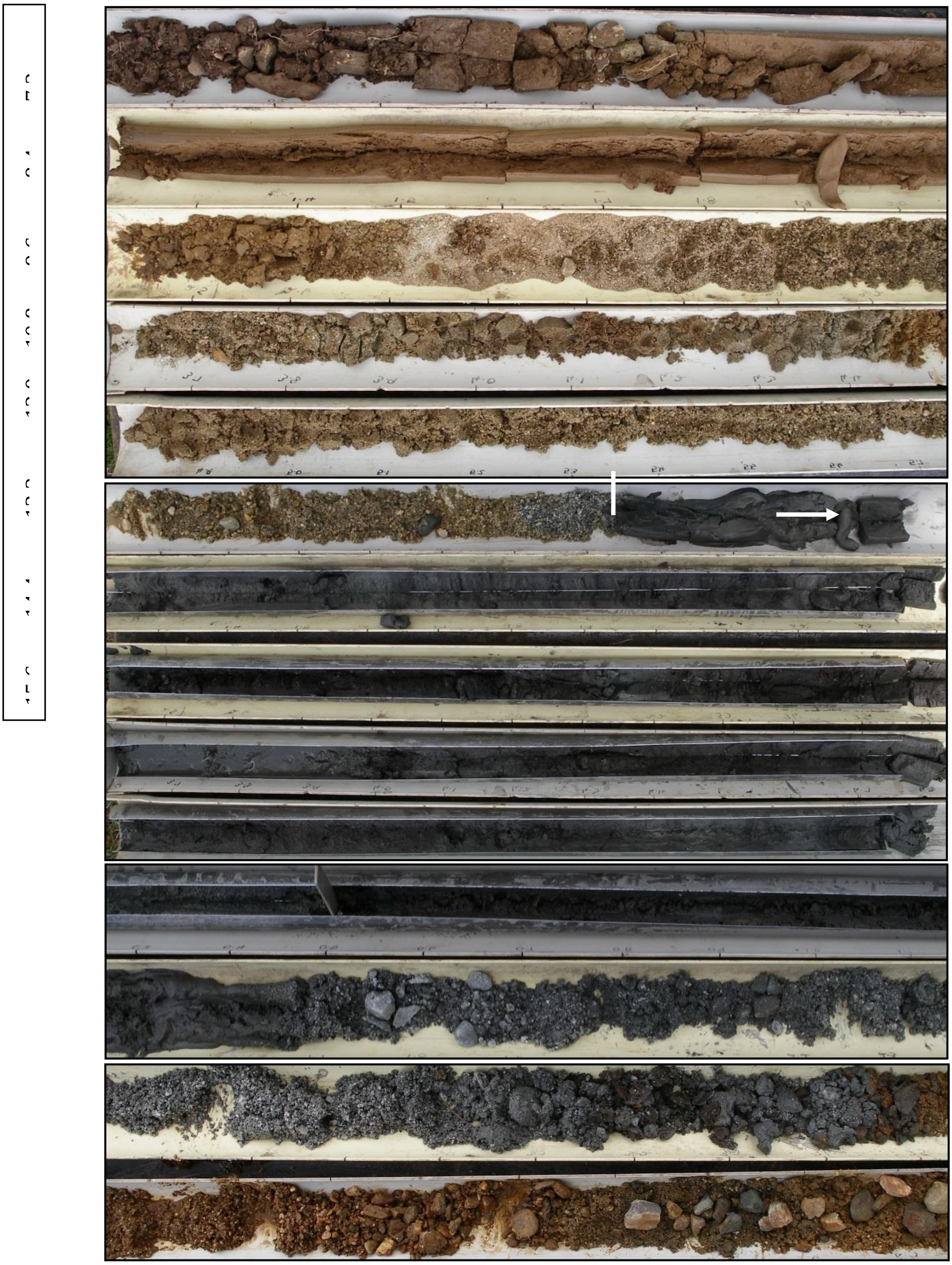

Plate 21. Site 203 Soil Profile to 16.8m

Cairns

The chenier ridges which would have dominated the Cairns landscape in pre-development times are generally 1 to 2m AHD elevation. The low areas between the chenier ridges would have been dominated by intertidal mangroves and supratidal saltmarsh communities. During the development of Cairns the chenier ridges were either flattened out or the area between the ridges filled. Because of the landform modification Cairns area has been mapped as SDL (Sulfidic land under development)

Site 257 is located at Edge Hill on a undisturbed chenier ridge **(Plate 22)**. Evidence of the swale can be seen in the right side of Plate 22. Although growth rates for cycads vary according to species and nutrient levels, the large cycad pictured in Plate 22 on the chenier ridge suggest that this site has experienced little disturbance. The chenier ridge material **(Plate 23)** with a thickness of 1.65m is sitting directly on the surface of an oxidised marine deposit of mottled light clay from 1.65m to 2.0m. It had a pH of 4.2 and a recorded Total Actual Acidity of 44 mol H^+/t but sulfide was absent. A sandy clay loam PASS from 2.35m to 2.6m contains a sulfide concentration of 0.28%S and the fine sandy loam PASS layer below this contains 1.0%S. Both of these layers contain shell but not a significant amount of self-neutralising capacity. This overlies a highly organic peat PASS layer with 2.3%S. At 4.05m a reddish coloured medium clay of pre-Holocene origin is encountered (the Pleistocene surface).

Plate 22. Site 257, Location: Edge Hill, Map unit: SDL, LiDAR elevation: 2.9m AHD, PASS depth: 2.8m, PASS elevation: 0.1m AHD.

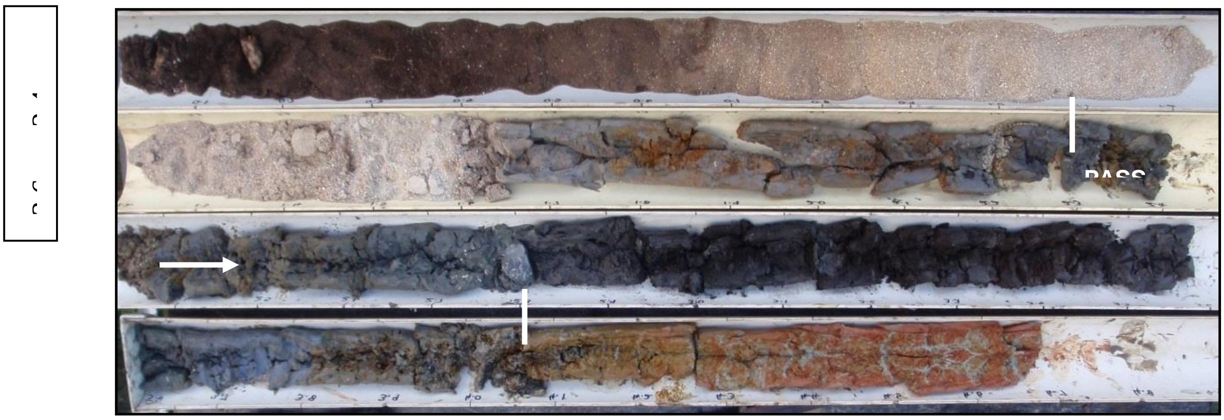

Plate 23. Site 257 Soil Profile to 4.8m

At Manoora to the north western boundary of the survey area, **Site 187** consists of a light clay AASS horizon from 0.1m to 0.7m, with the presence of jarosite, and a pH reading of 4.8 from the surface to a depth of 1.25m. A TAA of 66 mol H^+/t and a sulfide concentration of 0.147%S was recorded in the sample taken from 0.2 to 0.3m. The pre-Holocene surface was reached at a depth of 1.2m.

The subtidal progradational sediments (above the Pre-Holocene surface) thicken from this site southwards to reach a depth of approx 25m bordering Trinity Inlet (Boyd, 1970). The self-neutralising layer is not present in the north west boundary of the SDL unit at Manoora for sites 189 and 191. This is probably due to lack of a direct marine influence during deposition.

Site 183 is located in Mooroobool in the central west of Cairns **(Plate 24)**. Some disturbance and fill occurs to 0.2m **(Plate 25)**. Non-ASS sandy clay loam layers occur to 2.1m. PASS clay layers start at 2.1 and continue to 4.35m, with a thin sandy clay loam self-neutralising layer occurs from 2.2m to 2.4m. The top of the pre-Holocene heavy clay from 3.75m to 4.35m, has a sulfide concentration of 0.5% which is enough to be considered an ASS.

Plate 24. Site 183, Location: Mooroobool Cairns City Park, Lennon St, Bungalow, Map unit: SDL, LiDAR elevation: 2.5m AHD, PASS depth: 2.1m, PASS elevation: 0.4m AHD.

Plate 25. Site 183 Soil Profile to 4.8m

The modification of the Cairns landscape not only included the filling in of swales but also the straightening of intertidal creeks into drains. The Fearnley Street drain was once a meandering creek but has since been highly modified and straightened. Other modified creeks in Cairns include Saltwater Creek at Manunda and Chinaman Creek at Bungalow.

Site 188 located near the Cairns central business district, is mapped as SDL and located in an area that has undergone significant disturbance from a previous development with fill material to a depth of 1.1m **(Plate 26 and 27)**. Below the fill is a sand layer from 1.1m to 1.6m and PASS sand occurs from 1.35m. Below the PASS sand a fibric peat layer from 1.6m to 2.0m has a sulfide concentration of 1.1%S. A recognisable mangrove fruit from a *Xylocarpus species* (puzzle nut) was found within the fibric peat at 1.85m. Self -neutralising clays containing shells occur below the peat layer.

Plate 26. Site 188, Location: Cairns CBD, Map Unit: SDL, LiDAR elevation: 2.39m AHD, PASS depth: 1.35m, PASS elevation: 1.04m AHD.

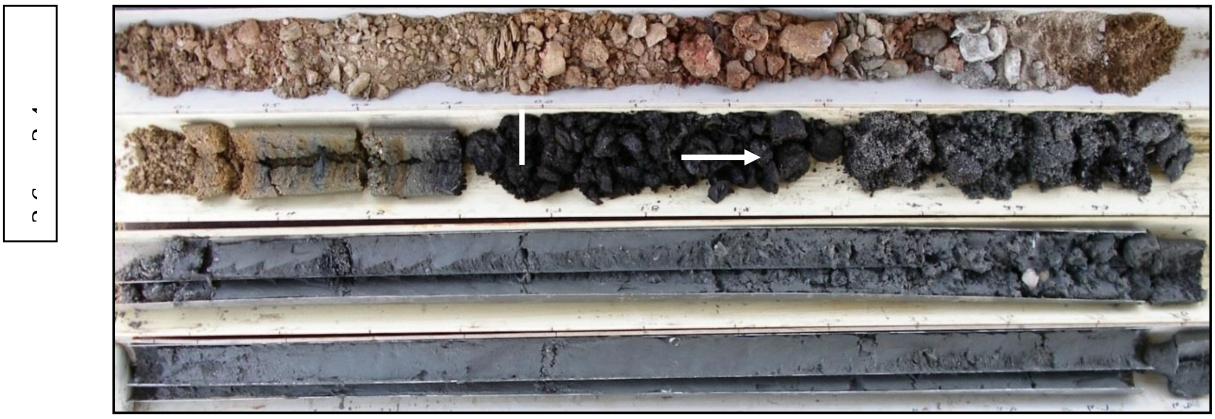

Plate 27. Site 188 Soil Profile to 4.8m

Source: John Oxley Library

Plate 28. Cairns Harbour Board Office at the intersection of Lake and Hartley Streets, 1910. Seawater intrusion after high tide is noticeable.

Source: John Oxley Library

Plate 29. Cairns Harbour mud flats in 1920; Photo location estimated to be the intersection of Sheridan and Hartley Streets. The Cairns Harbour Office can be seen in center right of photo surrounded by a picket fence. In the front of the photo is dredge spoil from Trinity Inlet used to fill some of the tidal flats of Cairns. Reproduced from an original glass negative no. 283

Trinity Inlet

Site 145 is located on the western side of Trinity Inlet in the S0 unit and is representative of a tidally dominated, low energy environment **(Plate 30)**. The site was sampled within dense mangroves of Rhizophora stylosa using hand augers to 2.6m. PASS fibric clay loam occurs from 0.0m to 2.0m with sulfide concentration of 1.3%S to 3.3%S **(Plate 31)**. Below the fibric clay loam is a transitional clay layer from 2.0m to 2.2m with a sulfide concentration of 4.5%S. Below 2.2m the abundance of brown mottles increases until red mottles are encountered at 2.5m. Sulfide concentration into the clay reduces with depth and the abundance of mottles and the firmness of the clay increase.

Plate 30. Site 145, Location: Sewerage Treatment Plant Swallow, Road, Map unit: S0, Approximate elevation: 0m AHD, PASS depth: 0m, PASS elevation: 0m AHD.

Plate 31. Site 145 Soil Profile to 2.6m

Site 193 is located at the northern extent of the Mulgrave fan in the LP mapping unit **(Plate 32)**. The profile is dominated by a non-ASS red mottled clay **(Plate 33)**. pH readings to 4.7 were recorded from the surface to 1.25m. The fan material was not incised in this area to allow the deposition of ASS material. North of this site the Mulgrave fan terrestrial material is covered by Trinity Inlet Holocene marine mud deposits of ASS.

Plate 32. Site 193, Location: Wrights Creek, Southern Trinity Inlet, Map unit: LP, Approx elevation: 1.6m AHD , PASS depth: nil, PASS elevation: N/A

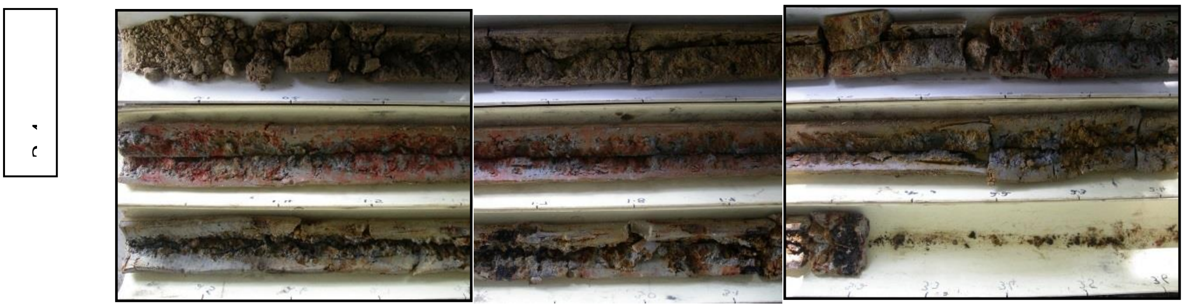

Plate 33. Site 193 Soil Profile to 3.2m

Site 192 is located on Mackeys Creek within a stand of *Bruguiera sp.* and *Xylocarpus moluccensis* mangroves **(Plate 34)**. The position of the stream below the level of the Mulgrave fan can be seen in the background of **(Plate 35)**. Site 192 is a typical example of the incision into the Mulgrave fan material by the numerous streams that flow into Trinity Inlet. Alluvial clays to 0.8m were found to have a low sulfide concentration of 0.057%S at 0.5 to 0.6m **(Plate 36)**. PASS clay occurs from 0.8 to 4.3m with maximum sulfide concentration of 2.48%S. A PASS transition horizon of coarse sandy light clay occurs from 4.3 to 4.5m. Pre-Holocene mottle clay occurs from 4.5m

Plate 34. Site 192 Location: Looking east from site, Mackeys Creek, Trinity Inlet.

Plate 35. Site 192, Location: Looking west from site, Mackeys Creek Trinity Inlet, Map unit: S0, Approximate elevation: 1.0m AHD, PASS depth: 0.8, PASS elevation: 0.2m AHD.

Plate 36. Site 192 Soil Profile to 5.6m

During major rainfall events the Mulgrave River flows north over the Mulgrave fan to Trinity Inlet. The numerous incised streams that flow into Trinity Inlet over the Mulgrave fan have had in some places alternate paths suggesting the migratory switching of streams. This has led to alluvial material being deposited naturally over prior streams capping ASS soil material beneath.

Site 178 is located on a prior stream of Simmonds Creek, at Trinity Inlet with buried ASS below alluvial material **(Plate 37)**. Mottled alluvial clay loan to 0.9m overlies sandy clay loam layers to 2.3m **(Plate 38)**. Actual ASS found from 1.1 to 1.6m a with pH of 4.0 and 87 mol H^+/t. PASS sandy loam and coarse sand layers occur from 2.3 to 6.35m. A transitional horizon of silty medium clay from 6.35 to 6.9m contains no ASS. Pre-Holocene mottle clay occurs from 6.9m.

Plate 37. Site 178 Location: Branch of Simmonds Creek, Trinity Inlet.

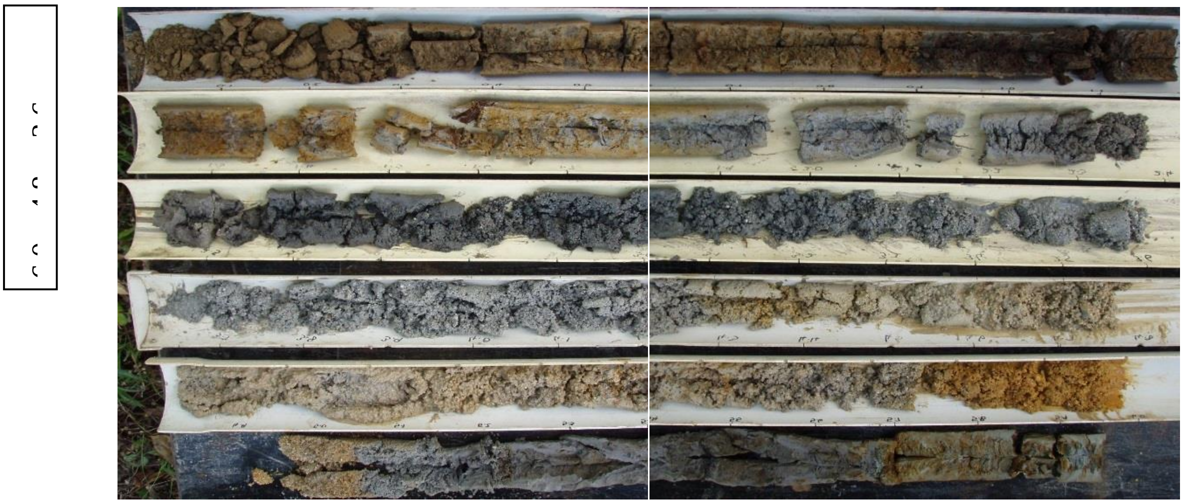

Plate 38. Site 178 Soil Profile to 7.2m

Some of the prior streams on the Mulgrave fan will be naturally filled with riverine gravely sand deposits because they were not sufficiently incised for marine deposition to have occurred; sites 177 and 165 are such examples. Some of the smaller streams that contain ASS on the Mulgrave fan have been filled in (capped), straightened or excluded from tidal exchange by floodgates. This modification may cause ASS oxidation and the formation of AASS.

Site 170 is located on the eastern side of Trinity Inlet within a stand of *Excoecaria agallocha* and *Ceriops australis* mangroves **(Plate 39)**. To the west of the site is sugarcane growing on granitic fan material deposited from localised streams **(Plate 40)**. The site is within the S0 mapping unit. Loam and clay loam layers occur from 0.0m to 0.2m with sulfide concentrations of 0.07%S and 0.10%S respectively **(Plate 41)**. Below 0.2m is an increase in the sand content of the horizons to a depth of 3.4m. The sand for these horizons is supplied from the surrounding granitic hills. These layers contain sulfide concentrations just above the action criteria. Below 3.4m is non-ASS mottled pre-Holocene clay.

Plate 39. Site 170 Location: Eastern Trinity Inlet, Map unit: S0, Approx elevation: 1.5m AHD, PASS depth: 0.0, PASS elevation: 1.5m AHD.

Plate 40. Site 170 Location: Eastern Trinity Inlet

Plate 41. Site 170 Soil Profile to 4.4m

Small bund walls less than 0.5m high can be found in some locations on the eastern side of Trinity Inlet at the edge of the interface between the mangroves and fan deposits to protect sugarcane from tidal inundation.

East Trinity

East Trinity is a prime example where the bund walls were placed within the intertidal zone. Prior to the establishment of a sugarcane farm in the 1970s, much of the East Trinity site was a tidally affected zone dominated by mangrove and samphire communities. A bundwall was constructed with floodgates placed on the creek outlets, and a large pump was sited at the floodgates on Hills Creek with the intention of eliminating tidal water and lowering the natural watertable to facilitate cane production. Some 30 years later, after much clearing and substantial recontouring (including laser levelling), considerable drying of marine muds has resulted in the oxidation of extensive areas of formerly benign ASS. This has caused the release of sulfuric acid and associated heavy metals from the soil, as well as the shrinking of some of the land surface to 1–2 metres below the previous land level.

From May to December 2001, ‘a stratigraphic assessment of the distribution of ASS and sediments on the East Trinity site was carried out in order to provide the background data required for strategic site management and complementary scientific programs. Eighty-eight sample cores were drilled, described and analysed. Sixty-three of these cores were positioned on strategically located transects, with the remainder located to confirm distribution patterns. Stratigraphic relationships were then established for each of the transects, and these were used to postulate the geomorphological and sedimentary history of the site for the Holocene period’ (Smith et al. 2003).

The site management at East Trinity involved a lime-assisted tidal control strategy which was intended to progressively control the release of environmentally hazardous levels of acid and heavy metals—returning much of the 400 ha low lying Hills Creek former estuarine wetlands, to a relatively benign condition **(Plate 42 and 43)**. By August 2005, an additional one-hundred and fifty seven cores were sampled. Since August 2005 duplicate re-sampling of selected sites has been undertaken to follow soil chemical changes over time. An unpublished draft map of ASS at East Trinity was produced by Malcolm et al. 2009 and has been incorporated into the mapping area of this study.

photo by Steve Wilbraham

Plate 42. East Trinity remediation 03/10/2003

photo by Steve Wilbraham

Plate 43. East Trinity remediation 31/05/2006

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Glossary

Acid sulfate soils (ASS): Soil or sediment containing highly acidic soil horizons or layers affected by the oxidation of iron sulfides (actual ASS) and/or soil or sediment containing iron sulfides or other sulfidic material that has not been exposed to air and oxidised (potential ASS). This includes:

- non-oxidised and therefore non-acidic soils or sediments with significant amounts of oxidisable iron sulfides (ie. PASS);
- partially oxidised soils or sediments with variable ratios of existing acidity and unoxidised iron sulfides (ie. PASS/AASS); through to
- completely oxidised (no remnant sulfides) soils or sediments with significant existing acidity (ie. AASS).

The term acid sulfate soil generally includes both actual and potential ASS. Actual and potential ASS are often found in the same soil profile, with actual acid sulfate soils generally overlying potential acid sulfate soil horizons.

Actual acid sulfate soils (AASS): Soil or sediment containing highly acidic soil horizons or layers affected by the oxidation of soil material that are rich in iron sulfides, primarily pyrite. This oxidation produces hydrogen ions in excess of the sediment's capacity to neutralise the acidity, resulting in soils of pH 4 or less. These soils can sometimes be identified by the presence of secondary sulfate salts such as jarosite.

Potential acid sulfate soils (PASS): Soil or sediment containing iron sulfides or sulfidic material that have not been exposed to air and oxidised. The field pH of these soils in their undisturbed state is pH 4 or more, and may be neutral or slightly alkaline.

Acid Base Accounting (ABA): The process by which the various acid-producing components of the soil are compared with the acid neutralising components so that the soil's net acidity can be calculated.

Action criteria: The critical net acidity values (expressed in units of equivalent % pyrite sulfur, or equivalent mol H^+/t) for different soil texture groups and sizes of soil disturbance that trigger the need for ASS management.

Actual Acidity: A component of existing acidity. The soluble and exchangeable acidity already present in the soil, often as a consequence of previous oxidation of sulfides. It is this acidity that will be mobilised and discharged following a rainfall event. It is measured in the laboratory using the TAA method. It does not include the less soluble acidity (ie. retained acidity) held in hydroxy-sulfate minerals such as jarosite.

Aglime: A neutralising agent used to treat acidic soils; by composition, it is commonly 95–98% pure calcium carbonate, $CaCO_3$; it is sparingly soluble in pure water, with a pH of ~8.3; application rates will depend on the purity and fineness of the product.

AHD: Australian Height Datum. The datum used for the determination of elevations in Australia. The determination used a national network of benchmarks and tide gauges, and sets mean sea level as zero elevation.

ANC: Acid neutralising capacity. A measure of a soil's inherent ability to buffer acidity and resist the lowering of the soil pH.

ANC_{BT}: Acid neutralising capacity by back titration. Acid neutralising capacity measured by acid digest followed by back titration of the acid that has not been consumed.

ANC_E: Excess acid neutralising capacity. Found in soils with acid neutralising capacity in excess of that needed to neutralise the acidity generated by oxidation of sulfides. The soil is oxidised with peroxide, then a titration is performed with dilute hydrochloric acid to a pH of 4, followed by a second peroxide digestion. If a soil has a positive ANC_E result then the TPA result is zero and vice versa.

Borehole: The actual hole created when an auger, push-tube or similar is inserted into the soil body; the portion removed (the core) will demonstrate the soil profile.

Ca_A: Reacted calcium. The calcium soluble after the peroxide digest and TPA titration that was not soluble following KCl-extraction and TAA titration. (Ca_P – Ca_{KCl}). It can be used (in combination with Mg_A) to provide an estimate of the soil carbonate content, but may be an underestimate if the HCl-titration to pH 4 has not been performed as part of the TPA/ANC_E procedure.

Ca_{KCl}: Potassium chloride extractable calcium measured following the TAA analysis, which includes soluble and exchangeable calcium as well as calcium from gypsum.

Ca_P: Peroxide calcium. Calcium measured following the TPA analysis, which includes soluble and exchangeable calcium, calcium from gypsum, as well as calcium (eg. from carbonates) dissolved as a result of acid produced due to oxidation of sulfides by peroxide.

Chemical equations: There is a wide range of chemical equations involved in acid sulfate soils. Some of these are detailed below. Further information (especially regarding the intermediate steps involved in pyrite oxidation) can be found in the *Acid Sulfate Soils Laboratory Methods Guidelines* (Ahern et al. 2004).

Pyrite formation can be generalised by equation (1):

$$4SO_4^{2-} + Fe_2O_3 + 8CH_2O + {}^1/_2O_2 \rightarrow 2FeS_2 + 8HCO_3^- + 4H_2O \quad (1)$$

sulfate ions + iron oxide + organic matter + oxygen → pyrite + bicarbonate ions

The overall reaction for the complete oxidation of pyrite is given by equation (2):

$$FeS_2 + {}^{15}/_4O_2 + {}^7/_2H_2O \rightarrow Fe(OH)_3 + 2SO_4^{2-} + 4H^+ \quad (2)$$

In moist environments, jarosite slowly decomposes (usually by hydrolysis) releasing iron and acid, as shown in equation (3):

$$KFe_3(SO_4)_2(OH)_6 + 3H_2O \rightarrow 3Fe(OH)_3 + 2SO_4^{2-} + 3H^+ + K^+ \quad (3)$$

Equation (4) shows the reaction between aglime and the acid produced from pyrite oxidation:

$$CaCO_3 + 2H^+ + SO_4^{2-} + H_2O \rightarrow CaSO_4.2H_2O + CO_2 \quad (4)$$

Chromium Suite: The acid base accounting approach used to calculate net acidity which uses the chromium reducible sulfur method to determine potential sulfidic acidity. A decision tree approach based on the pH_{KCl} result is then used to determine the other components of the acid base account.

Disturbance of ASS: Any activity or action that will or is likely to expose ASS to oxidising conditions eg. movement, excavation or drainage of ASS.

Existing Acidity: The acidity already present in acid sulfate soils, usually as a result of oxidation of sulfides, but which can also be from organic material or acidic cations. It can be further sub-divided into actual and retained acidity, ie. Existing Acidity = Actual Acidity + Retained Acidity.

Fineness factor: A factor applied to the acid neutralising capacity result in the acid base account to allow for the poor reactivity of coarser carbonate or other acid neutralising material. The minimum factor is 1.5 for finely divided pure agricultural lime, but may be as high as 3.0 for coarser shell material.

Holocene: A period of time from about 10 000 years ago to the present, an epoch of the Quaternary time period.

Horizon: A soil layer that differs in physical, chemical or biological properties such as colour, texture, structure, consistency, pH etc from the layers above and below.

Jarosite: An acidic pale yellow (straw or butter coloured) iron sulfate mineral: $KFe_3(SO_4)_2(OH)_6$. Jarosite is a by-product of the acid sulfate soil oxidation process, formed at pH less than 3.7; commonly found precipitated along root channels and other soil surfaces exposed to air.

Mg_A: Reacted magnesium. The magnesium soluble after the peroxide digest and TPA titration that was not soluble following KCl-extraction and TAA titration. (Mg_P – Mg_{KCl}). It can be used (in combination with Ca_A) to provide an estimate of the soil carbonate content, but may be an underestimate if the HCl-titration to pH 4 has not been performed as part of the TPA/ANC_E procedure.

Mg_{KCl}: Potassium chloride extractable magnesium measured following the TAA analysis, which includes soluble and exchangeable magnesium.

Mg_P: Peroxide magnesium. Magnesium measured following the TPA analysis, which includes soluble and exchangeable magnesium, as well as magnesium (eg. from carbonates) dissolved as a result of acid produced due to oxidation of sulfides by peroxide.

Monosulfides: The term given to the highly reactive iron sulfide minerals found in ASS that have the approximate formula 'FeS' and which are soluble in hydrochloric acid (as opposed to iron disulfides such as pyrite that aren't appreciably soluble in hydrochloric acid); formed as intermediates during the formation of pyrite. Monosulfides are highly reactive and oxidise rapidly. Includes amorphous FeS, mackinawite $\approx Fe_9S_8$ and greigite $\approx Fe_3S_4$.

Net Acidity: The result obtained when the values for various components of soil acidity and acid neutralising capacity are substituted into the Acid Base Accounting equation. Calculated as: Net Acidity = Potential Acidity + Existing Acidity – (Acid Neutralising Capacity/Fineness Factor).

Neutralisation: The process whereby acid produced (by the oxidation of soil iron sulfides) is counteracted by the addition of an ameliorant such as aglime ($CaCO_3$); there are formulae for calculating the amount of ameliorant needed to bring the soil closer to a pH value of 7.

NR&M: Queensland Department of Natural Resources and Mines.

NRW: Queensland Department of Natural Resources and Water.

pH: A measure of the acidity or alkalinity of a soil or water body on a logarithmic scale of 0 to 14 units. A pH reading less than 7 indicates an acid, pH equal to 7 indicates a neutral substance, while pH more than 7 indicates an alkaline substance. Note that one unit change in pH is equivalent to a ten-fold change in acidity.

pH_F: Field pH. Field determination of pH in a soil:water paste.

pH_{FOX}: Field peroxide pH. Field determination of pH in a soil:water mixture following reaction with hydrogen peroxide.

pH_{KCl}: Potassium chloride pH. pH in a 1:40 (W/V) suspension of soil in a solution of 1 M potassium chloride measured prior to TAA titration.

pH_{OX}: Peroxide oxidised pH. pH in a suspension of soil in a solution after hydrogen peroxide digestion in the SPOCAS method.

Potential (sulfidic) acidity: The latent acidity in ASS that will be released if the sulfide minerals they contain (eg. pyrite) are fully oxidised. It can be estimated by titration (ie. TSA) if no acid neutralising material is present, or calculated from S_{POS} or S_{CR} results.

Pyrite: Pale-bronze or brass-yellow, isometric mineral: FeS_2; the most widespread and abundant of the sulfide minerals.

QASSIT: Queensland Acid Sulfate Soils Investigation Team.

Quaternary: A geological time period extending from 1.8 million years ago to present time; incorporates both the Pleistocene and Holocene time periods.

Retained Acidity: The 'less available' fraction of the existing acidity (not measured by the TAA) that may be released slowly into the environment by hydrolysis of relatively insoluble sulfate salts (such as jarosite, natrojarosite, and other iron and aluminium hydroxy-sulfate minerals).

S_{CR}: The symbol given to the result from the Chromium Reducible Sulfur method (Method 22B). The S_{CR} method provides a measure of reduced inorganic sulfide content using iodometric titration after an acidic chromous chloride reduction. This method is not subject to interferences from organic sulfur.

S_{KCl}: Potassium chloride extractable sulfur measured following the TAA analysis, which includes soluble and adsorbed sulfate as well as sulfate from gypsum.

S_P: Peroxide sulfur. Sulfur measured following the TPA analysis, which includes soluble and exchangeable sulfate, sulfate from gypsum, as well as sulfide converted to sulfate and that released from organic matter as a result of peroxide oxidation.

S_{POS}: Peroxide oxidisable sulfur from the SPOCAS method. The sulfur soluble after the peroxide digest and TPA titration that was not soluble following KCl-extraction and TAA titration. $S_P - S_{KCl}$). It provides an estimate of the soil sulfide content, but is affected by the presence of organic sulfur.

S_{RAS}: Residual acid soluble sulfur. The sulfur measured by 4 M HCl extraction on the soil residue remaining after peroxide digestion and TPA titration of the SPOCAS method. It provides an estimate of the sulfate contained in jarosite and similar low solubility hydroxy-sulfate minerals (and can be used to estimate retained acidity).

Self-neutralising soils: This term is given to ASS where there is sufficient acid neutralising capacity (with the relevant safety factor applied) to neutralise the potential sulfidic acidity held in the soil (ie. the net acidity from the Acid Base Account is zero or negative). Soils may be 'self-neutralising' due to an abundance of naturally occurring calcium or magnesium carbonates (eg. crushed shells, marine animal exoskeletons, coral) or other acid-neutralising material.

SPOCAS: An acronym standing for Suspension Peroxide Oxidation Combined Acidity and Sulfur method (Method Code 23), the peroxide-based method that supersedes the previous POCAS and POCASm methods.

SPOCAS Suite: The acid base accounting approached used to calculate net acidity based on the Suspension Peroxide Oxidation Combined Acidity and Sulfur method. A decision tree approach based on the values of pH_{KCl} and pH_{OX} is used to decide what analytical path is followed in order to allow calculation of net acidity.

TAA: Titratable actual acidity. The acidity measured by titration with dilute NaOH following extraction with KCl-solution in the SPOCAS method. Previously referred to as Total Actual Acidity in the POCAS and POCASm methods.

TPA: Titratable peroxide acidity. The acidity measured by titration with dilute NaOH following peroxide digestion in the SPOCAS method. Previously referred to as Total Potential Acidity in the POCAS and POCASm methods.

TSA: Titratable sulfidic acidity. The difference in acidity measured by titration with dilute NaOH following extraction with KCl-solution and the acidity titrated following peroxide digestion in the SPOCAS method. (TPA – TAA). Previously referred to as Total Sulfidic Acidity in the POCAS and POCASm methods.