Acid Sulfate Soils of Cannonvale to Funnel Bay, Airlie Beach area, North Queensland

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Acid sulfate soils of Cannonvale to Funnel Bay, Airlie Beach area, North Queensland

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Summary

Acid sulfate soils (ASS) are wetland soils and unconsolidated sediments that contain iron sulfides which, when exposed to atmospheric oxygen in the presence of water, form sulfuric acid with the subsequent release of toxic levels of iron, aluminium and other heavy metals. These products are hazardous to both natural and man-made environments. There are an estimated 2.3 million hectares of these sediments located along 6500 km of the Queensland coastline. The identification of these areas and analysis of the chemical characteristics of these deposits have been undertaken by the Department of Natural Resources and Water over the past ten years.

This study, funded by the Natural Heritage Trust, involves an area of some 345 ha around Airlie Beach, North Queensland, and is part of the statewide program to identify acid sulfate soil (ASS) hazard areas. The Airlie Beach area is subject to urban expansion on the coastal fringe and, as such, represents potential disturbance of these sensitive coastal soils. The values obtained and mapped in this project constitute a current appraisal of the risks inherent in any change of land use as well as data useful to any determination of current release of oxidation products.

The survey area extends from Cannonvale to Funnel Bay. ASS were mapped at a scale of 1:25 000 from 27 boreholes, which were located using free survey techniques. The total survey area is 345 ha. Profiles were described in the field and field peroxide oxidation tests were carried out at regular 0.25 m intervals down the profile, or from within horizons thinner than 0.25 m.

Soil samples for analysis were taken mainly at intervals of 0.5 m from each borehole. No actual acid sulfate soils (AASS) were found, with only potential acid sulfate soils (PASS) being found in the embayments and surrounding lands. The PASS were analysed by the chromium reducible sulfur method (S_{CR}). Some of the PASS contained fine shell or coral fragments and as such displayed acid neutralising capacity in the field tests. These samples were also analysed by the acid neutralising capacity back titration method (ANC_{BT}). Some 110 samples were analysed to determine the potential acid sulfate soil layers.

Map units were allocated a PASS code (**S**), and a depth code number (**1**) indicating the depth to these soil layers, based on the laboratory data. Colouring on the acid sulfate soil map highlights the depth to a potential acid sulfate soil layer and associated level of risk. Sediments with an acid neutralising capacity (ANC) from either finely crushed shells or coral are indicated on the map units by green dots and the label includes the N subscript, eg. $S4_N$.

The study identified 222 hectares (ha) of PASS in the study area. Mapping shows that 192 ha (86%) of the PASS occur in the tidal areas up to the level of the highest astronomical tide (HAT). ASS are shallowest in the tidal zone and occur mainly in the surface half metre of the profile (S0 map units). On other landforms such as creek flats and frontal dunes, they are deeper, mainly at depths between 2 and 5 m (S2 to S5 map units).

The PASS are mainly clay sediments with only a few loamy sediments. No sandy PASS sediments were found. The clayey PASS have a mean oxidisable sulfur (%5) value of 1.3%. This level is significantly higher than those found in similar sediments in the Bowen and Mackay areas of north Queensland.

The main disturbances of ASS at Airlie Beach are from the dredging of Pioneer Bay to reclaim land at Abel Point marina and the Airlie lagoon, and the filling of tidal areas with non-sulfidic fill for urban development. In the first instance the high neutralising capacity provided by fine shell and coral fragments in the sediments of Pioneer Bay meant that the sulfuric acid produced was neutralised *in situ* and did not leach into the bay. Filling of tidal lands was also found not to have any negative impacts on the underlying ASS.

1. Introduction

A mapping project to identify the extent of acid sulfate soils (ASS) at six coastal locations in Central Queensland was initiated in 2004 by the Fitzroy Basin Association, Mackay Whitsunday Natural Resource Management Group and the Department of Natural Resources and Water (NRW) with funding support from the Natural Heritage Trust. Priority areas of mapping are centered around the Mackay and Rockhampton districts. As well as providing substantial in-kind support, NRW was contracted to identify areas for mapping, undertake field surveys, install water monitoring equipment and provide laboratory analyses of soil and water.

Acid sulfate soils are soils or sediments containing sulfides (primarily pyrite) or an acid-producing layer as a result of the oxidation of sulfides. They commonly occur in low-lying, very poorly drained, coastal land at elevations less than 5 m AHD (Australian Height Datum). Excavating soil or sediment, extracting groundwater or filling of land may cause disturbance of ASS. When exposed to air, sulfides oxidise to produce sulfuric acid. Disturbed land can release acid, aluminium, iron and heavy metals into drainage waters, thus affecting aquatic plants and animals. Concrete and steel infrastructure including pipes, foundations and bridges are susceptible to acidic corrosion leading to accelerated structural failure (Ahern *et al.* 1998, Powell and Martens 2005). Other potential impacts include deoxygenation of waterways (Bush *et. al.* 2004) and the stimulating of cyanobacteria blooms such as *Lyngbya majuscula* (fireweed). More detailed information on ASS, its formation and effects can be found in Malcolm *et al.* (2002).

In recent times, coastal lowlands around Airlie Beach have been subject to increased development pressure from urban expansion. The Airlie Beach landscape indicates that ASS would be present, and work by Hardy (2001, 2003) identified the presence of ASS. However what was needed was information as to the extent and distribution of ASS in this area, and more importantly, the depths at which ASS occur. The Airlie Beach area was therefore identified as one of three high priority areas to be assessed in the Mackay district of the Central Queensland coast. Other areas identified in the Mackay district included the Proserpine River delta and the Sarina coastal communities.

The aims of this study were to map the extent of ASS at a scale of 1:25 000. The information from this project will be used by state and local government authorities to manage ASS in the Whitsunday area, and act as a guide to developers and consultants.

1.1 Survey area

The survey area extends from Cannonvale to Funnel Bay. This includes the tidal areas and creek flats of Pioneer Bay at Cannonvale, and Airlie, Muddy and Funnel Bays (Figure 1).

The coastline around Airlie Beach is dominated by steep hills of the Airlie Volcanics (acid to intermediate volcanic rocks) that rise abruptly from the shore line (Photograph 1). The coastline therefore consists of small to medium sized embayments between rocky headlands. It is in these embayments that estuarine sediments of sands, silts and clay have been deposited in the Holocene Epoch (last 10 000 years), and the ASS were formed during this time. After the sea level stabilised at its current level some 4000 to 6000 years BP (Chappell 1987), sand dune deposits were laid down at some of the beach fronts with mangrove forests colonising the wetter intertidal areas either behind these sand barriers or in the bays themselves as they infilled. Limited alluvial deposition buried these estuarine sediments on some of the creek flats that adjoin the bays.

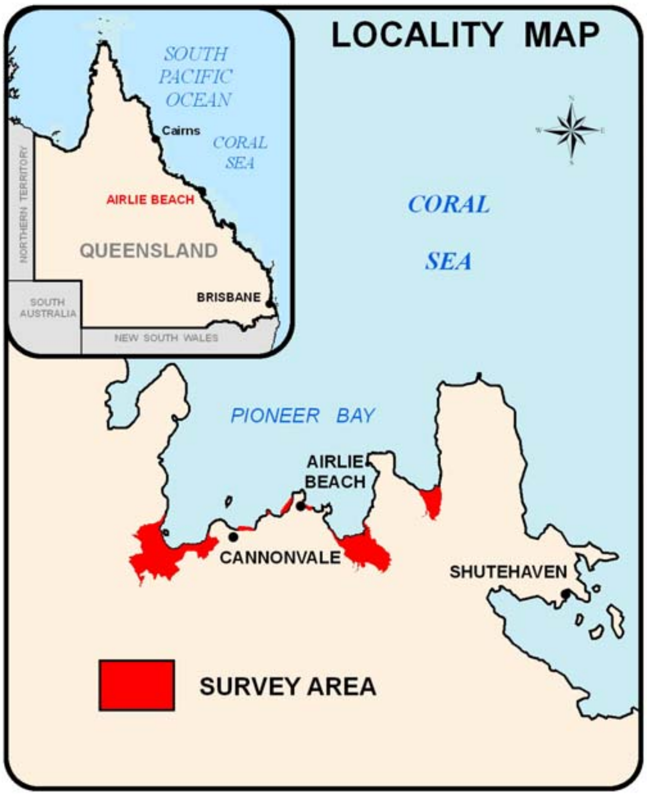

Figure 1. Location of the Airlie Beach survey area

Photograph 1. Coastline of Airlie Beach showing the steep hills that rise directly from the water's edge, with the self-neutralising PASS sediments of Muddy Bay in the foreground.

2. Methods

Field sampling

The Proserpine 1:250 000 geological maps, and topographic information covering the study area were reviewed before field work began. Hardy (2001) had mapped the ASS of this area, but with limited soil sampling and analyses. This work was also used as a guide.

Black and white aerial photographs from 1975, at a scale of approximately 1:25 000, and the 1:50 000 colour aerial photographs of 2003 were used for aerial photo interpretation of the landscape, location of borehole sites, and mapping of soil boundaries. No elevation data was available during the field work period, and so each site has not been assigned an elevation.

Free soil survey techniques were employed, with boreholes located at various spacings depending on the landform (Reid 1988). As the ASS occur mainly in the mangrove forested tidal areas access was severely limited. Therefore boreholes on this landform were spaced at wide intervals. Other landforms outside of the tidal zone were small in size and minor in extent. In these areas, the normal 1:25 000 scale spacing of 250 m was used.

A total of 27 boreholes were examined, described and sampled for this study area. Starting on the lowest-lying land of the tidal flats, boreholes were located progressively up the catchment until ASS were no longer encountered, or a landform boundary identified that defined the inland limit of the Holocene ASS deposition. The soil profile was examined using various methods depending on the landform being sampled. A tapered gouge auger, 1.8 m long with an 83 mm diameter, was used to sample in mangrove areas and, occasionally, on supratidal flats (saltpans) that were wet and inaccessible to a four-wheel-drive-vehicle (Photograph 2).

A trailer-mounted, vacuum-vibro soil-coring rig was used to obtain intact 50 mm cores of saturated sediments to a maximum depth of 6.0 m (Photograph 3). Depending on the type of sediments present, the drier overlying soil materials were first removed with hand augers. This soil was laid out in half-metre sections on a vinyl tarpaulin. When the soil materials were moist and soft enough, the vibro-corer was inserted into the augered hole to sample the deeper, saturated sediments. The cores were extruded into 2 m x 100 mm PVC trays and cut in half for recording soil properties and for sampling. A Geoprobe® coring machine was used for the stony creek flats and colluvial footslopes as the large gravels in the soils of these landscapes made hand augering impossible (Photograph 4).

The properties of the soil materials such as texture, colour, mottles, structure, soil moisture status, coarse fragments and segregations were described according to McDonald *et al.* (1990) and recorded in code format for each horizon on NRW field sheets. The soils were classified using the Australian Soil Classification (Isbell 1996), and other features of the land such as landform, slope and microrelief were also recorded. Mangrove and tree species were identified either from Lovelock (1993), Lear and Turner (1977), and Alcock and Champion (1989), or were sampled and identified by NRW vegetation management officers.

Field pH (pH_F) and peroxide oxidised pH (pH_{FOX}) were measured with a portable electronic pH meter (TPS Ionode WP84) at 0.25 m intervals down the profile, or within other soil horizons if these were less than 0.25 m thick. Soil samples were also taken at 0–0.1 m, 0.2–0.3 m or 0.4–0.5 m, 0.5–0.6 m and 0.8–1.0 m intervals in the upper metre, and then at 0.5 m intervals throughout the remainder of the soil profile, with approximately 500 grams of soil placed in sealed plastic bags. Soil samples were refrigerated in the field and transferred to a freezer for longer-term storage. They were then sent frozen to the NRW soil laboratory at Indooroopilly for analysis. One hundred and eleven soil samples were analysed by the methods described below.

Photograph 2. Gouge auger, 1.8 m long, used for hand sampling in mangrove forests and saltpans

Photograph 3. Trailer mounted vibro-coring soil rig used for sampling wet sediments

Photograph 4. Geoprobe® used for sampling the very gravelly soils

Laboratory soil analysis

The method of analysis selected depended on whether the ASS layers were assessed as being AASS or PASS. Actual acid sulfate soil (AASS) samples containing *jarosite*, or with a pH_F (field pH) of 4 or less, are analysed by the suspension peroxide oxidation combined acidity and sulfate method (SPOCAS) (Ahern *et al*. 2004) and later in the project by the chromium suite of analyses.

Analytes from the SPOCAS methods include:

- total actual acidity (TAA)
- total potential acidity (TPA)
- peroxide sulfur (S_P)
- 1M potassium chloride (KCl) extractable sulfur (S_{KCl})
- 4M HCl extractable sulfur (S_{HCl})
- 1M KCl and peroxide oxidised extracted calcium and magnesium (Ca_{KCl} and Mg_{KCl}, and Ca_p and Mg_p)

Total sulfidic acidity (TSA) is calculated from the acid trail (TSA = TPA–TAA), while the peroxide oxidisable sulfur (S_{POS}) is determined by the sulfur trail ($S_{POS} = S_p – S_{KCl}$). An additional analyte of the SPOCAS method is the 4M HCl extractable sulfur (S_{HCl}), which enables net acid soluble sulfur (S_{NAS}), otherwise known as retained acidity ($S_{NAS} = [S_{HCl} – S_{KCl}] x\ 0.75$), to be calculated (Ahern *et al*. 2004). The chromium suite is essentially similar except that the oxidisable sulfur is determined by the chromium reducible sulfur method, and the other analyses include TAA, S_{KCl}, S_{HCl} and 1M KCl extracted calcium and magnesium.

The potential acid sulfate soil (PASS) samples were analysed by the chromium reducible sulfate (S_{CR}) method (Sullivan *et al.* 2000) only. If fine shells or corals were present, the acid neutralising capacity (ANC) was determined by the back titration method (ANC_{BT}) (Ahern *et al*. 2004).

All field and laboratory data were entered into the NRW Soil and Land Information (SALI) database and are available from NRW upon request.

Interpretation of field and laboratory data

The determination of which horizons constitute an AASS or PASS is based on an assessment of field morphological properties (eg. soil colour, mottles and coarse fragments such as shell), field pH test results, and laboratory results. The texture-based action criteria (Ahern *et al.* 1998) are used to identify ASS based on laboratory results. The action criteria are based on the sum of existing acidity plus potential and retained acidity (ie. net acidity), soil texture and the amount of soil being disturbed. For disturbances of 1 to 1000 tonnes of soil, the action criteria are 0.03% S for sands, 0.06% S for loams to light clays, and 0.1% S for medium to heavy clays. If more than 1000 tonnes of soil are being disturbed, the action criterion is 0.03% S regardless of texture. If these values are met or exceeded, the soil is an acid sulfate soil and will require treatment. For the purposes of this report, the identification of ASS is based on the action criteria where the volume of disturbance is 1 to 1000 tonnes.

Potential acidity was assessed using the S_{CR} method for PASS samples, or S_{POS} and TPA results for the AASS. If these values met or exceeded the texture-based ASS action criteria, the soil was identified as PASS. Existing acidity (ie. AASS) was assessed using TAA laboratory results above the action criteria, the presence of jarosite and a field pH (pH_F) and/or laboratory value (pH_{KCl}) of 4 or less. Neutralising capacity was assessed using either the sum of reacted calcium and magnesium cations for the AASS, or the acid neutralising capacity back titration method (ANC_{BT}) for the PASS samples.

The results of selected laboratory analyses and field pH test results are reported in the Appendix.

Mapping unit categories

The presence and depth to ASS layers form the primary basis for defining the mapping units. The upper depth of the first horizon in which the action criteria have been exceeded has been assigned a 'depth to sulfide' code, as follows:

- **S0** indicates that the action criteria were exceeded between 0 and 0.5 m.
- **S1** indicates that the action criteria were exceeded in the 0.5 to 1 m interval.
- **S2** indicates that the action criteria were exceeded in the 1 to 2 m interval.
- **S3** indicates that the action criteria were exceeded in the 2 to 3 m interval.
- **S4** indicates that the action criteria were exceeded in the 3 to 4 m interval.
- **S5** indicates that the action criteria were exceeded in the 4 to 5 m interval.
- **S5**+ indicates that the action criteria were exceeded at depths greater than 5 m.

Some of the PASS layers were found to have significant quantities of fine shell or coral, thus providing effective ANCs for these layers. The 'N' subscript at the end of a map unit code indicates the presence of neutralising agents in the ASS sediments, eg. $\mathbf{S4_N}$.

Other map units used in the project are:

$\mathbf{S_{LA}}$—(limited assessment) indicates land that was inaccessible to field survey because of its topography or thick vegetation, but was in a landscape position that indicated it had a high probability of being underlain by ASS.

$\mathbf{S_{DL}}$—(disturbed lands) indicates various types of disturbed land that were likely to contain or be underlain by ASS.

LP—(low probability) indicates land at or below an elevation of 5 m AHD (Australian Height Datum), which field survey showed had little if any probability of being underlain by ASS.

NA—(not assessed) indicates land not assessed by field survey, and therefore excluded from the defined ASS map units.

Soil mapping

The areas of ASS were mapped onto the 1975 black and white aerial photographs, based on interpretation of the field data and landforms on the photographs. Quite often, a distinct landform change was used to identify the limit of ASS. When this was not available, such as on the creek flats, the boundary was determined using additional boreholes. Once analytical data were available, the ASS were subdivided into units of the previously mentioned categories showing the PASS codings. PASS depth categories are coloured in shades of red, pink, orange and brown, with red denoting the shallowest depth. Those map units that were found to have significant neutralising capacity, at least 1.5 times the level of oxidisable sulfur, are indicated by green dots.

The location of each site is also shown on the map. Cartographers at NRW Rockhampton transferred the linework from the aerial photographs to a base map to produce the 1:25 000 ASS map.

3. Results: Description of ASS map units and analytical data

Due to the steep elevated topography of the coastline in the Airlie Beach area, the majority of ASS are confined to the intertidal lands below highest astronomical tide (HAT) level. ASS were also found underlying two small valley flats at Funnel Bay and at Cannonvale, and also the underlying the frontal dunes at Funnel Bay. As the hills rise rapidly from the coast, rises in sea level have had a relatively small effect in terms of subaqueous space available for sediment filling. Even the creeks that flow into the bays are only short coastal streams that are limited in their ability to cut down into the valleys of relatively resistant country rock.

The ASS mapping of the Airlie Beach area identified no AASS, and 222 ha of PASS. The main areas of PASS occur in the tidal zone (S0 and S1 map units; 179 ha), with only 7 ha underlying the creek flats, and 6 ha underlying the Funnel Bay frontal sand dunes.

There are also 3 ha of inaccessible stranded sand dunes in the mangrove forests at Cannonvale that are the limited assessment lands (S_{LA}), and 26 ha of disturbed lands (S_{DL}) at Abel Point marina and the Airlie lagoon that have been reclaimed with self-neutralising PASS. Former tidal lands which have been filled for urban development and recreational facilities are also included in this category. There are 123 ha of LP lands as the steep coastal hills which rise up sharply from the coastline limit the area of land below 5 m AHD. As no boreholes were examined above an elevation of 5 m, no LP5 lands were defined on the ASS map.

All of these areas are described in more detail in the following sections. Table 1 below outlines the areas for each of the map units in the Airlie Beach survey area.

Table 1. Areas and proportions of the Airlie Beach ASS survey map units

Map unit	Map unit area (ha)	Percentage of area assessed (%)
Potential acid sulfate soils		
S0	173	50
S1	6	2
S2	10	3
S4	4	1
Total	**193**	**56**
Acid sulfate soil on undisturbed land		
S_{LA}	3	1
Acid sulfate soil on disturbed land		
S_{DL}	26	7
Low probability land		
LP	123	36
Total area	**345**	**100**

3.1 Potential acid sulfate soils on relatively undisturbed land

S0 (PASS layer: 0 to 0.5 m depth)

The S0 map units are all within the intertidal zone, predominantly in the mangrove forests, but also extending out onto the wetter saltpans. It is the main ASS map unit with an area of 173 ha. The mangrove areas consist of dense forests of red mangrove with interwoven aerial roots (Photograph 5), and occasionally low forests of yellow or grey mangrove (Photograph 6).

Photograph 5. Red mangrove in the wetter areas of the tidal zone, S0 map units

Photograph 6. Yellow mangroves on the fringe of the mangrove forests, S0 map units

Photograph 7. Drier saltpan in the Muddy Bay tidal zone, S1 map unit

The red mangrove soils have black, light clay surface soils (10YR2/1) with very dark brown or grey-brown, silty light clay C horizons (10YR2/2, 3/2). Occasionally coarse gravel layers in the PASS prevented sampling beyond these layers. The PASS layers have sulfides contents of between 0.1% S to 2.1% S. Overall, the subsurface sediments have sulfide levels of between 0.6% S to 4.4% S (1.7% S average). These levels are consistently above 1% and the average is twice as high as that found at Mackay and Bowen (Muller & Coutts 2005; Muller 2006). Fine shells are only occasionally present in layers below depths of 0.5 m and these provide acid neutralising capacities (ANCs) equivalent to 0.6% S to 4.6% S.

The soils of the yellow and grey mangrove forests and saltpan areas are slightly drier than the red mangrove soils, with the PASS occurring between depths of 0.3 to 0.45 m. As these areas are drier than the red mangrove forests, there is often more profile development with a well developed B horizon present. The surface soil is 0.1 m to 0.15 m thick and is a black to brown (5Y2/1; 10YR3/2, 4/1, 5/3), light clay with 10 – 20%, orange or brown mottles. The subsoil extends to depths of 0.3 to 0.45 m and is a dark grey or grey (5Y4/1, 5/1; 2.5Y5/0; 10YR5/1), light clay with 20 – 50%, orange or brown mottles. The subsoil overlies black to very dark grey (5Y2/1, 3/1; 10YR 2/1), silty light or light clay PASS sediments. The surface soil and subsoil are non-sulfidic with sulfur contents <0.03% S, while the underlying sediments have 0.37% S to 1.5% S (average of 1%).

S1 (PASS layer: 0.5 to 1 m depth)

Only one S1 map unit, with an area of 6 ha, occurs on the slightly more elevated and drier saltpan at the back of the tidal zone of Muddy Bay (Photograph 7). This saltpan is mainly bare with only some clumps of samphires and a few, low, grey mangrove trees. The soil profile is essentially the same as for the S0 saltpans, but with the PASS occurring just below 0.5 m. As this map unit is at the rear of the basin, the PASS layer is relatively thin and overlies heavy clay Pleistocene basement at 0.7 m. The surface soil layers are non-sulfidic (<0.02% S), while the PASS and upper layer of the basement have sulfur contents of 0.21% S and 2.1% S respectively.

S2 (PASS layer: 1 to 2 m depth)

Two small S2 map units were found around Funnel Bay and have a total area of 10 ha. They occur on a swale at the rear of the frontal dunes (Photograph 8), and on a creek flat of Flame Tree Creek that drains the surrounding hills and flows into Funnel Bay (Photograph 9).

The swale has 1.1 m of gravelly soil that overlies PASS. This soil has 0.45 m of fine sand topsoil that overlies a mottled, brown (10YR5/6), fine sandy light clay subsoil. These layers are non-sulfidic with sulfur levels <0.02% S and are gravelly with 20 – 50% of 2 – 6 mm subrounded volcanic gravels. The PASS is a very dark grey (5Y3/1), sandy light clay with >50%, 6 – 20 mm gravels, and a sulfur content of 0.23% S in its upper 0.5 m. Deeper sampling was prevented by a layer of coarse gravels at 1.5 m. This frontal dune area is largely cleared with only a few isolated Moreton bay ash trees remaining.

The other S2 area is a long, narrow creek flat that adjoins the tidal zone. It has 1.9 m of moderately to very gravelly, light to light medium clay layers that overlie a black (2.5Y2/0), silty light clay PASS. This upper PASS layer is only 0.5 m thick but has a very high sulfur content of 2.7% S. This sediment overlies a 1 m thick, coarse gravelly horizon composed almost entirely (>90%) of 20 – 60 mm, rounded volcanic gravels. The sediment between the stones is an unconsolidated, liquid, sulfidic light clay that has sulfur levels of 1% S to 1.2% S. This material has also some natural acid neutralising capacity equivalent to 0.26% S to 0.32% S. The gravelly layer directly overlies the gley, non-sulfidic (<0.02% S) heavy clay basement at 3.55 m. The creek flat has been cleared and was previously used for sugar cane production before being left to revert to guinea grass. However the fringing vegetation of the creek line indicates that it originally supported rainforest vegetation.

S4 (PASS layer: 3 to 4 m depth)

There is only one S4 map unit, which occurs on the frontal dune of Funnel Bay (Photograph 10) and has an area of 4 ha. This dune is also largely cleared of original vegetation with rows of coconut trees planted along the foreshore. The frontal dune has 3.2 m of shelly, fine sandy layers that overlie the very dark grey (2.5Y3/0), fine sandy clay loam PASS. The PASS and sandy layers below 2.7 m are also gravelly and contain 10 – 50% of 20 – 60 mm, subrounded volcanic gravels. The PASS has a high sulfur concentration of 1.1% S and deep sampling of this and other layers was prevented by the large gravels at 3.6 m. The PASS layer also contains 2 – 10% of fine, broken shells that are 2 – 20 mm in size. The finer of these shells provided the acid neutralising capacity equivalent to 4.8% S.

3.2 Acid sulfate soils on relatively undisturbed land

S_{LA} (Limited field assessment on lands underlain by ASS)

The S_{LA} map units have a total area of 3 ha, and consist of two stranded sand dunes in the dense mangrove forests of the Cannonvale embayment. These dunes most likely represent a former shoreline that became stranded in the tidal zone as the basin continued to fill with sediment and extended seawards. It is expected that both of these dunes would also be underlain by PASS, similar to the sediment in the surrounding mangrove forests.

3.3 Acid sulfate soils on disturbed land

S_{DL} (Disturbed lands likely to contain ASS)

A total of 26 ha of disturbed lands underlain by ASS occur from Cannonvale to Muddy Bay as a result of filling around the edges of these bays and tidal lands for urban development (Photograph 11). Bore holes were drilled in two of these areas at Cannonvale and these confirmed the presence of PASS at depths of 1.3 and 2.1 m below the fill. However none of these disturbances were found to be having or have had any impact on the ASS.

Land was also reclaimed by dredging just offshore for the Abel Point marina and Airlie lagoon developments (Photograph 12). As these were significant excavations of sediments below 5 m AHD, acid sulfate soil investigations were required. These showed that the bay sediments (well below the level of the lowest astronomical tide) are sulfidic, with a sulfur content of between 0.1% and 0.8% S.

However these studies also found that these sediments contain significant levels of fine shell and coral providing a natural acid neutralising capacity which, on average, is equivalent to up to seven times the sulfur levels of the PASS. As a result none of these excavations required liming to neutralise the sulfides. The ASS study for the proposed Muddy Bay marina found similar levels of sulfides and ANC in the sediments there as well.

The other areas of disturbed land shown on the map are former tidal lands or creek flats that were filled for urban developments. These disturbances are low risk and have not impacted on the surrounding PASS as it has sufficient strength to support the fill loads without being displaced above the watertable (A. Williams, *pers. comm.*).

3.4 Land with a low probability of acid sulfate soil occurrence

LP (Land predominantly less than an elevation of 5 m AHD)

The LP lands comprise the footslopes of the hills and rocky headlands around the survey area (Photograph 13). The footslopes of the hills have deep colluvial clay subsoil horizons that sometimes overlie gley, Pleistocene clay basement below depths of 1.3 m. A feature of these soils is the significant amount (50 – 90%) of rounded gravels and cobbles that are present. This was found to be consistent with the soil mapping of Hardy (2003) who attributed this rock content to landslips and mud flows during periods of cyclonic activity. The LP lands have an area of 123 ha.

Photograph 8. Swale in the Funnel Bay frontal dunes, S2 map unit

Photograph 9. Creek flat of the Flame Tree Creek, Funnel Bay, S2 map unit

Photograph 10. Fore-dune at Funnel Bay, $S4_N$ map unit; note the fine shell on the beach

3.5 Potential acid sulfate soil analytical data summary

The PASS sediments at Airlie Beach were found to be either loams or clays, with the clay texture group by far the greater at 88% of all the samples. No sandy PASS sediments were recorded in any of the profiles, with the only sandy sediments being the aeolian deposits of the frontal dune at Funnel Bay (Photograph 10). This is not surprising given the geomorphology of the area and that the bedrock in the catchment areas is mainly intermediate volcanic rocks.

As can be seen in Figure 2, the clay PASS is consistently high in sulfides with most samples being greater than 0.75% S, with an average of 1.3% S, and a maximum of 4.4% S. This is significantly higher than the levels found in the Mackay ASS study (Muller & Coutts 2005) and the Bowen ASS study (Muller 2006) which recorded means of 0.88% S and 0.79% S respectively. Again this is consistent with the geomorphology of the area, which indicates still-water deposition conditions that favour the formation of sulfides. Only six loamy PASS samples were recorded over the survey area, and these are similar to the clay sediments with most samples being greater than 0.5% S, again with a high average of 0.89% S. This compares to 0.35% S and 0.55% S for the Mackay and Bowen studies respectively.

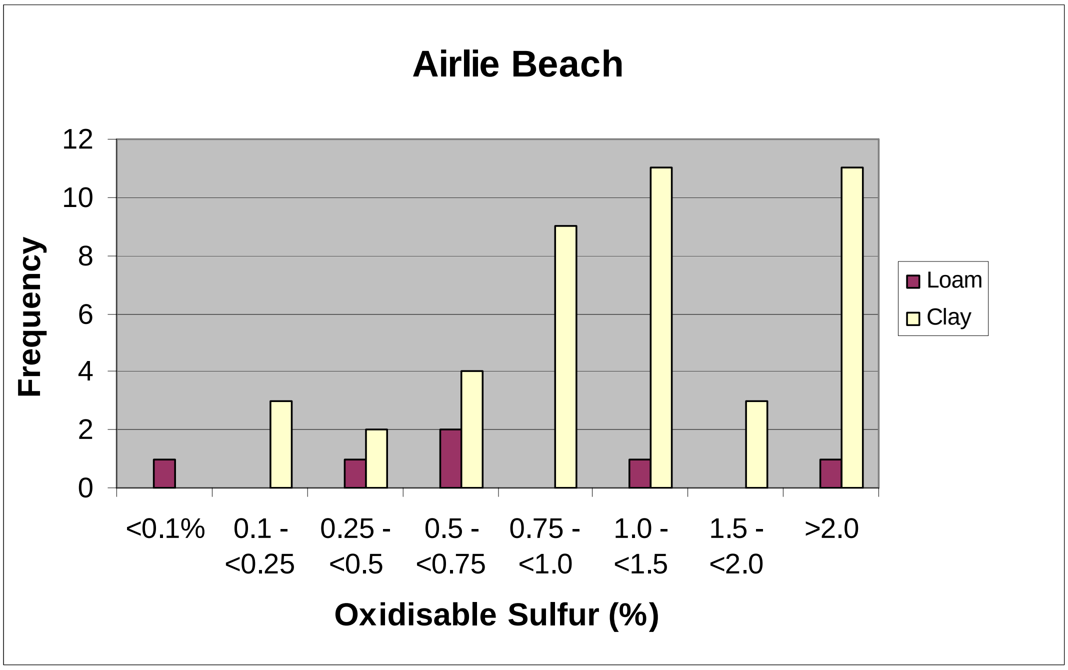

Figure 2. Frequency of PASS samples within oxidisable sulfur ranges for the loam and clay ASS texture groups

Photograph 11. Former tidal lands filled for the Airlie Lagoon, S_{DL} map unit

Photograph 12. Dredged PASS used for land reclamation at the Abel Point marina, S_{DL} map unit

Photograph 13. Footslopes at Cannonvale below 5 m AHD, LP map unit

4. Discussion

The ASS at Airlie Beach consists entirely of PASS, which occurs in the small embayments in the valleys between the coastal headlands. No AASS were found across the survey area. Deposition of ASS is restricted to these small embayments due to the topography of this part of the Whitsunday coast. The short coastal creeks were only able to carve out shallow, narrow basins in these valleys, which penetrate only a maximum distance of one kilometre inland. This is shown in Figure 3 where the red line indicates the limit of the deposition of the ASS sediments.

These bays are all protected from the dominant south-easterly winds and to a lesser extent the northerly breezes by the steep coastal hills, which are up to 300 m high. As a result Pioneer Bay is sheltered from the winds and the large headland to the east of Airlie Beach protects it from the coastal currents. This means that the sediments that were deposited in Pioneer Bay are predominantly clay, and as a result, sulfides were able to form in these sediments at a significant distance offshore as well as in the more protected embayments within the valleys.

This sheltered environment is one reason why the sulfur levels are significantly higher in this part of the Whitsunday coast. The relatively still conditions in Pioneer Bay are also ideal for the formation of sulfides in these muddy sediments. As a result the sulfur levels are almost twice as high, on average, as those found in the Bowen and Mackay areas. There is also a complete lack of sandy PASS in the three estuaries of the Airlie Beach study area, with only clay and loamy sediments being found. While only a few of these estuarine sediments contained shell and coral fragments, the sediments seaward of the mangrove forests and headlands are rich in crushed shell and coral to the extent that it always provides the PASS with excess acid neutralising capacity (ANC). The ANC of the sediments in the mapped areas is more variable, with it varying from 0.2 to 5 times the sulfur levels of the PASS, when it is present.

The study identified 222 ha of PASS, nearly all of which occur at the shallowest depth of 0 – 0.5 m, or the S0 map unit. The only other PASS units are the S1, S2 and S4 map units where the PASS increases in depth from 0.5 – 1 m to 3 – 4 m.

Two main disturbances of ASS have occurred in the Airlie Beach area. Sulfidic sediments dredged from the bay were used to reclaim land at the Abel Point marina and the Airlie lagoon. However due to the high content of crushed shell and coral in these sediments, the PASS was fully self-neutralising and did not require liming or other management. The situation is similar in Muddy Bay at the site of the proposed Port of Airlie marina.

The other areas of disturbed land shown on the map are former tidal lands or creek flats that were filled for urban developments. These disturbances have not impacted on the surrounding PASS as it has sufficient strength to support the fill loads without being displaced upwards above the watertable (A. Williams, *pers. comm.*).

Figure 3. Aerial photograph showing the small embayments (in red) and the steep coastal hills of the Airlie Beach study area

5. References

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6. Glossary

Acid sulfate soils (ASS): Soils or soil horizons which contain sulfides, or acid soil horizons affected by oxidation of sulfides. Acid sulfate soils is the common name given to naturally occurring sediments and soils containing iron sulfides (principally iron disulfide or their precursors). The exposure of the sulfide in these soils to oxygen by drainage or excavation leads to the generation of sulfuric acid. The term ‘acid sulfate soils’ includes both actual and potential acid sulfate soils. (See below).

Action criteria: The oxidisable sulfur (%S) values of soil samples which exceed the Queensland acid sulfate soils guidelines (Ahern *et al.* 1998). Soils that exceed these criteria are classed as ASS, and may require remedial treatment such as application of neutralising agents if disturbed or drained. The action criteria used as the determinant of PASS are:

- 0.03% S or 18 mol H^+/t for sands
- 0.06% S or 36 mol H^+/t for loams to light clays
- 0.1% S or 62 mol H^+/t for light medium to heavy clays.

Note that when excavations exceed 1000 tonnes (or m^3), the action criterion of 0.03% S or 18 mol H^+/t applies regardless of texture.

Actual acid sulfate soils (AASS): Soils containing highly acidic soil horizons or layers resulting from the aeration of soil materials that are rich in iron sulfides, primarily pyrite. This oxidation produces hydrogen ions in excess of the capacity of the sediment to neutralise the acidity, resulting in soils of pH of 4 or less, and often the formation of the iron mineral jarosite. These soils can usually be identified by the presence of yellow mottles and coatings of jarosite.

Anaerobic: Conditions where oxygen is excluded, usually by waterlogging.

Australian Height Datum (AHD): The datum used for determining elevations in Australia. Using a national network of benchmarks and tide gauges, a mean sea level has been set as zero elevation.

Borehole: The hole created when an auger or push tube is inserted into the soil body. The portion removed (the core) demonstrates the soil profile and is used for profile description and soil sampling.

Holocene: The period of time about 10 000 years before present. It is an epoch of the Quaternary period (the last 1.8 million years).

Jarosite: An acidic, pale yellow iron sulfate mineral, $KFe_3(OH)_6(SO_4)_2$. The most conclusive indicator of AASS, jarosite is a byproduct of the acid sulfate soil oxidation process, and forms at a pH less than 3.7. It is commonly found along root channels and other soil surfaces exposed to air.

Pleistocene: An epoch of the Quaternary period—the period of time from 1.8 million years ago to about 10 000 years ago (the start of the Holocene epoch).

Potential acid sulfate soils (PASS): Soils containing iron sulfides of sulfidic material, which have not been exposed to air or have oxidised. The field pH of these soils in the undisturbed state can be 4.1 or more, and may be neutral or slightly alkaline. However, they pose a considerable environmental risk when disturbed, as they will become very acidic from oxidation of the iron sulfides to sulfuric acid when exposed to air.

Pyrite: Pale bronze or brass yellow, isometric mineral (FeS_2). It is the most widespread and abundant of the sulfide minerals.

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

Watertable: The portion of the ground saturated with water; often used specifically to refer to the upper limit of the saturated ground.

Chemical acronyms used for acid sulfate soil analytical procedures

POCAS: Peroxide oxidation, combined acidity and sulfate method

SPOCAS: Suspension peroxide oxidation, combined acidity and sulfate method

pH_F: Field pH

pH_{FOX}: Field oxidised pH of the soil sample by 30% hydrogen peroxide

pH_{KCl}: pH of a 1:5 solution of soil and 1 molar (M) potassium chloride (KCl)

S_{CR}: Chromium reducible sulfur method

S_{POS}: Oxidisable sulfur measured by the SPOCAS method

TAA: Titratable actual acidity

TPA: Titratable peroxide acidity

TSA: Titratable sulfidic acidity

ANC_{BT}: Acid neutralising capacity estimated by the back titration method

Notes for the appendix

Texture codes: The texture codes, such as 'FS' for fine sand, used in the Appendix are from McDonald *et al.* (1990)

s-ANC_{BT}: The ANC converted to %S units, ie. % $CaCO_3$ ÷ 3.121 = equivalent %S

- The dotted line between some samples indicates a change in soil horizon, due mainly to texture, but also because of changes in colour, mottles, gravels and shells, calcareous and/or manganese concretions and sediment type.
- Not all the field pH data is presented in the Appendix. Full data sets are available from NRW upon request. The data shown is only for those horizons that were sampled and analysed.

Appendix

Selected profile pH and analytical data

Site	Depth (m)	Texture	pH_F	pH_{FOX}	S_{CR} %S	ANC_{BT} $\%CaCO_3$	s-ANC_{BT} %S
600	0.5-0.6	FSLC	6.5	4.5	<0.02		
	0.9-1.0	FSLC	6.3	2.7	0.06		
	1.4-1.5	SLC	5.8	1.5	0.23		
601	0-0.1	ZLC	5.6	3.8	0.17		
	0.2-0.3	ZLC	5.7	0.9	2.5		
	0.5-0.6	ZLC	5.8	0.7	2.2		
	0.9-1.0	ZLC	6.0	0.9	2.1		
	1.4-1.5	ZLC	6.1	0.7	2.3		
602	0.9-1.0	SLMC	6.8	6.1	<0.02		
	1.4-1.5	SLC	6.7	6.0	<0.02		
	1.9-2.0	ZLC	5.8	0.9	2.7		
	2.4-2.5	LC	6.1	2.4	1.2	0.8	0.26
	2.9-3.0	LC	6.3	1.3	1.2	1.0	0.32
	3.4-3.5	LC	6.2	1.2	1.0	0.9	0.29
	3.9-4.0	MHC	6.6	6.1	<0.02		
	4.4-4.5	MHC	6.6	7.2	<0.02		
603	2.4-2.5	FS	8.3	7.0	<0.02		
	2.9-3.0	FS	7.3	6.8	<0.02		
	3.4-3.5	FSCL	7.7	5.9	1.1	15.0	4.8
604	0-0.1	FSCL	5.5	4.3	0.08		
	0.25-0.35	FSL	5.9	1.0	0.64		
	0.5-0.6	FSL	6.2	0.8	2.6		
605	0-0.1	ZLC	6.2	1.1	0.46		
	0.2-0.3	ZLC	6.3	0.6	1.0		
	0.5-0.6	ZLC	6.5	0.4	0.66		
	0.9-1.0	ZLC	6.2	0.7	1.1		
	1.4-1.5	ZLC	6.2	0.7	0.98		
606	0-0.1	FSLC	5.9	0.9	0.58		
	0.2-0.3	ZLC	6.0	0.6	1.7		
	0.5-0.6	ZLC	6.2	1.4	1.5		
607	0.9-1.0	CS	7.6	6.8	<0.02		
	1.9-2.0	MHC	8.3	6.8	<0.02		
	2.9-3.0	MHC	8.5	7.2	<0.02		
	3.4-3.5	MHC	8.5	7.4	<0.02		
608	0-0.1	ZLC	5.7	1.2	2.1		
	0.2-0.3	ZLC	6.2	0.9	4.4		
	0.5-0.6	ZLC	6.2	0.8	2.0		
	0.9-1.0	ZLC	6.3	0.8	2.0		
609	0-0.1	LC	6.5	4.5	0.03		
	0.2-0.3	LC	6.4	4.9	0.03		
	0.5-0.6	ZLC	6.4	2.0	0.37		
	0.9-1.0	ZLC	6.3	1.1	0.85		
	1.2-1.3	ZLC	6.5	2.3	1.5	5.7	1.8
610	0.9-1.0	MHC	7.5	6.8	<0.02		
	1.9-2.0	SLC	7.8	6.8	<0.02		
	2.4-2.5	SLC	7.7	6.7	<0.02		
	2.9-3.0	gravel	7.6	6.1	<0.02		
	3.4-3.5	SLMC	7.9	6.9	<0.02		
	3.9-4.0	SLMC	7.6	6.9	<0.02		
	4.4-4.5	SLMC	8.1	7.7	<0.02		
611	0-0.1	FSLC	6.6	1.5	0.32		
	0.2-0.3	ZLC	6.8	1.3	0.77		
	0.5-0.6	ZLC	6.8	4.2	0.97	2.0	0.64

Selected profile pH and analytical data (cont).

Site	Depth (m)	Texture	pH_F	pH_{FOX}	S_{CR} %S	ANC_{BT} $\%CaCO_3$	s-ANC_{BT} %S
612	0-0.1	LC	6.2	0.8	0.79		
	0.2-0.3	ZLC	6.4	0.8	1.0		
	0.5-0.6	ZLC	6.4	0.7	1.3		
	0.9-1.0	ZLC	6.4	5.5	1.2	8.8	2.8
646	0-0.1	LC	5.8	4.9	<0.02		
	0.2-0.3	LC	5.7	5.0	<0.02		
	0.5-0.6	LC	5.7	1.3	2.1		
	0.9-1.0	MC	5.5	1.2	2.1		
647	0-0.08	FSLC	6.1	5.3	0.03		
	0.4-0.5	FSLC	6.0	0.6	1.1		
	0.9-1.0	FSLC	5.9	0.7	0.92		
648	0-0.1	LC	6.6	7.3	<0.02		
	0.4-0.5	LC	5.9	0.1	1.0		
	0.9-1.0	LC	6.1	1.4	0.9	2.6	0.83
650	0-0.1	FSLC	7.0	7.8	<0.02		
	0.4-0.5	LC	6.2	0.5	0.92		
	0.9-1.0	MC	6.5	4.6	1.1		
651	0-0.1	LC	7.3	7.9	<0.02		
	0.4-0.5	LC	6.7	0.8	1.1		
	0.9-1.0	LC	6.7	5.1	0.89	14.4	4.6
685	0.9-1.0	MC	6.6	5.7	<0.02		
	1.9-2.0	MC	7.7	6.8	<0.02		
	2.9-3.0	MC	7.5	6.5	<0.02		
	3.9-4.0	LMC	7.9	8.0	<0.02		
792	0.9-1.0	KS	6.7	7.8	<0.02		
	1.4-1.5	KS	6.7	6.9	<0.02		
	1.9-2.0	MC	7.7	7.9	<0.02		
	2.4-2.5	MC	7.9	7.5	<0.02		
	2.9-3.0	MC	7.5	7.5	<0.02		
	3.9-4.0	MC	7.6	7.2	<0.02		
793	0.5-0.6	LMC	7.7	7.9	<0.02		
	0.9-1.0	LC	7.0	6.7	<0.02		
	1.4-1.5	MC	6.5	5.9	<0.02		
	1.9-2.0	LC	6.2	5.9	<0.02		
	2.4-2.5	LC	6.2	0.1	0.57		
	2.9-3.0	LC	6.7	0.1	0.64		
	3.4-3.5	MHC	6.6	4.7	0.57		
794	0-0.1	ZLC	6.5	5.7	<0.02		
	0.4-0.5	LC	7.4	7.2	<0.02		
	0.9-1.0	LMC	7.1	6.9	<0.02		
	1.4-1.5	SLC	7.1	4.8	0.15	0.8	0.26
	1.9-2.0	SLC	7.4	1.3	3.0		
795	0-0.1	LC	5.9	4.6			
	0.9-1.0	MC	6.8	6.3	<0.02		
	1.9-2.0	MC	7.7	8.2	<0.02		
	2.9-3.0	MC	7.6	6.5			
799	0-0.1	LC	6.7	5.8	0.56	5.9	1.9
800	0.9-1.0	MC	6.4	5.9	<0.02		
	1.9-2.0	LC	7.2	6.7	<0.02		
	2.4-2.5	LC	7.8	6.3	<0.02		
	2.9-3.0	LC	7.6	6.5	<0.02		
	3.4-3.5	LMC	8.3	6.4	<0.02		
	3.9-4.0	MC	8.5	6.5	<0.02		
	4.4-4.5	MC	8.8	6.6	<0.02		
	4.9-5.0	MC	8.6	6.3	<0.02		

Selected profile pH and analytical data (cont).

Site	Depth (m)	Texture	pH_F	pH_{FOX}	S_{CR} %S	ANC_{BT} $\%CaCO_3$	s-ANC_{BT} %S
801	0.9-1.0	MC	7.3	7.5	<0.02		
	1.9-2.0	LMC	7.0	5.7	<0.02		
	2.7-2.8	LC	7.1	6.7	<0.02		
831	0-0.1	CL	5.8	3.0	<0.02		
	0.9-1.0	LMC	7.2	6.2	<0.02		
	1.9-2.0	LMC	7.2	7.0	<0.02		
	2.9-3.0	LMC	7.5	6.8	<0.02		

1 741721 075005