

**Coastal acid sulfate soil
processes in Barker Inlet, South
Australia**

Doctor of Philosophy

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Chapter One

1. Introduction**1.1. Overview of Acid Sulfate Soils**

Acid sulfate soil is the name given to soils or unconsolidated sediments that contain soil materials with sulfide minerals or are soils that are affected by transformations of iron sulfide minerals. These soils may contain sulfuric acid or have the potential to form sulfuric acid in amounts that have an effect on the main soil characteristics (Dent 1986; Dent and Pons 1995; Fanning 2002; Pons and Zonneveld 1965; Pons 1973). When sulfidic material is disturbed and exposed to oxygen, acid sulfate soils have the potential to deoxygenate surface waters and release acidity and contaminants to the environment (e.g. Rabenhorst and Fanning 2006).

In general, the following three broad genetic soil materials in acid sulfate soils are recognised:

- **Sulfuric material** (Isbell 2002) and **Sulfidic horizon** (Soil Survey Staff 2010); containing sulfuric acid but may also contain iron sulfide minerals at shallow depths. These materials or horizons were previously referred to as actual, active or raw acid sulfate soil materials.
- **Sulfidic material** (Isbell 2002; Soil Survey Staff 2010); hypersulfidic or hyposulfidic materials (see Chapter 2 for revised definitions), containing mainly iron sulfide minerals (FeS_2) previously called potential or unripe acid sulfate soil materials.
- **Monosulfidic material** (see Chapter 2 for revised definitions), which contain predominantly iron monosulfide minerals (FeS) that are still waterlogged. A previous term used was monosulfic black ooze (MBO) (Bush *et al.* 2004a).

Coastal estuaries and mangrove swamps are an ideal setting for the build-up of sulfide minerals such as iron pyrite due to the highly reducing conditions that form in these waterlogged and organic rich environments with input of sulfur from the sea. Sulfidic

soils are benign while they remain in a reduced condition below the water table, but may become strongly acidic (pH <3.5) as sulfuric acid forms when they are disturbed and exposed to air, and kept moist. Sulfuric acid may leak into drains, creeks, lakes and estuaries, corrode steel and concrete, dissolve weatherable minerals, such as calcium carbonate, and attack clay in the soil liberating soluble aluminium, which is toxic to vegetation and aquatic life. Heavy metals, soluble at low pH, can be transported from the landscape and impact water quality and soil structure.

Acid sulfate soils are widespread in low-lying coastal areas of Australia and other parts of the world (Dent 1986). They mostly occur in Holocene-aged sediments that were deposited in response to post-glacial sea level rise. Of the 215,000 km² of acid sulfate soil in Australia, 58,000 km² are coastal acid sulfate soil and 157,000 km² are inland acid sulfate soils (Fitzpatrick *et al.* 2008a). In the coastal zone of Australia, 41,000 km² are exposed at some point during the tidal cycle, with the remaining 17,000 km² being permanently subaqueous. South Australia has approximately 2,410 km² of coastal area containing sulfidic material with an estimated acid reservoir of 2 million tonnes (Fitzpatrick *et al.* 2006).

More than 126 km² of coastal acid sulfate soils in Australia containing *sulfuric material* have been mapped, however according to Fitzpatrick *et al.* (2008e) this is a significant underestimate, which will be modified with ongoing field investigations and acquisition of more detailed local spatial data sets (e.g. this thesis).

The hazards presented by acid sulfate soil are magnified by their location and specific properties. In Australia, the majority of people reside in coastal areas and primary industries, such as sugar and dairy, have reclaimed significant areas of coastal land. Substantial developments (urban and industrial), infrastructure and utility supply, agriculture, aquaculture, sand and gravel extraction as well as dredging for ports and marinas, have the potential to disturb acid sulfate soils. Coastal development and primary industries around Australia are facing a \$10 billion legacy of poor acid sulfate soils management (Acid Sulfate Soil Management Advisory Committee (ASSMAC) 2000; Fitzpatrick *et al.* 2006). The cost to environmental systems is unknown, but almost certainly is very high in many areas. On a national scale the problem is probably

even more extensive as additional information on the extent of acid sulfate soils across inland regions becomes recognised (e.g. Thomas *et al.* 2009; Wallace 2009).

However, responsible management of acid sulfate soils can improve the quality of discharge water, increase agricultural productivity and protect infrastructure and the environment. These improvements can generally be achieved by low-cost land management strategies based around the identification and avoidance of acid sulfate soil materials. Where disturbance is unavoidable, acid sulfate soil management relies on slowing or stopping the rate and extent of pyrite oxidation and retaining acidity within the acid sulfate soil landscape. Acidity and oxidation products that cannot be retained on-site may be managed by other techniques such as acidity barriers or wetlands that intercept and treat contaminated water before its final discharge point into a river or estuary.

Ultimately, the different types of acid sulfate soil materials in coastal landscapes pose particular environmental hazards that require tailored management and amelioration methods. Management options also need to be specific to the development and infrastructure proposed in order to achieve desirable environmental outcomes.

1.2. Research purpose and methodology

Internationally, the best characterised acid sulfate soils are known from tropical areas and much has been published on pyritic sediments (and their reclamation) in northern Europe (e.g. Aström 2001; Burton *et al.* 2007; Dent 1992; Dent and Pons 1995; Johnston *et al.* 2009b; van Breemen 1993). Very little has been published on the properties and management of coastal acid sulfate soils in temperate (Mediterranean type) climates, such as South Australia.

Investigations along the South Australian coastline (Fitzpatrick *et al.* 1993b; Merry *et al.* 2003; Thomas *et al.* 2004a) have indicated several aspects where temperate (Mediterranean) acid sulfate soils differ from those observed in the sub tropical regions of north-eastern Australia. Coastal landforms in South Australia generally contain:

- Larger quantities of calcite (CaCO_3) in most soils,

- Larger quantities of halite and gypsum (CaSO_4) and other salt efflorescences in several soils due to higher evaporation demands,
- Estuaries are mainly tidally dominated with low sedimentation rates due to lower rainfall, smaller rivers (terrestrial inputs),
- Mangrove woodlands are mono-cultures and are backed by saline marsh and cyanobacterial mats,
- Supra-tidal sabkhas are common in the north of Gulf St Vincent and Spenser Gulf) due to very low relief and a predominantly arid climate,
- Sea level history, tidal cycle and tidal extent differs around the Australian coastline,
- Evidence that C cycling and turnover may differ in mangrove and samphire soils because of the high concentration of sapric material in these soils, which is more finely divided and reactive than the coarser, “fibric” materials observed in tropical areas, where organic carbon decomposition rates are much faster (Fitzpatrick *et al.* 1993b).

Insufficient detailed soil information has therefore been available on the properties and distribution of coastal acid sulfate soils in temperate regions of Australia to make suitable management decisions.

The Barker Inlet in the Gulf St Vincent was chosen to evaluate the potential environmental hazards posed by acid sulfate soil materials South Australia (Figure 1-1). Previous investigations in the Barker Inlet by the author had identified approximately 12 km² of acid sulfate soils, of which, about 1.5 km² was estimated to contain sulfuric material, located in the Gillman area (Thomas *et al.* 2003). In addition the Gillman area was known to have contamination issues, as well as there being pressure to develop the land for industrial purposes.

It is critical that detailed, integrative research investigations be conducted in environments containing both disturbed and undisturbed acid sulfate soils. Consequently, preliminary soil mapping and literature research, aided by a review of historical aerial photography for the Barker Inlet, revealed two suitable localities for evaluating and characterising the acid sulfate soil landscape (Figure 1-1):

- (i) the Gillman study site provided a prime study area as it was known to have an acid sulfate soil issue, and contained matched sites, where “near pristine” mangrove areas abut reclaimed areas with sulfuric material.
- (ii) The St Kilda mangrove conservation area, about 6 km north of the Gillman site, was to be used as a control “near pristine” area as it was less influenced by anthropogenic activity.

The situation at these two sites was highly appropriate for conducting detailed research to monitor the seasonal and diurnal variation in acid sulfate conditions (i.e. pedological, hydrogeological and biogeochemical). The information gained would allow development of process models that help explain the spatial variability and complex interactions of environmental degradation processes within the Barker Inlet. The models assist when formulating appropriate management methodologies.

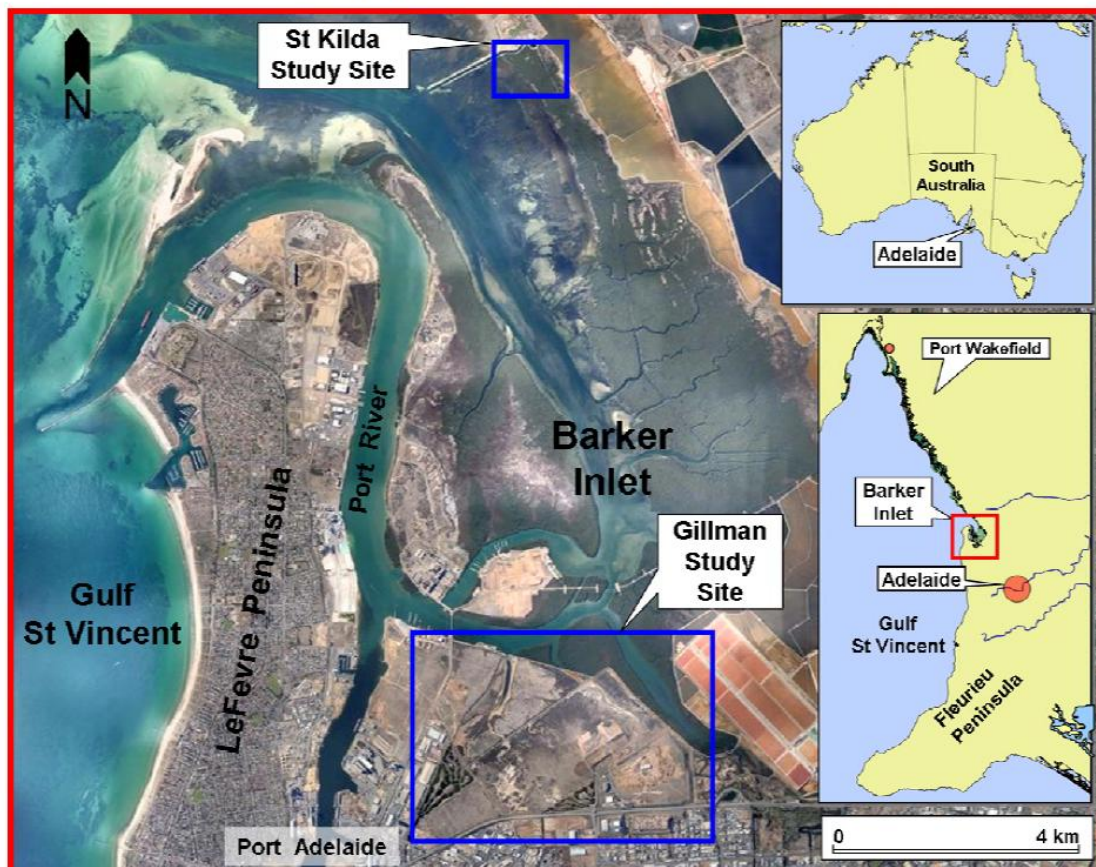


Figure 1-1 Barker Inlet is located 20 km north of Adelaide, South Australia. Large tracts of intertidal and supratidal land surrounding Barker Inlet have been reclaimed since the early 1900s by the construction of 2-4 m high bund walls to preclude tidal inundation. The two sites that form the focus of study for this thesis were selected for their contrasting drainage histories. The St Kilda study site has largely remained un-altered and contains intertidal mangrove and samphire vegetation in a conservation area. Intertidal and supratidal areas at the Gillman study site have been progressively drained since the 1930s, for industrial purposes. Land reclamation in the Gillman area has caused the oxidation of sulfidic material and formation of sulfuric material which has acidified groundwater and severely degraded the landscape. Aerial photo was taken in March 2010.

1.3. Objectives

The objectives of this thesis were to:

1. Review acid sulfate soil problems in consultation with local and state councils, land developers and environmental groups that had a vested interest in the management of the two study areas, taking into account future plans for the areas (e.g. storm water pondage basins and industrial development).
2. Comparative study of the two contrasting study sites, focussing on describing soil and landscape characteristics, soil morphology, spatial variability and biogeochemistry of the soils, at a variety of scales (i.e. from landscape scale using field based soil survey techniques to sub-millimetre scale using microscopic techniques),
3. Develop soil-regolith models and maps that relate environmental hazards to acid sulfate soil processes.
4. Use the models and maps to:
 - (i) Increase understanding of environmental degradation processes related to acid sulfate soil materials.
 - (ii) Identify acid sulfate soil mitigation techniques appropriate for the various soil types, landscapes and subject to development pressures.
 - (iii) Establish regional applications for the research findings, such as development of regional scale acid sulfate soil hazard maps.
5. Provide recommendations for future work.

This is a new approach to the characterisation and mapping of acid sulfate soil landscapes for management purposes.

1.4. Outline of this thesis

The flow diagram in Figure 1-2 outlines the structure and linkage of chapters presented in the thesis.

- *Chapter 1* summarises the aims and structure of the thesis.
- *Chapter 2* provides relevant background information to acid sulfate soils.
- *Chapter 3* describes the study sites with reference to locality, climate, land use, vegetation, geology, geomorphology, hydrology and reviews related historical literature.
- *Chapter 4* describes the field and laboratory methods employed and explains the concepts for developing soil-regolith process models.
- *Chapter 5* describes and characterises soil-regolith processes within the intertidal floodplain at St Kilda.
- *Chapter 6* describes and characterises soil-regolith processes within intertidal and reclaimed areas at Gillman.
- *Chapter 7* produces acid sulfate soil-landscape maps with hazard ratings for the St Kilda and Gillman study areas.
- *Chapter 8* describes the methods developed to monitor redox conditions within contrasting environments and develop soil-regolith redox models to explain the variations measured at different positions in the landscape.
- *Chapter 9* describes the geochemistry and hydrochemistry of representative sites and develops soil-regolith models to explain the movement of acidity and contaminants within contrasting landscapes.
- *Chapter 10* describes the mineralogy and develops soil-regolith models to explain seasonal mineral formation and transformation processes relating to the storage and release of trace elements.
- *Chapter 11* uses micromorphology and other compositional changes to determine mineral weathering mechanisms under changing hydrological and biogeochemical conditions.
- *Chapter 12* outlines the general impact of the work presented in this thesis in a regional setting and implications for managing coastal landscapes.
- *Chapter 13* contains conclusions, outcomes and proposed future work.

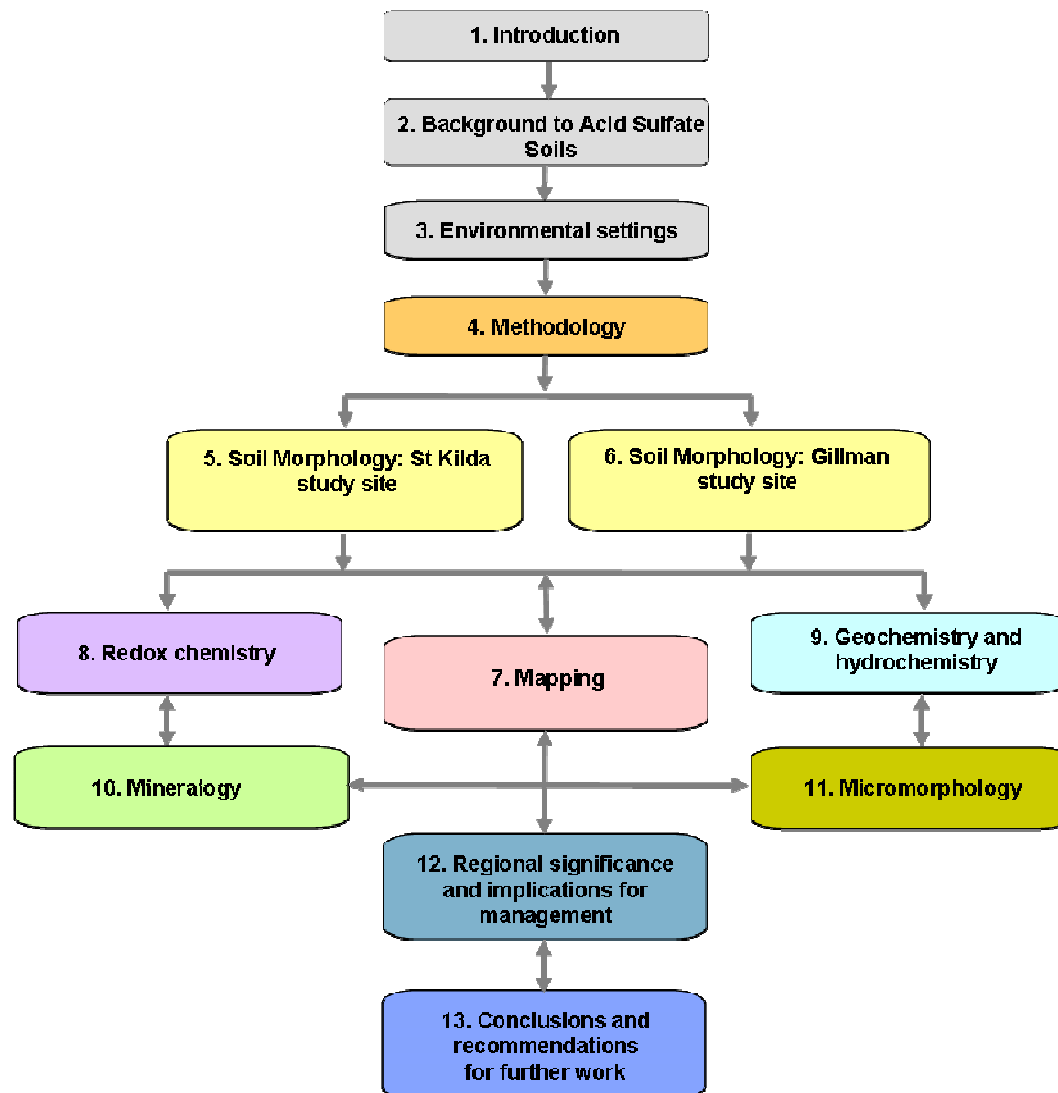


Figure 1-2 Outline of the key components of the thesis.

Chapter Two

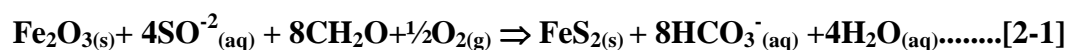
2. Background to Acid Sulfate Soils

2.1. Formation of Sulfidic Compounds

An important consequence of bacterial sulfate reduction is the formation of iron sulfide minerals. They form readily in the sediments and soils of lagoons or bays where stagnant marine or brackish water can supply sulfate and decomposable organic matter is abundant. Sulfide formation is mainly an anaerobic process that results from the biochemical reduction of dissolved sulfate and is mediated by sulfate reducing bacteria such as *Desulfovibrio desulfuricans* (e.g. Canfield *et al.* 2006; Jones and Starkey 1962; Postma and Jakobsen 1996).

The greater part of sulfidic compounds found in acid sulfate soil environments are present in the form of pyrite (FeS₂) because it is much more stable than ferrous sulfide, (FeS). Figure 2-1 shows an electron photomicrograph of pyrite framboids formed in sulfidic soil at Gillman. According to Stumm (1970), under acid conditions, elemental sulfur is formed as a result of the reduction of SO₄²⁻ as an intermediate product and once formed may persist as elemental sulfur within recent marine sediments. This process requires partial oxidation of sulfides (van Breemen and Pons 1978).

These chemical processes are complex, but can be summarised by equation:



This reaction produces alkalinity.

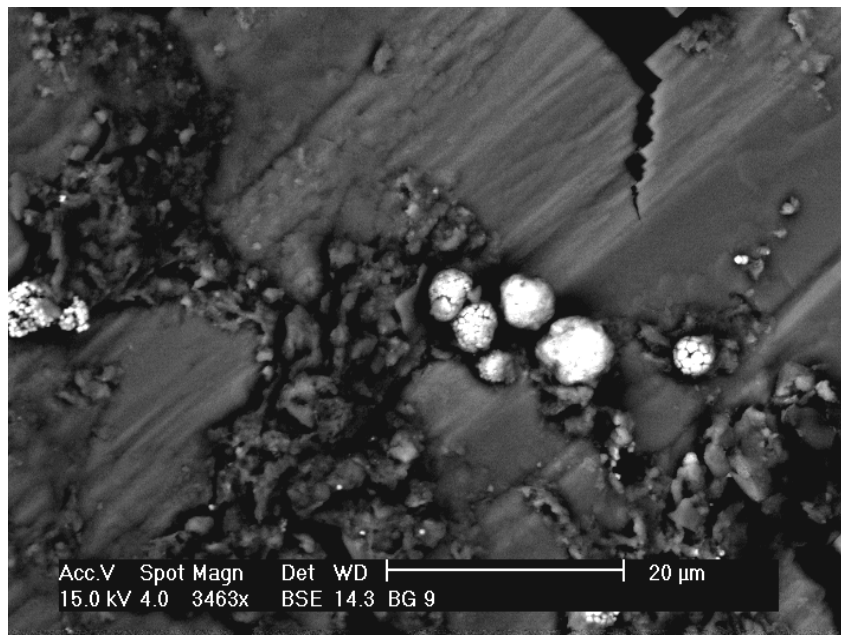


Figure 2-1 SEM (Back scatter electron mode) of sulfidic sediment from Gillman, showing pyrite framboids and organic matter on the smooth surface of a gypsum crystal.

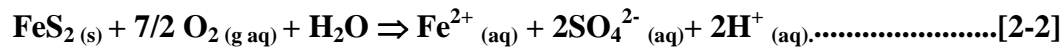
2.2. Oxidation of Sulfidic Compounds

Pyrite and ferrous sulfides are relatively stable while they remain in a saturated, reduced, coastal environment. However they react when exposed to oxygen or ferric iron and water, releasing acidity and sulfate. Exposure to oxygen may occur when the water table is lowered naturally due to seasonal rainfall variations, droughts, evapotranspiration, and a drop in sea level due to tides, glaciations, or even up-lift from seismic activity or isostatic rebound. Oxidation of sulfides can also occur when sulfidic sediments are disturbed by human activities such as dredging, excavation, draining and reclaiming swamps or intertidal areas, and dewatering or over-pumping of groundwater. The pyrite oxidation process has been extensively studied and has been reviewed (Nordstrom 1982). The overall sequence of mineral reactions for pyrite oxidation is described by the following equations. The relationships between oxidizing agents, catalysts and mineral products are explained by Figure 2-2.

Pyrite oxidation is among the most acid-producing of all weathering processes in nature and is generally accepted to proceed in 4 steps:

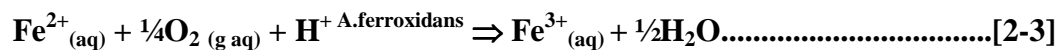
Step 1

In the initial step, pyrite reacts with oxygen and water to produce ferrous iron, sulfate and acidity (equation 2-2).



Step 2

The second step involves the conversion of ferrous iron to ferric iron (equation 2-3). This reaction is very slow and has been described as the rate-determining step in pyrite oxidation (Singer and Stumm 1970). However, when the pH drops below 4, the rate of pyrite oxidation is increased by the catalytic oxidation of ferrous iron by iron oxidising bacteria (e.g. *Acidithiobacillus ferroxidans*) to ferric iron, which acts as a pyrite oxidant. The oxidation of ferrous iron to ferric iron consumes oxygen and has been responsible for reducing the oxygen levels of large water bodies (Bush *et al.* 2004b). In relation to this reaction, it is worth noting that liming of sulfide-containing sediments at an early stage in their reclamation can retard the oxidation of pyrite (Murakami 1965).



Step 3

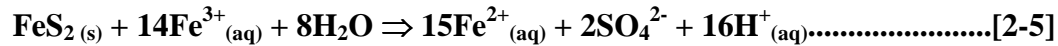
The third stage is pH dependent and involves the hydrolysis of ferric iron with water to form the solid ferric hydroxide (ferrihydrite) and additional acidity (equation 2-4). Under very acid conditions of less than about pH 3.5, the solid mineral does not form and ferric iron remains in solution. At higher pH values, a precipitate forms.



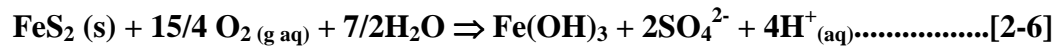
Step 4

The fourth step involves the oxidation of additional pyrite by ferric iron (equation 2-5). The ferric iron is generated by the initial oxidation reactions in steps one and two. This reaction is fast (van Mensvoort and Dent 1998), does not require oxygen and is also

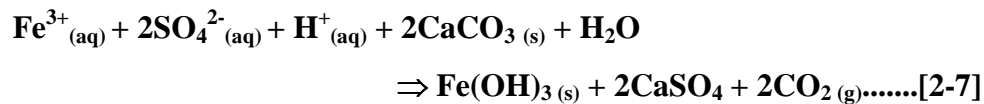
biochemically mediated. The cyclic propagation of acid generation by iron continues until the supply of ferric iron or pyrite is exhausted.



The overall reaction for pyrite oxidation yields 4 moles of acidity from each mole of pyrite and is expressed by equation [2-6].



When carbonate is present in the soil (such as shell fragments), the acidity is neutralised and the oxidation of Fe^{2+} to Fe^{3+} proceeds rapidly (equation 2-7). Iron precipitates and the calcium and sulfate ions form gypsum (Ritsema 1993).



Excess acidity can react with soil minerals releasing major constituents to groundwater such as potassium, magnesium, aluminium and silicon, as well as trace elements such as As, Cu, Cd, Cr, Ni and Zn. These potentially toxic elements, along with any remaining acidity, may then be exported off-site. Minerals such as gibbsite ($\text{Al}(\text{OH})_3$) and jarosite ($\text{KFe}_3(\text{SO}_4)_2(\text{OH})_6$) may form as intermediate oxidation products of pyrite oxidation and mineral decomposition in acidic soils and can hydrolyse to release more acidity (Figure 2-2).

NOTE:
This figure is included on page 13 of the print copy of
the thesis held in the University of Adelaide Library.

Figure 2-2 The overall sequence of mineral reactions for pyrite oxidation showing the relationships between oxidising agents, catalysts and mineral products (modified after Nordstrom 1982).

2.3. Environmental Impacts

Oxidation can occur naturally during dry seasons or drought , or can be accelerated when acid sulfate soils are disturbed when developed for agriculture or urban / industrial uses (Sammur *et al.* 1995; Sammur *et al.* 1996; van Breemen 1993; Willett *et al.* 1992). Acid-rich drainage waters, often containing toxic elements, can leach from the acid sulfate soils to nearby streams and estuaries where it can cause fish kills, contaminate shellfish, drinking water and groundwater, and can corrode concrete and steel of underground pipes and building foundations (Sammur *et al.* 1996; van Breemen 1993; White *et al.* 1996; Wilson *et al.* 1999).

Sulfidic sediments of most concern are those which were deposited during the last 10,000 years, the Holocene period (Pons 1973). Sea level rise following the end of the last ice age led to the drowning of river valleys, the deposition of deltas and the infilling of coastal embayments and estuarine floodplains with sulfidic sediments (Thom and Chappell 1975; Thom and Roy 1985). Land in Scandinavia is rising due to isostatic rebound following the melting of ice, exposing sulfidic materials around the coasts (Boman *et al.* 2009).

The hazards presented by acid sulfate soils can be magnified by their location and specific properties. For example, the depth to acidic soil layers (sulfuric material) or sulfidic materials, as well as the concentration of salts or minerals (e.g. sodium chloride, jarosite or pyrite), is critical.

2.3.1. Flora and fauna

When coastal land is reclaimed, the loss of habitat is a substantial concern, but acid sulfate soils can also adversely effect the surrounding environment. Soil acidification can cause agricultural and indigenous plant species to wane, allowing invasive species to succeed, or for bare salt scalded areas to develop. Acid sulfate soils can impact plant growth by causing soil acidification, Al toxicity, and Fe stress, and deficiencies in P, Ca and Mg (Auxtero and Shamshuddin 1991; Moore and Patrick 1991). Increased salt loads create conditions of osmotic stress similar to neutral salts. Aquatic plants can also be killed due to smothering by metal precipitates (Sammut *et al.* 1996).

In Australia the majority of coastal acid sulfate affected land occurs on the north east coast and was developed for production of sugar cane. Sugar cane is an acid tolerant plant species and can withstand pH between 3.5 and 5, and relatively high Al concentrations (Hetherington *et al.* 1988).

In Indonesia large tracts of coastal land have been developed to grow rice, coconuts and citrus, of which about half of the land has been abandoned due to soil acidification (Andriessse and van Mensvoort 2006; Toan *et al.* 2004). Loss of arable land due to acid sulfate soils is a global phenomenon, but tropical, lowland coastal areas are most severely affected. Other well documented regions, to name a few, where acid sulfate

soils have impacted agriculture include: Thailand (van Breemen 1973), Malaysia (Shamshuddin *et al.* 2004), Vietnam (Brinkman *et al.* 1993; Dent and Pons 1995; Willett *et al.* 1993), Florida (Thomas *et al.* 1995), Senegal (Sadio and van Mensvoort 1993), Netherlands (Dent 1986), Finland (Aström 2001), Bengal and India (Ponnamperuma and Bandyopadhyay 1980), Iraq (Fitzpatrick 2004).

2.3.2. Fauna

Dissolved metals, metalloids and acidity released from acid sulfate soil landscapes can have devastating effects on aquatic organisms in creeks and estuaries, particularly following rain events. The effects are generally more acute in freshwater environments, which have less acid buffering capacity, and include: habitat degradation, outbreaks of disease, fish kills, changes in community structures, reduced food resources and weed invasion (Acid Sulfate Soil Management Advisory Committee (ASSMAC) 2000). Large fish kills have been attributed to low pH waters and high concentrations of inorganic aluminium damaging the gills of aquatic organisms and have been attributed to the decline or failure of fishery and aquaculture industries (Cook *et al.* 2000; Sammut *et al.* 1995). Fish kills have also been attributed to asphyxiation due to deoxygenated water following floods that mobilise monosulfidic materials in the Richmond River, in northern NSW (Bush *et al.* 2004b).

There is evidence that high iron and silica concentrations released by acid sulfate waters may be responsible for cyanobacterial blooms (Ahern *et al.* 2000), which can be toxic to aquatic and terrestrial organisms, including humans (Dennison *et al.* 1999).

2.3.3. Amenities and structures

The aesthetics and water quality issues can be obvious in degraded acid sulfate soil landscapes (Figure 2-3). High concentrations of orange iron oxyhydroxide precipitates and white aluminium hydroxides can discolour water bodies. The prevention of tidal flushing can cause surface and groundwaters to become hypersaline causing salt scalds to form around water bodies and groundwater discharge sites. Thick, soft, black deposits containing reduced manganese and iron monosulfides can block drains and creeks, and can devastate down-gradient ecosystems if mobilised during flood events (Bush *et al.* 2004a). The high salinity and acidity of acid sulfate soil landscapes can greatly enhance corrosion of concrete and metal structures such as drains, bridges and tidal gates (Figure

2-3), which can be very expensive to repair. Groundwater extraction wells can be come clogged with iron oxyhydroxides (Dent 1986) and aluminium gels (Shand *et al.* 2006). Building in coastal landscapes can be costly as load bearing structures require additional engineering solutions due to the high water content and low load bearing capacity of soils. There is also a requirement for coastal developments in South Australia to have a minimum floor height of 3.55 m AHD to account for predicted (100 year) sea level heights (Coastal Protection Board 2003).



Figure 2-3 (a) stranded tidal creek at Gillman with water containing orange iron oxyhydroxide and surrounded by white salt deposits and dead mangrove tree stumps. This site has low aesthetic characteristics. (b) corroded concrete drain at Gillman.

Noxious odours

Foul, offensive odour problems have been encountered near areas rich in sulfidic materials. For example, St Kilda, north of Adelaide, is sometimes plagued with noxious smells during the warmer months when sulfidic soils are exposed during low tide (Coleman and Cook 2003). These offensive smells occur when sediments extremely enriched in sulfides are exposed to the atmosphere. Hydrogen sulfide production (H_2S – the rotten egg smell) by drying sulfidic materials is thought to be a significant cause of the noxious smells. Drying sulfidic materials also produce sulfur dioxide (SO_2) (Kinsela *et al.* 2007; Macdonald *et al.* 2004). Aside from the foul odour problem, H_2S and SO_2 are also of concern for human health at high concentrations e.g. in confined spaces such as excavations. A number of malodorous organic-S gases (such as dimethyl oligosulfides) can also be produced under the conditions favourable to H_2S production (Franzmann *et al.* 2001).

2.3.4. Greenhouse Gas Emissions

Drainage of acid sulfate soils results in the production of the greenhouse gas as carbon dioxide (CO₂). Carbon dioxide is produced by accelerated decomposition (oxidation) of organic matter, the reaction of acid with soil carbonates and reaction of acid with seawater bicarbonate. In undisturbed wetlands, the oxidation rate is slow resulting in the accumulation of carbon as soil organic matter, forming a major carbon sink. Studies (Fitzpatrick and Merry 1999; Hicks *et al.* 1999a; b) have shown that the CO₂ released from drained coastal wetlands in Australia is higher than carbon input and could be as high as 33 tonnes of C per hectare (121 t CO₂-e) from the decomposition of organic matter and reaction with soil carbonates. The neutralization of released acidity by seawater contributes an additional 8 tonnes of C per hectare (29 t CO₂-e). These are likely to be 'high' level estimate as not all acid sulfate soils have high organic C, however sulfidic materials may produce methane at very low redox potentials. Methane is a much more effective greenhouse gas than CO₂ (Lelieveld and Crutzen 1992). Australia's greenhouse gas emissions of carbon due to land use change (primary land clearing) have been estimated at 62.9 Mt CO₂-e per year (17.2 Mt of C per year) (Fitzpatrick and Merry 1999).

2.4. Classification of acid sulfate soil materials

The distinguishing feature of acid sulfate soil materials has been either the presence of sulfide minerals sufficient to cause severe acidification, or contain severe acidity as a result of the oxidation of those sulfide minerals (Pons 1973; van Breemen 1973). These processes have traditionally been distinguished by the terms: **sulfidic material** (i.e. soil material that has the potential to form severe acidity (pH < 4) by means of iron sulfide oxidation) and **sulfuric material** (i.e. soil material that contains actual acidity (pH < 4) from partially or fully oxidised sulfide minerals), and is not determined by the soils pH alone e.g. (FAO 1998; Isbell 2002; IUSS Working Group WRB 2006; Soil Survey Staff 2010).

The term 'sulfidic', as used this way in soil classification, differs from the definition traditionally used by other scientific disciplines (e.g. ecology, geology, geochemistry, zoology) when describing soil, sediment, rocks and water (Sullivan *et al.* 2009). The

broader scientific community use the term 'sulfidic' to describe any materials that contain sulfides.

To accommodate sulfide-containing soil materials that do not have the capacity to acidify, but do have the capacity to pose other sulfide-related environmental hazards, (Sullivan *et al.* 2009) proposed changes to the classification system of acid sulfate soil materials. Recently, the Acid Sulfate Soils Working Group of the International Union of Soil Sciences agreed to adopt, in principle, the following five descriptive terminology and classification definitions of acid sulfate soil materials proposed by Sullivan *et al.* (2009) at the 6th International Acid Sulfate Soil and Acid Rock Drainage Conference in September 2008 in Guangzhou, China. The proposed definitions essentially replace the term 'sulfidic' with *hypersulfidic*, and include the new term *hyposulfidic* to account for sulfidic soil material that is not capable of severe acidification as a result of oxidation of contained sulfides. The term *monosulfidic* has also been included to distinguish soil materials containing detectable monosulfides from other sulfidic materials.

Although severe acidification is a major environmental hazard that can arise from the disturbance or mismanagement of sulfide-affected soil materials, much recent literature on the behaviour of sulfide-containing soil materials indicates that acidification is not the only important environmental hazard arising from these soil materials. Other environmental hazards associated with sulfide-containing soil materials include: (i) enhanced mobilisation of trace metals, metalloids and non-metals, (ii) decrease in oxygen in the water column when monosulfidic materials are mobilised, (iii) enhanced nutrient release and, and (iv) production of noxious gases. Some of these additional environmental hazards are the result of sulfide-related processes that are redox-driven and not directly associated with acidification (Burton *et al.* 2006a; Burton *et al.* 2009; Sullivan *et al.* 2002).

The improved classification system for acid sulfate soil materials has been used in this thesis because the newly defined terms better distinguish between contemporary and potential environmental hazards posed by the soil materials (Sullivan *et al.* 2010). Representing these newly defined acid sulfate soil materials on soil maps; therefore, better represents landscape processes and the environmental hazards that these specific soil materials pose.

The definitions for acid sulfate soil materials used in this thesis are as follows:

1) Sulfuric materials – soil material that has a pH less than 4 (1:1 by weight in water, or in a minimum of water to permit measurement) as a result of the oxidation of sulfidic materials when measured during dry season conditions. Evidence that low pH is caused by oxidation of sulfides from one of the following:

- (i) mottles and coatings with accumulations of jarosite or other iron and aluminium sulfate or hydroxysulfate minerals such as natrojarosite, schwertmannite, sideronatrite, tamarugite, etc., or
- (ii) 0.05 % or more by weight of water-soluble sulfate, or
- (ii) underlying sulfidic material.

2) *Sulfidic materials – soil materials containing detectable sulfide minerals (defined as containing greater than or equal to 0.01% sulfidic S). The intent is for this term is to be used in a descriptive context (e.g. sulfidic soil material or sulfidic sediment) and to align with general definitions applied by other scientific disciplines such as geology and ecology (e.g. sulfidic sediment). The method with the lowest detection limit is the Cr-reducible sulfide method, which currently has a detection limit of 0.01%; other methods (e.g. X-ray diffraction, visual identification, Raman spectroscopy or infra red spectroscopy) can also be used to identify sulfidic materials.

**This term differs from previously published definitions in various soil classifications e.g. (Isbell 2002).*

3) Hypersulfidic material – is a sulfidic material that has a field pH of 4 or more and is identified by experiencing a substantial* drop in pH to 4 or less (1:1 by weight in water, or in a minimum of water to permit measurement) when a 2 - 10 mm thick layer is incubated aerobically at field capacity. The duration of the incubation is either: a) until the soil pH changes by at least 0.5 pH unit to below 4, or b) until a stable** pH is reached after at least 8 weeks of incubation.

**A substantial drop in pH arising from incubation is regarded as an overall decrease of at least 0.5 pH unit.*

***A stable pH is assumed to have been reached after at least 8 weeks of incubation when either the decrease in pH is < 0.1 pH unit over at least a 14 day period, or the pH begins to increase.*

4) Hyposulfidic material – is a sulfidic material that (i) has a field pH of 4 or more and (ii) does not experience a substantial* drop in pH to 4 or less (1:1 by weight in water, or in a minimum of water to permit measurement) when a 2 - 10 mm thick layer is incubated aerobically at field capacity. The duration of the incubation is until a stable** pH is reached after at least 8 weeks of incubation.

**A substantial drop in pH arising from incubation is regarded as an overall decrease of at least 0.5 pH unit.*

***A stable pH is assumed to have been reached after at least 8 weeks of incubation when either the decrease in pH is < 0.1 pH unit over at least a 14 day period, or the pH begins to increase.*

5) *Monosulfidic materials – soil materials with an acid volatile sulfur content of 0.01%S or more.

**Monosulfidic soil materials are conceptually similar to Monosulfidic Black Oozes (MBO) but differ from MBOs in that monosulfidic soil materials encompass a wider array of soil textures and consistencies. For example, monosulfidic soil materials include monosulfidic sands, which are excluded (on the basis of consistency) from being MBOs.*

Table 2-1 Correlation between classification of acid sulfate soil materials/horizons and the different major soil taxonomic systems and common descriptive terms (Sullivan *et al.* 2010).

NOTE:

This table is included on page 20 of the print copy of the thesis held in the University of Adelaide Library.

2.5. Management of acid sulfate soil

Acidification of soils and waterways by sulfuric acid is a major problem in landscapes affected by acid sulfate soils, acid mine drainage, or acid rain. Although their distribution in the landscape may differ significantly, they do share similar bio-geochemical processes controlling the formation of acidity. Therefore management strategies developed for acid mine drainage or areas affected by acid rain can be applied to acid sulfate soil landscapes and vice versa.

The basic principles of acid sulfate soil remediation are to curtail pyrite oxidation and to neutralise or leach existing acidity, at the same time managing the discharge of acidic water and toxic oxidation products. Oxidation of sulfides can only be curtailed by removing the oxygen supply - by re-flooding or burial beneath a capping layer. Even then, the oxidation of pyrite by Fe(III) may continue. Oxidation may be slowed by decreasing the rate of Fe(III) production with (i) bactericides that inhibit the *Acidithiobacillus* to functioning, or (ii) by the addition of soil amendments which complexes or precipitates iron. However, these are only temporary solutions, more suited to short-term management requirements, such as stockpiling acid sulfate soil during engineering works. Neutralization of acid can be achieved by the addition of basic substances such as agricultural lime and by establishing reducing conditions. Leaching of acid from the soil is another option but not recommended and is only acceptable in Australia using a water management system that discharges acidic surface water at times of high flow so as to reduce environmental impact. A range of acid sulfate soil remediation techniques based on these principles has been proposed (e.g. Bowman 1993; Dent 1992). However few of these techniques have been intensively developed or field-trialled in Australia (Bowman 1996; Johnston *et al.* 2009a; Powell and Martens 2005; Smith and Yerbury 1996; Stone *et al.* 1998; Thomas 2004; Thomas *et al.* 2004a; White and Melville 1993).

Coastal development projects such as land reclamation, digging ponds for aquaculture, sand and gravel extraction or dredging for ports and marinas are likely to disturb acid sulfate soil. Where acid sulfate soil is disturbed, they potentially present a hazard to human health, local infrastructure and the local environment. However, appropriate

management of acid sulfate soil during development can improve discharge water quality, increase agricultural productivity and protect infrastructure and the environment (Ahern *et al.* 2004; Thomas *et al.* 2004a). Such improvements can generally be achieved by applying low-cost land management strategies based on the identification and avoidance of acid sulfate soil materials, slowing or stopping the rate and extent of pyrite oxidation, and by retaining existing acidity within the acid sulfate soil landscape (Dear *et al.* 2002). Acidity and oxidation products that cannot be retained on-site may be managed by other techniques such as acidity barriers or wetlands that intercept and treat contaminated water before it is finally discharged into rivers or estuaries.

Appropriate management options will depend on the nature and location of the acid sulfate soil materials, and their position in the landscape. Reliable acid sulfate soil hazard maps, at appropriate scales, provide an important communication and educational tool that aids in the adaptive management of these coastal landscapes.

Priorities for the Management of Coastal Acid Sulfate Soils in South Australia are

(after Dear *et al.* 2002; Thomas *et al.* 2004a):

- Minimise disturbance or drainage of acid sulfate soil materials, through education;

Select an alternative non-acid sulfate soil site, rather than undertake remediation. If an alternative site is not feasible, design works to minimise the need for excavation or disturbance of acid sulfate soil materials, by undertaking shallow excavations for drainage measures or foundations, and avoiding lowering groundwater depth that may result in exposure of soils. If acid sulfate soil materials are close to surface, cover with clean soil to lessen the chance of disturbance and insulate from oxygen.

- Prevent oxidation of sulfidic material;

This may include staging the development project to prevent oxidation of sulfidic material by covering it with an impermeable barrier (e.g. clay), or placing any excavated sulfidic material quickly back into an anaerobic environment, usually below the water table.

- Surface loading of acid sulfate soil to minimise risk of further disturbance and curtail oxidation (Thomas and Fitzpatrick 2006c);

Burying acid sulfate soil materials with fill provides a barrier that reduces the risk to further disturbance. The cover also slows the oxidation of sulfidic material. In suitable areas (with low bulk density soils) loading may aid neutralisation of acidity by pushing sulfuric materials below the permanent ground water table, enabling reducing conditions to re-establish.

- Minimise oxidation rate and isolate higher risk materials from exposure;

This may include covering acid sulfate soil materials with soil or water to reduce oxygen availability and control the movement of water, or by controlling bacteria or by applying other limiting factors (e.g. alkalinity) through either physical or chemical means to reduce oxidation rate.

- Contain and treat acid drainage to minimise risk of significant offsite impacts;

Typically, this would involve installing a leachate collection and treatment system (e.g. using lime), a permeable reactive barrier (e.g. lime slot) to intercept and neutralise acidic groundwater as it moves through the soil, or installing an impermeable barrier to locally confine acidic groundwater.

- Provide an agent to neutralise acid as it is produced;

This would involve mixing the acid sulfate soil material with an excess of lime, or other neutralising agent.

- Separate sulfidic materials;

Requires mechanical separation, such as sluicing or hydrocyclone to separate heavy sulfide minerals (e.g. pyrite) from the sulfidic material, followed by treatment (e.g. liming) or disposal of the sulfide mineral in an anaerobic environment.

- Hasten oxidation and collection and treatment of acidic leachate;

This involves spreading the acid sulfate soil materials in a thin layer on an impervious area to activate rapid oxidation. Rainfall or irrigation leaches the acid and this leachate is collected and treated (e.g. by liming).

- Management of stockpiled acid sulfate soil materials;

This includes minimising the quantity and duration of storage, minimising the surface area that can be oxidised, covering the soil to minimise rainfall infiltration, stormwater control measures, controlling erosion and collection, and treatment of runoff (leachate).

Chapter Three

3. Environmental settings

The Barker Inlet estuary is located 20 km north of Adelaide and contains the largest stand of grey mangroves (*Avicennia marina*) in Australia. Grey mangroves are the only species of mangrove in South Australia. Much of the formerly intertidal land around Barker Inlet has been reclaimed for industrial and agricultural purposes (Figure 3-1). At Gillman a number of site investigations have identified the occurrence of 'sulfide containing' or acidic soils within the reclaimed area (Belperio 1985b; Belperio and Rice 1989; Fitzpatrick *et al.* 1996a; Harbison 1986a; Kinhill Engineers Pty Ltd *et al.* 1996; Thomas *et al.* 2004a). The northern portion of Barker Inlet is less developed, with a mangrove conservation park being established at St Kilda.

This chapter brings together existing information relating to soils, land use, physiography, ecology, hydrology and site contamination history for the Gillman and St Kilda study sites, as a resource for mapping and characterising acid sulfate soils, and to provide a holistic understanding of contaminant issues pertaining to the site that ultimately affects their management.

3.1. Site Locations

This study was conducted at two study sites in the Barker Inlet region, north of Adelaide, South Australia: (i) Gillman and (ii) St Kilda (Figure 3-1). The Gillman study site was chosen because it was known to have an acid sulfate soil problem as well as there being pressure to develop the land for industrial purposes. It is also ideally suited for comparative research because it contains "paired sites" that have intertidal samphire and mangroves abutting drained soils caused by construction of bund walls to reclaim land for urban development. The intertidal soils, however, are also adjacent to extensive salt evaporation ponds, industrial estates and the former Wingfield and Garden Island landfills (Figure 3-1), presenting some contamination potential issues. Therefore, a

control site was selected at the St Kilda mangrove conservation area, 6 km north of Gillman (Figure 3-1), which was less influenced by anthropogenic alteration and contaminants.

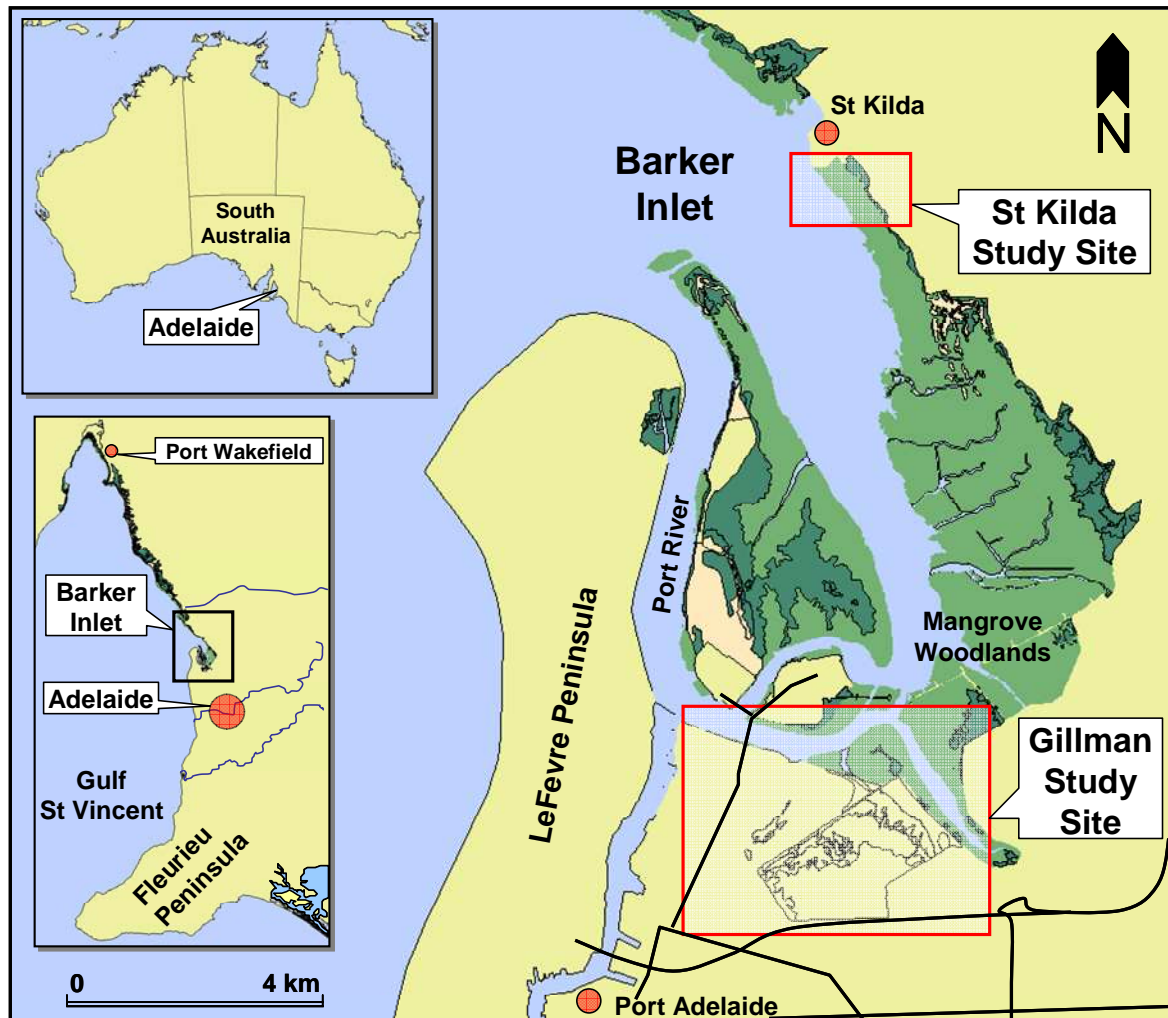


Figure 3-1 Location map of the St Kilda and Gillman study sites. The natural component of the Barker Inlet estuary is characterized by seagrass meadows adjoining mudflats, grey mangrove woodlands and intertidal samphire wetlands. The Gillman study site is located to the south of Barker Inlet, about 15 kms north of Adelaide. The St Kilda study site is located within the St Kilda mangrove conservation area, 6 km north of Gillman.

Gillman

The Gillman study site, which covers approximately 1000 ha, is located about 15 km north of Adelaide and adjoins the North Arm of Barker Inlet. This study site includes much of the former Multi-Function Police (MFP) core site (Coffey Partners International Pty Ltd 1990). The North Arm of Barker Inlet, and the Grand Trunkway form the northern and western boundaries of the Gillman study site, respectively, with the Wingfield landfill and the Port Adelaide expressway forming the eastern and

southern boundaries (Figure 3-2). Most of the land at Gillman was reclaimed from intertidal and supratidal areas of Barker Inlet in 1935 when a bund wall was constructed (Figure 3-3 and Figure 3-4). Consequently, broad scale soil acidification resulted in soils that contained pyrite and had limited buffering or neutralising materials. Acidification of soils and interstitial waters led to various degrees of degradation of the immediate and receiving environments. Bund walls now prevent tidal inundation and form stormwater retention basins that release stormwater to the Barker Inlet at low tide. The major land uses in and surrounding the Gillman study site are: stormwater ponding basins, salt evaporation ponds, vacant land zoned for industrial development, landfills, fresh and intertidal (saline) wetlands (Figure 3-2). A large proportion of the Gillman study site has remained vacant since reclamation and the current owners propose environmental remediation, conservation and commercial and/or industrial development of the area. Along North Arm Creek, the natural tidal component of the estuary is characterised by seagrass meadows adjoining mudflats, mangrove woodlands and intertidal samphire wetlands (Figure 3-2).

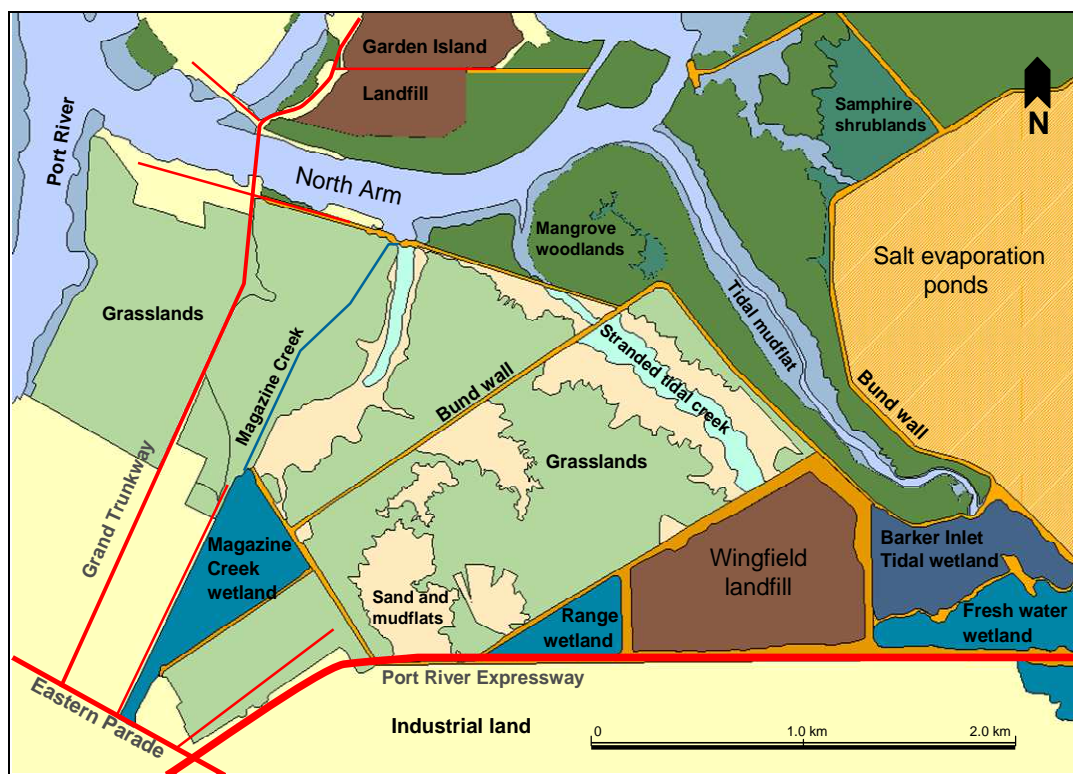


Figure 3-2 The Gillman study site is predominately vacant, consisting open grasslands, samphire shrublands and salt and sand flats. It is bordered by urban and industrial development to the south and abuts tidal mangrove woodland along North Arm. The Gillman area has been progressively reclaimed from the intertidal and supratidal environments of Barker Inlet since the 1930s by construction of a series of bund walls that prevent tidal inundation.

St Kilda

The St Kilda study site is located within the St Kilda mangrove conservation area, 6 km north of Gillman and adjacent to the St Kilda township (Figure 3-3). It is also within the intertidal zone of mangrove and samphire vegetation. A wooden boardwalk provided access to field sites. The site is tidally flooded with tidal flows limited by a bund wall that forms the eastern boundary to the study site (Figure 3-3). The bund wall is part of the extensive salt evaporation ponds that fringe the eastern side of the Barker Inlet, and continue for 40 km along the coast of St Vincent Gulf.

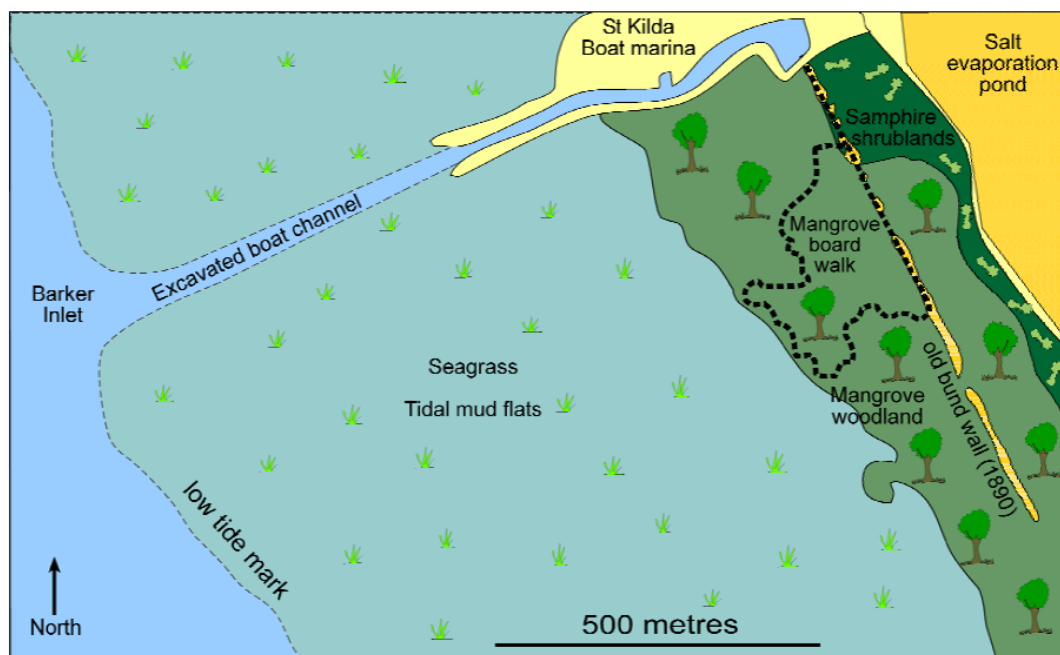


Figure 3-3 The St Kilda study site. An old bund wall runs north-south through the site and dissects the intertidal zone. It was built in 1890 but was breached and abandoned after 1914, allowing the tide to once again flood the reclaimed area to its east. A new bund wall and salt evaporation ponds were constructed east of the old bund during the 1930s.

3.1.1. History of Land Reclamation

Europeans began development of the Barker Inlet estuary by draining intertidal wetlands to the south and east, excluding tidal waters with bund wall embankments. These bunds were built along the landward extent of mangrove woodlands so the samphire could be used as pasture. The first bund was constructed in the 1890s, along the eastern side of the estuary, running south from St Kilda to Swan Alley Creek (Figure 3-4). The bund was breached several times between 1914 and 1918, and eventually abandoned allowing tidal waters to return to the drained areas. Mangrove trees colonised the re-flooded area

and have progressively moved inland at a rate of up to 17 m per year (Burton 1982a). The rapid encroachment of mangroves into areas that were previously colonised by samphire vegetation may be a legacy of draining the soils. From 1935 a bund wall was constructed from Swan Alley to North Arm Creek and across about half of the Gillman site (Figure 3-4). The salt evaporation ponds were also established at this time and were producing salt products by 1959 (Talbot 1985). In 1965 the bund wall at Gillman was extended westward to the Port River (Figure 3-4).

3.2. Physiography

3.2.1. Local Climate

The Adelaide area has a Mediterranean type climate, which is characterized by cool to mid wet winters and extended hot dry summers. The average daily temperature is ~23°C during summer and ~14°C during winter months. Extreme temperatures of >40°C during summer and <0°C in winter are not common. The mean annual rainfall for the area is 470 mm, occurring mainly between May and September (Pavelic and Dillon 1993a; b). The mean annual evaporation rate is 1,760 mm with summer rates up to 250 mm, and winter rates up to 60 mm. The high potential evaporation demand exceeds rainfall by almost four to one (Pavelic and Dillon 1993a) with evaporation exceeding rainfall during most months of the year. There is no official weather station at Gillman or St Kilda. However, the study areas should have very similar weather to that recorded by the Bureau of Meteorology's Garden Island weather station. The annual, predominant wind across the study area is from the southwest. During the summer, the wind tends from SW to SSE, during autumn it is generally from the SSE, during spring the south-westerlies predominate and during the winter there are NNE to NE winds (Pavelic and Dillon 1993a). Vegetation controlled microclimates across the salt marsh and cleared sections of the study site are limited by the lack of a tall shrub or tree canopies, leaving the ground shading function to the low shrubs, herbs and thin grasses growing on the site (Coleman 1999).

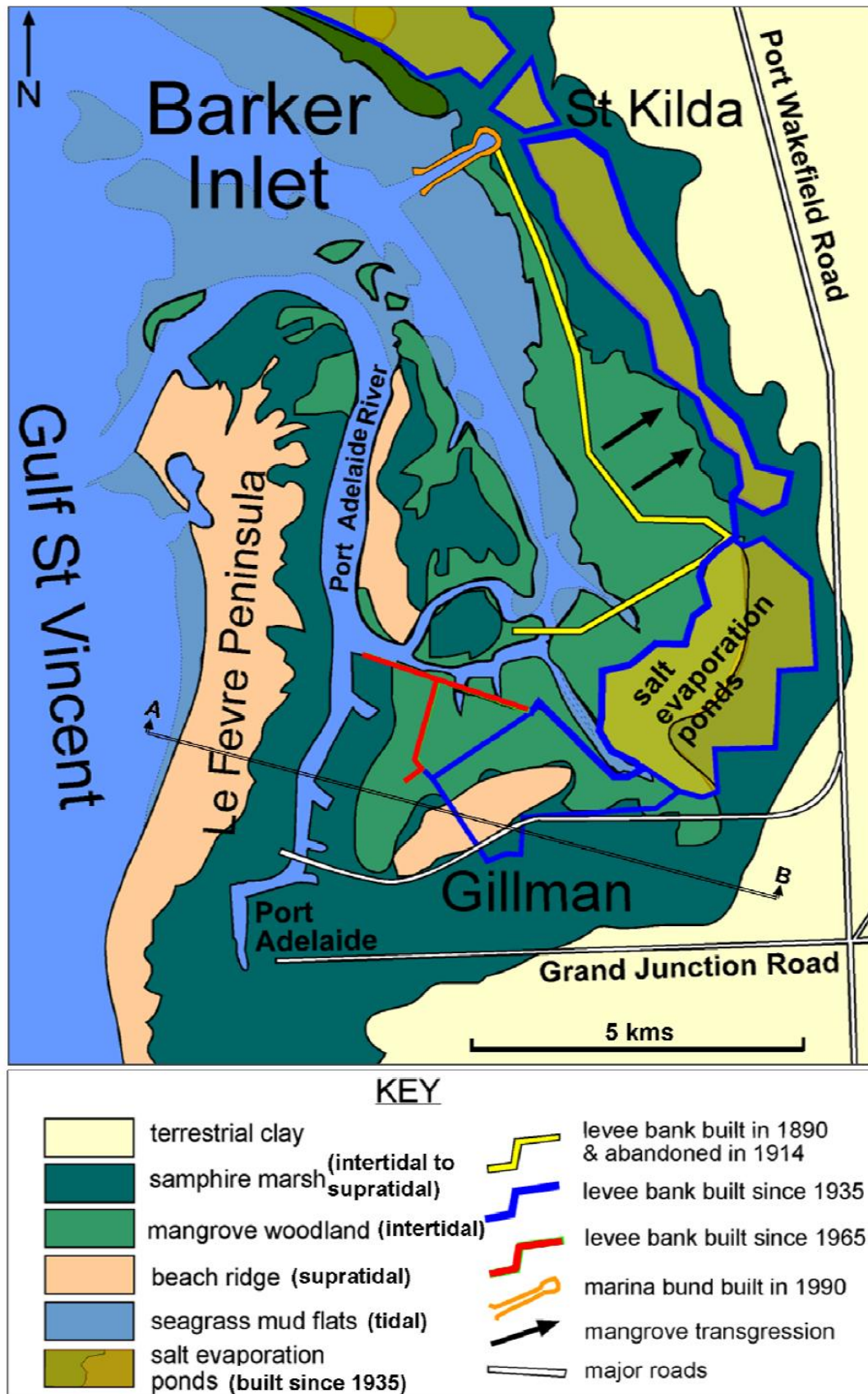


Figure 3-4 Pre-European coastal environments of the Barker Inlet estuary and the 2-4 m high bund walls that were progressively constructed over the last 100 years to exclude tidal waters and reclaim intertidal land for agricultural and industrial purposes. Refer to Figure 3-5 for Cross-section A-B.

3.2.2. Vegetation

The Gillman and St Kilda study sites contain the following groups of flora: Mangrove Fringed Herbland, Exotic Grassland, Silky Wilsonia Herbland, Salt Marsh Herbland Complex and Bare Ground (Fotheringham 1994; Gibbs and Dowd 1992; Green 1996). Five main vegetation associations were mapped and described by Fotheringham (1994). (Burton 1984) reported that since European settlement there may have been little net loss in the area occupied by mangroves in the Port River Estuary. However, the distribution of mangroves has changed considerably. Burton (1984) concluded that approximately 80% of samphire vegetation in the region has been cleared to date and not replaced. Prior to European settlement and the development of levees, the Gillman study area was under intertidal/supratidal influence, vegetated with mangrove and samphire, and some areas had dune vegetation (Fotheringham 1994). Overall, more samphire vegetation has been cleared than mangroves (Banham 1992; Kinhill Stearn 1985; Kucan 1979). The continuing development of the site has resulted in substantial environmental degradation including modification of vegetation cover and type, but some areas of remnant vegetation remain. Large areas of the Gillman study site are presently being used for stormwater ponding basins for urban stormwater runoff. The ponding has been identified as the major cause of soil erosion along drainage channels and loss of habitat for samphire vegetation (Maunsell 1984). The ponding basins constitute over one third of the Gillman study site.

3.2.3. Geomorphology of the Adelaide Coastal Zone

The morphostratigraphy within the Port Adelaide Estuary was established from 51 vibrocores taken across both reclaimed and undisturbed portions of the tidal wetlands, supplemented with data from pre-existing drill holes (Belperio and Rice 1989). Seventeen of these cores were taken from wetlands at Gillman, 4 of which are from natural wetland. Cores provided information on, and samples of, subsurface strata. Near surface shell or mangrove samples were used for radiocarbon dating, establishing ages of 450 ± 35 years (Gillespie and Polach 1979). The recent geological evolution of the study areas has been largely controlled by global sea level fluctuations (Edmonds 1995). Belperio co-authored a series of investigations that led to the development of the geomorphic and geologic history of the area. The stratigraphic sequence is variable and

complex and reflects many depositional environments. For example, Belperio and Rice (1989) identified the following 6 surficial environments, which were present prior to levee bank construction and land reclamation:

- | | |
|----------------------------------|---------------------------------|
| 1. intertidal mud and sand flats | 4. stranded sandy shore facies |
| 2. intertidal mangrove woodland | 5. back barrier sand plain, and |
| 3. supratidal marsh | 6. alluvial coastal plain. |

These surficial environments give rise to the following 9 separate sedimentary facies, which reflect the various depositional environments that have occurred in the Barker Inlet area:

- | | |
|--------------------------------------|------------------------------|
| 1. coastal barrier / sandy foreshore | 6. inter-tidal mangrove |
| 2. back-barrier sand | 7. supratidal samphire marsh |
| 3. tidal channel sand | 8. subtidal lagoon |
| 4. subtidal seagrass bank | 9. transgressive |
| 5. intertidal sand flat | |

Two major Quaternary marine transgressions were largely responsible for the sedimentary environment. Figure 3-4 shows the pre-European and current coastal morphology.

Reworking of coastal sediments since sea level stabilization (about 7500 B.P.) resulted in the northerly extension of the Le Fevre Peninsula beach ridge system. This northerly extension of the Le Fevre Peninsula and Torrens River outlet in conjunction with the establishment of extensive sea-grass meadows has led to the rapid accumulation of marine and estuarine sediments, resulting in coastal progradation throughout the late Holocene. Progradation led to simultaneous back barrier development of marshes and mangrove swamps parallel to the shoreline. The embayment is now mostly infilled except for the Port River estuary (Figure 3-4).

Historical records and air photographs provided information on the former extent of wetland environments (see Appendix A).

3.2.4. Geology

The St Kilda study site, and most of the Gillman site are located on Quaternary deposits, specifically upon the prograded Holocene St Kilda Formation and overlain in places by modern intertidal and swamp deposits (Department of Mines SA 1969). The latter consists of unconsolidated coastal marine muds, spongy peat or shelly or clayey sands (Belperio and Rice 1989; Daily *et al.* 1976; Sprigg 1952; Tate 1879). Grain size generally becomes finer toward the east (Belperio 1985b). In the Gillman study site area, the St Kilda Formation forms a north-westward thickening wedge, ranging from less than 1 m thick in the east to about 6 m thick in the west (Figure 3-5). Its sediments are soft and loose, and it has a watertable near the surface (Pavelic and Dillon 1993a). The St Kilda Formation ranges from about 7500 years B.P, when the last marine transgression stabilized, to present day as it is still forming in foreshore and subtidal mangrove and samphire environments.

The St Kilda Formation overlays the Pleistocene Pooraka Formation. The Pooraka Formation is the major alluvial deposit of the North Adelaide Plains and occurs at shallower depths in the east, extending westward beneath the St Vincent Gulf (Figure 3-5) and comprises firm to very stiff clay or silty clay of high plasticity with the main coarser constituent being rounded to subrounded quartz grains (Howchin 1888). This Formation has a bluish grey colour and may have rust coloured mottles and streaks due to iron oxide staining and overlays the Glanville Formation. The Glanville Formation is approximately 3 m thick consisting of calcareous and silty sands with abundant shells, and is capped by a thin veneer of limestone or calcrete known as the Bakara Calcrete in some areas. Glanville Formation sediments are exposed at the surface at the north of the former Dean Rifle Range in the Gillman area.

The alluvial Pleistocene Hindmarsh Clay occurs below the Glanville Formation and is a stiff, red-brown clay of up to 70 m thick, with reasonable bearing capacity and low permeability (Belperio 1985a). At Gillman the average depth to the top of the Hindmarsh Clay is estimated to be 11 m (Belperio and Rice 1989), however Pavelic and Dillon (1993a) reported it to be considerably greater. The Hindmarsh Clay includes up to six discrete layers of sand and gravel to form the Quaternary aquifer system (Pavelic

and Dillon 1993a). Tertiary formations underlying the Hindmarsh Clay include the Carrisbrook Sand, Dry Creek Sand and the Port Willunga Formation.

NOTE:
This figure is included on page 34 of the print copy of
the thesis held in the University of Adelaide Library.

Figure 3-5 schematic cross-section from Le Fevre Peninsula to the Mount Lofty Ranges, showing relationships between Quaternary coastal marine and continental facies of the St Vincent Basin, (after Belpario 1995). Refer to Figure 3-4 for location of Cross-Section A-B.

3.2.5. Topography

Gillman study site

The majority of the site is natural surface, comprising coastal dunes and undulations between stranded tidal creeks. A digital elevation model (DEM) of the Gillman area is shown in Figure 3-6, with elevations given in Australian Height Datum (AHD). The AHD is -0.047 m relative to mean sea level. The lowest areas usually contain water and include the drains, wetlands, and areas where sand was scraped for embankment construction. A distinct feature of Gillman is its flat (<1% slope) and low-lying topographic relief. Natural elevation ranges from -1.0 m AHD in creek channels to 1.5 m AHD on undulating mounds between tidal creeks. Much of the area is between 0.0 m AHD and 1.0 m AHD. The rifle range backstop, still visible in the digital elevation

model, was removed in 2005 for construction of the Port River Expressway. The Wingfield landfills are between 10 to 30 m high. Raised areas include the levees, drain and wetland spoils, reconstructed wetlands, rifle range backstop, roads and tracks and the waste disposal mounds.

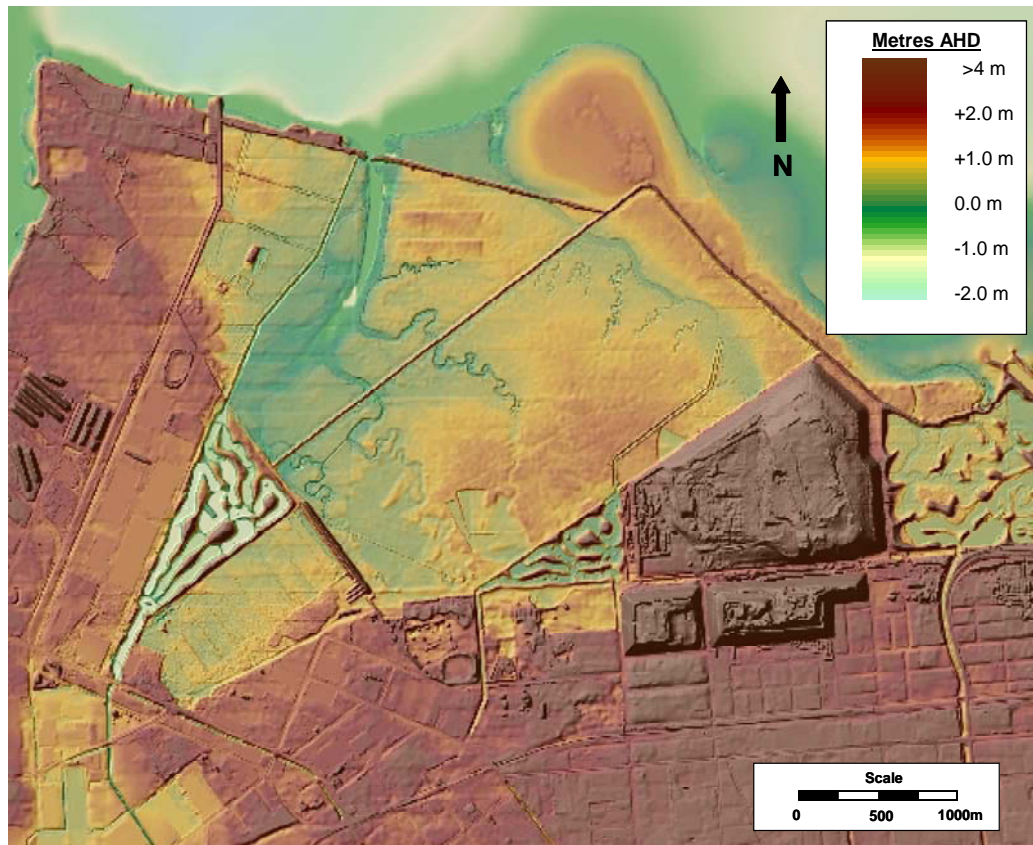


Figure 3-6 Digital elevation model (DEM) showing the low lying topography of the Gillman study area.

St Kilda study site

The St Kilda study site is near flat (slope <1%), low-lying land with elevation ranging from -1.0 m AHD on the tidal mudflats to 1.5 m AHD on an intertidal chenier ridge. Networks of tidal creeks meander through the mangrove forest, generally running in an east-west direction. A chenier ridge forms a topographic high that runs in a north north-westerly direction. The topography of the site can be inferred from vegetation type which is related to tidal influence (Figure 3-7). Seagrass and mudflats occur in the lowest lying areas to the west of the site and are generally between -1.0 and 0.0 m AHD high, mangrove trees cover the majority of the site where elevation ranges between 0.0 and 1.0 m AHD high, while samphire vegetation occurs along shell-grit mounds that have less tidal influence, ranging 1.0 to 1.5 m AHD high.

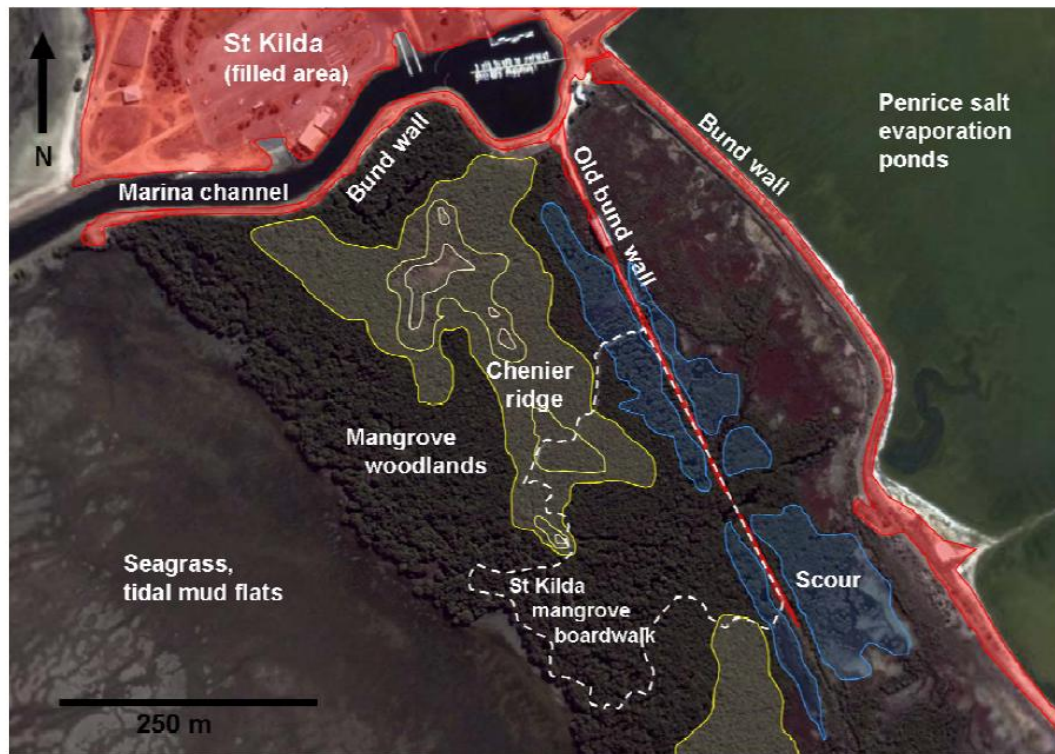


Figure 3-7. Aerial photograph of the St Kilda study site with major topographic features highlighted. The topography of the site is very much related to vegetation type, corresponding to tidal influence. Seagrass and mudflats occur in the lowest lying areas to the west of the site and are generally between -1.0 and 0.0 m AHD, mangrove trees cover the majority of the site where elevation ranges between 0.0 and 1.0 m AHD, while samphire vegetation occurs along shell-grit mounds that have less tidal influence, ranging 1.0 to 1.5 m AHD. Levee banks form the highest land features at the study site, being between 2 and 3 m AHD.

Levee banks form the highest land features at the St Kilda study site, being between 1.5 and 3 m AHD high. The lowest of these linear levees runs in a north north-westerly direction near the eastern side of the study site and is about 1.5 m to 2.0 m AHD high. It was built in the 1890s and has since been breached at a number of locations along its length. Soil was scoured from either side of the levee to form the embankment. The scour marks can be seen as water filled depressions (circled by a blue line in Figure 3-7). This old bund wall joins a 3 m AHD high embankment that runs east-west beside the St Kilda boat marina channel. The Penrice salt evaporation ponds form the eastern extent of the St Kilda study site and are surrounded by a bund wall about 3 m AHD high.

Land Subsidence

Land subsidence on the coastal plains north of Adelaide could be due to tectonic movements of the Adelaide "horst and graben" formation, but is also likely to be the result of sediment consolidation. According to Belperio (1993b) the amount of regional

settlement is commonly accepted to be in the region of 100 mm per 100 years, and can be expected to continue. Land subsidence in the Gillman area is also attributed to reclamation of Holocene wetlands and groundwater extraction from Tertiary aquifers (Belperio 1993b). Fifty years of groundwater extraction has created a potentiometric cone of depression in excess of 20 m beneath the Port Adelaide estuary – causing an estimated 2.8 mm per year subsidence. From 1935 to 1979, mangroves in the Gillman area advanced inland at a rate of approximately 17 m per year, most likely due to the effects of localized subsidence shifting the intertidal zone landwards (Burton 1984). Overcrowding of the intertidal creeks by mature mangroves has slowed their transgression. Between Light River and Port Gawler (15 km north of St Kilda), mangrove progradation is approximately 18 m per year, while between Pt. Gawler and St Kilda little or no migration of mangroves is occurring. According to (Belperio and Harbison (1992), at Gillman, 0.7 m of ground subsidence coincides with an area of about 400 ha of exposed mangrove peat subject to meteoric infiltration and aeration.

3.3. Hydrology

3.3.1. Tides

Tides in the estuary are complicated by the presence of Torrens Island, and the incoming tide travels south around both sides of the island. There is a tidal lag of approximately 34 minutes between the Outer Harbour Pilot Station at the head of Le Fevre Peninsula the North Arm, directly adjacent to the Gillman study area. Tidal fluctuations at the North Arm bank (Figure 3-2) have a dominant period of 13 hours that facilitates infiltration of seawater into surficial, sandy aquifers (Trefry and Johnston 1998). In this study, all tidal data presented is corrected to m AHD. The highest recorded astronomical tide reached 1.3 m AHD in 1990 (Coffey Partners International Pty Ltd 1990). In addition to astronomical tides, storm surges may add up to 1.5m to the predicted tide. The tidal influence in the estuary is large in terms of sediment movement, because the estuary is sheltered from the wave action of the ocean. Thus tidal action is the major driver of erosion and deposition in the lower reaches of the estuary. Hydrological models for the Barker Inlet have been developed by several workers (Hancock 1988; Lord and Associates 1996; Pattiarachi and Burling 1995) and more recently by Cheshire *et al.* (2002).

3.3.2. Surface Waters

The Barker Inlet forms a shallow U shaped tidal estuary surrounding Garden and Torrens Islands and has a total catchment area of 328 km². The Port River estuary is the largest tributary of the Barker Inlet and has a catchment in excess of 54 km² (Lord and Associates 1996). Since European settlement, the hydrology of the system has been progressively modified by the construction of levees and tidal gates along North Arm to exclude tidal flow.

At Gillman, levees and sluices constructed to prevent marine flooding and allow low-tide discharge of ponded stormwater have artificially lowered the watertable by 1.0 m relative to the unconfined marine water table (Belperio and Harbison 1992). The Gillman study area drains from the south to the north and then out to the North Arm through the seawall via the Magazine Creek, which is the main drainage system in the study site. Tidal creeks, which are apparent on recent and early aerial photographs and DEM (Figure 3-6) of the site, supply this creek. Since the construction of the tidal levees, low areas fill with water after heavy rains. The Range wetland overflows into a drainage channel that feeds a large ponding area immediately to its north. This area is connected hydrologically by a small culvert to a ponding area on the west of the levee bank running through the centre of the Gillman area. Both basins are located on a large tidal creek that was once lined by mature mangroves (Figure 2-3). There are no tidal gates connecting these eastern basins to the estuary. The north western portion of the Gillman study site forms the Magazine Creek ponding basin (Figure 3-2) that fills during heavy rains, but releases water to the estuary through a tidal gate during low tide.

The Barker Inlet, Range and Magazine Creek wetlands were constructed by the Land Management Corporation (LMC), Salisbury and Port Adelaide Enfield City Councils along the southern and eastern boundaries of the Gillman area (Figure 3-2). All three wetlands discussed in Table 3-1 receive stormwater from a significant proportion of this catchment (62 km² - 48%) and provide valuable protection to the waters of the Port River estuary as well as providing valuable flora and fauna habitats. Reports investigating the treatment efficiency (Murphy 1999), and urban stormwater inflows to Barker Inlet Wetlands (Williams 1997) suggest that the wetland removes a significant load of pollution under a wide range of flow conditions.

Table 3-1 Constructed Wetlands at the Gillman study site (Figure 3-2).

Constructed Wetlands	Wetland area	Catchment	Constructed
Barker Inlet Wetland	172ha (water area 86ha)	4475ha	1995
Magazine Creek Wetland	36ha (water area 15.9ha)	1400ha	1996
Range Wetland	16.9ha (water area 7.1ha)	392ha	1996

The flow of tidal water at St Kilda has been influenced by the construction of a low bund wall in the late 1890s (since breached in a number of places), salt evaporation ponds and levee banks that line the St Kilda marina channel (Figure 3-2). These structures slow the flow of (or hold back) water as the tide retreats.

3.3.3. Groundwater

Surface aquifers in the Barker Inlet area are underlain by the Hindmarsh Clay, an aquitard that provides a uniform, weakly permeable barrier throughout the general area (Pavelic and Dillon 1993a). Interspersed within the Hindmarsh Clay lie six layers of sand/gravel containing the Quaternary aquifers (>5000 mg/L TDS) (Gerges 1987). The lower levels of clay form an impermeable barrier above Tertiary aquifers in the Carisbrook and Dry Creek Sands at depths of 80–150 metres (Figure 3-5). The Tertiary aquifers are used for industrial and agricultural purposes (1000-2500 mg/L TDS). Shallow regional aquifers containing saline/hypersaline groundwater underlie the Gillman study area. These aquifers are within St Kilda Formation sediments and Glanville Formation sediments, totalling about 10 metres thickness. The St Kilda formation aquifers are unconfined while those in the Glanville formation are semi-confined (PPK Consultants Pty Ltd *et al.* 1992b). The groundwater table level for the Gillman area, is governed by tidal influences as well as seasonal precipitation. The flow direction of shallow regional groundwater is north-westward (Martin and Gerges 1994). Annual recharge is estimated to be 40 to 50 mm per year with peak precipitation rates occurring during the wet winters (Martin and Gerges 1994). A groundwater mound of about 0.5 m currently exists beneath the Wingfield landfill, which has a marked effect on the direction of the flow of water within surface sediments (Woodward-Clyde 1999). The average groundwater surface slope is of the order of 0.05%, producing very low seepage rates (0.3 to 0.6 m/yr), but local gradients as high as 0.6% exist close to Magazine Creek (PPK Consultants Pty Ltd *et al.* 1992a). Due to the low hydraulic gradient of the surficial aquifer across the area, its ability to transport contaminants to

the estuary is considered relatively low (Dillon *et al.* 1989; Dillon and Gerges 1993; Gerges 1987). The potentiometric surface and flow direction of surface aquifers at Gillman is shown in Figure 3-8. Further details of the hydrogeological characterisation of the area are reported by Pavelic and Dillon (1993a) and Rayner *et al.* (1996).

NOTE:
This figure is included on page 40 of the print copy of
the thesis held in the University of Adelaide Library.

Figure 3-8 Potentiometric surface and flow direction of surface aquifers at Gillman (Belperio 1993b).

3.3.4. Contamination sources

The development of drains, salt evaporation pans, Bolivar Sewage Treatment Works and diversion of drainage pattern across the Adelaide plain has changed the sediment loads entering the estuary (Banham 1992). According to Lord (1996), the increased levels of nutrients in the Port River estuary were the most significant environmental pollutant in the Barker Inlet system. Sourced from sewage treatment works, industrial discharge and storm water runoff, nutrients support algal blooms (both toxic and non-toxic) and so may exacerbate low oxygen levels in the water column, leading to increased release of metals and further nutrients from the sediments. Floating macroalgal “bergs” may impact the health and regeneration of mangrove communities and also cause the release of decomposition gases (methane and hydrogen sulfide) (Coleman 1999). In the past,

North Arm was fed raw sewage from the Islington Sewage Treatment Works (STW) to the south (Maunsell 1984). Heated water discharged from the Torrens Island Power Station is an additional industrial pollutant. Several authors (Centre for Groundwater 1989; 1992a; b; Cheshire *et al.* 2002; French *et al.* 1998; Harbison 1986a; Hine *et al.* 1989; Lord and Associates 1996; Pavelic and Dillon 1993a) have related adjacent activities to the quality of the stormwater entering the site via the Magazine Creek and Range Wetlands and the Barker Inlet. Analysis of sediment and water from the drains and ponding basins has demonstrated the presence of heavy metals and metalloids (As, Cu, Pb and Zn), grease, oils and nutrients (Harbison 1986a). The drains also periodically carry accidental industrial waste spills. Dumping of liquid wastes in nearby mangroves, landfills and stormwater ponding areas has been reported by Gibbs and Dowd (1992).

Pavelic and Dillon (1993b) identified high concentrations of Al, As, Fe, Pb and Zn in a number of shallow groundwater piezometers that were close to or on the Gillman study site. According to Pavelic and Dillon (1993a), hypersaline groundwaters from the salt evaporation ponds only seem to affect the mangroves and areas adjacent to the outfall channels, which discharge surplus brines.

The main areas of solid contamination include the firing range, backstop and overshoot area of the Dean Rifle Range, Wingfield Landfill and areas of illegal dumping (Coffey Partners International Pty Ltd 1990; Maunsell 1984). Arsenopyrite, mined in the Mt Lofty Ranges, were the sulfur source for sulfuric acid production at the old Acid Plant at Snowden's Beach. This plant is a likely source of As contamination in the Port River (Coleman 2002). The Acid Plant burnt the arsenopyrite and a particulate deposition plume spread by the wind, across Torrens Island and Port Adelaide (Coleman 2002). Other atmospheric pollutant sources for the Adelaide region include automotive Pb (Tiller *et al.* 1987).

3.4. Soils

The presence of "sulfide-rich sediments" in the Gillman area were first identified by Harbison (1986c), and later in investigations (Belperio 1993b; Belperio and Harbison 1992; Belperio and Rice 1989). These authors also identified acid waters with pH values of < 3.5 that was likely caused by pyrite oxidation, which continue to oxidise pyrite and decalcify surrounding sediments to a depth in excess of 2 m. Decalcification is greatest in the oldest reclaimed areas at Gillman where gypsum is locally present at the sharp redox front between decalcified and unaltered marine sediments (Belperio and Harbison 1992; Sheard and Bowman 1996).

Fitzpatrick (1992) described the morphological, chemical and mineralogical properties of soils occurring in the supratidal salt-flat/samphire area between the intertidal mangrove systems on Garden Island, and classified them as Haplic Sulfaquents (Soil Survey Staff 1992) and Histic-sulfidic, Intertidal, Hydrosols (Isbell 1988). Fitzpatrick *et al.* (1993b) described similar soils occurring at St. Kilda and noted that they contain more than 20% organic carbon and have a histic epipedon (i.e. diagnostic surface O horizon) and hence classified them as Histosols (Soil Survey Staff 1992). At St Kilda a different kind of organic material (called "sapric" material) was identified (Fitzpatrick 1992; Fitzpatrick *et al.* 1992; Fitzpatrick *et al.* 1993b). Sapric material is more finely divided and reactive than the coarser, "fibric" materials observed in tropical areas where organic matter decomposition rates are faster. It is thought that soils consisting mostly of sapric material are unique to regions with temperate climates, where very slow deposition rates occur and organic detritus from seagrass, sea-lettuce (*Ulva* sp.) and mangroves is finely divided and easily decomposed (Fitzpatrick *et al.* 1992). It is also believed that intense reducing conditions (i.e. low redox potential or Eh values) measured in soils at St Kilda may be occurring in the low energy environment of the Gulf St Vincent because of increased nutrient loads (Coleman and Coleman 2001; Thomas *et al.* 2004b).

Work by (Fitzpatrick *et al.* 1992; 1993b) described the Histosols as containing sulfidic materials, because after incubation in the laboratory for 8 weeks they dropped in pH by

more than 0.5 pH units to a pH of < 4 (determined in 1:1 by weight in water, or in a minimum of water to permit measurement) (Soil Survey Staff 1992). The organic carbon consisted predominantly of sapric organic material (i.e. highly decomposed organic matter). Consequently, these soils classify as Terric Sulfisaprists (Soil Survey Staff 1992). The presence of sapric material in sulfidic materials was identified for the first time at these sites and new subgroup "Terric Sulfisaprists" was proposed (Fitzpatrick *et al.* 1993b). This proposal was accepted by USDA and included in the Keys to Soil Taxonomy (Soil Survey Staff 1994; 1999).

Acid sulfate soils containing sulfuric horizons/materials with pH <3.5 and bright yellow straw-coloured (2.5Y 8/6) mottles were identified and described by (Fitzpatrick 1992; Fitzpatrick *et al.* 1996a; Fitzpatrick and Mao 1997; Fitzpatrick and Self 1997). The presence of jarosite was confirmed using scanning electron microscopy, powder x-ray diffraction and DTA (Fitzpatrick *et al.* 1996a; Poch *et al.* 2009; Thomas *et al.* 2004b). Samples also contained more than 0.75% total sulfur with some samples containing over 5% reduced inorganic sulfur (Thomas *et al.* 2004b). Fitzpatrick *et al.* (1996a) recognised that the variable geomorphology of the drained landscape at Gillman gave rise to a variety of soil types that included: Terric Sulfosaprists, Hydraquentic Sulfaquepts, Salidic Sulfaquepts, Haplic Sulfaquents, Petrocalcic Xerochrepts and Petrocalcic Halaquepts (Soil Survey Staff 1996).

3.4.1. Fill materials

Aerial photographs taken in 1977 (refer to Appendix A) and an orthographic 1:20000 map of the Gillman study area (Department of Mines SA 1969) show "playas" of dredged fill in between the Grand Trunkway and Magazine Creek, and on a land adjacent to the Dean Rifle Range (Appendix A). It is likely that a proportion of the fill present at these sites consists of sediment formed by the discharge of limestone fines from the Penrice Soda Products Pty Ltd (then ICI) soda ash plant at Osborne (Coleman 1999). The stranded sandy shoreface facies (Belperio 1985b) was scalped (sand mined) for bulk fill materials used in the Dean Rifle Range Backstop, and the rifle range itself. The scalp marks are clearly visible from recent aerial photography (refer to Figure 6-1), and were present prior to aerial photographic images taken in 1935 (Appendix A).

3.5. Land Use

The Gillman area was originally a Defence Reserve, a vast swathe of land extending from the wharves in Port Adelaide around the Barker Inlet and up to Dry Creek. Between 1887 and 2003 the South Australian Rifle Association (SARA) established the south-eastern portion of the Gillman study site as the Dean Rifle Range (Figure 3-2). The North Arm Power Boat Club has a boat ramp on the North Arm, east of the Grand Trunkway. The amount of small boat traffic in the area is heavy. A high pressure gas pipeline that supplies the Torrens Island Power Station is located in the North Arm Bund wall and has an easement projecting 200 m to its south, into the study area. The Wingfield Landfill is operated by the City of Adelaide Council and is located in the south-east corner of the Gillman study area. The landfill ceased to accept solid household waste in 2004, and now only receives building waste such as bricks and concrete, green waste and tyres for recycling (Planning SA 1998). Garden Island was also used as a landfill until December 2000. Both landfill sites are currently being rehabilitated.

The major function of the Gillman study site is for stormwater ponding for urban stormwater runoff. Stormwater from Adelaide's northern and western suburbs drain into this region and large ponding basins are required for flood mitigation (Ruan Consulting 2006). Constructed wetlands now intercept a large portion of the stormwater, reducing the size of the ponding basins and reducing the frequency of flooding of the samphire areas. The Adelaide City Council and the Land Management Corporation commenced filling portions of the site in 2008 to provide much needed industrial land in order to meet the growth targets outlined in The Metropolitan Adelaide Industrial Land Strategy (Government of South Australia 2007).

During the study period, the only major human activity on the Gillman study site was off road vehicle use with trail bikes riding weekly.

3.6. Summary

Historical review of information provides a useful resource for assessing the likely occurrence of acid sulfate soil materials at Gillman and St Kilda, and where it is mapped to occur elsewhere around the coastline of South Australian (Geological Survey Branch 2000; Taylor 1974; Taylor *et al.* 1974). In coastal landscapes, the formation and hydrology of acid sulfate soils is closely relate to geomorphology, mean sea level and drainage features. The state in which the acid sulfate soil materials are likely to occur can therefore be inferred from the historic drainage history and elevation data of specific areas (e.g. using aerial photography and maps), verified from soil reports (Fitzpatrick 1992; Fitzpatrick *et al.* 1996a; Thomas *et al.* 2004a) and near surface groundwater and geotechnical investigations (Belperio and Rice 1989; Coffey Partners International Pty Ltd 1990; Delfin 1991; Pavelic and Dillon 1993a). The literature also provides information on the sources and types of contaminants and their likely position in the acid sulfate soil landscape.

Chapter Four

4. Field and laboratory methods: conceptual models and mapping

An objective of this study was to conduct field surveys and laboratory analysis of soils in several key study sites in Barker Inlet, to provide the following:

- A spatially valid data set of acid sulfate soil properties that are required to underpin the construction of descriptive and explanatory soil regolith process models.
- Maps showing the spatial heterogeneity of the soil properties and the distribution of acid sulfate soil materials by classification of the soil types.

Knowledge of the spatial heterogeneity of the range of acid sulfate soils is also required for preparation of alternative management options. For example, it may be possible to treat acid “hotspots” separately if they are identified, potentially saving resources.

This chapter describes the field and laboratory methods used to characterise the wide range of acid sulfate soil types within the St Kilda and Gillman study sites to help produce acid sulfate soil maps. To provide information to address the two objectives listed above, the survey design focused on providing a spatially distributed site data set to collect soil samples for analysis.

4.1. Field investigations

Soil layer and mineral samples were analysed from geographically well-distributed and locally representative soil profiles located on toposequences across map units that were definable on aerial photography (Figure 5-1 and Figure 6-1). The different soil units were mapped and deemed to represent the major physiographical features of the

soil landscape. Field investigation days were planned to be conducted to capture tidal, seasonal and event based variations. Hence, soil sampling dates were sporadically spaced between January 2002 and June 2009 with numerous intermittent field visits for water sampling, redox monitoring and field observations occurring between these dates (Table 4-1). Many of the intermittent site visits that were made over the past seven years helped refine map unit boundaries by point sampling using a spear auger, and by assessing the walls of open drainage channels (over 4.5 km in length) that cross the Gillman site. At the St Kilda study site sampling was carried out during low tide as all sites were submerged at high tide. Most sampling was carried out during dry conditions at the Gillman site due to poor vehicle access immediately following rain events. In total 290 soil samples were characterised from 41 profiles at the Gillman study site and 44 soil samples were characterised from eight profiles at the St Kilda study site.

Table 4-1 Main sampling dates and location of soil profiles (refer to Figure 5-1 and Figure 6-1).

Sampling Date	Focus Areas	Profile ID	No. of Samples
St Kilda study site			
January 2002	A, B	BSK 1 to BSK 5	32
May 2004	C	BSK 6 to BSK 7	12
Gillman study site			
January 2002	A, B, D	BG 1 to BG 15	91
January & February 2003	A, B, C	BG 16 to BG 28 & re-sampled BG 4 & BG 11	128
August 2003	A	Re-sampled BG 14	8
January 2004	A	Re-sampled BG 11	16
December 2005	D	GGT 1 to GGT 5	48
June 2009	A, C	BG 29 to BG 41	

The procedures for soil sample collection, preparation, analytical methods and storage are summarised in Figure 4-1. Corresponding methods associated with redox monitoring, hydrology, geochemistry and mineralogy are described in subsequent Chapters.

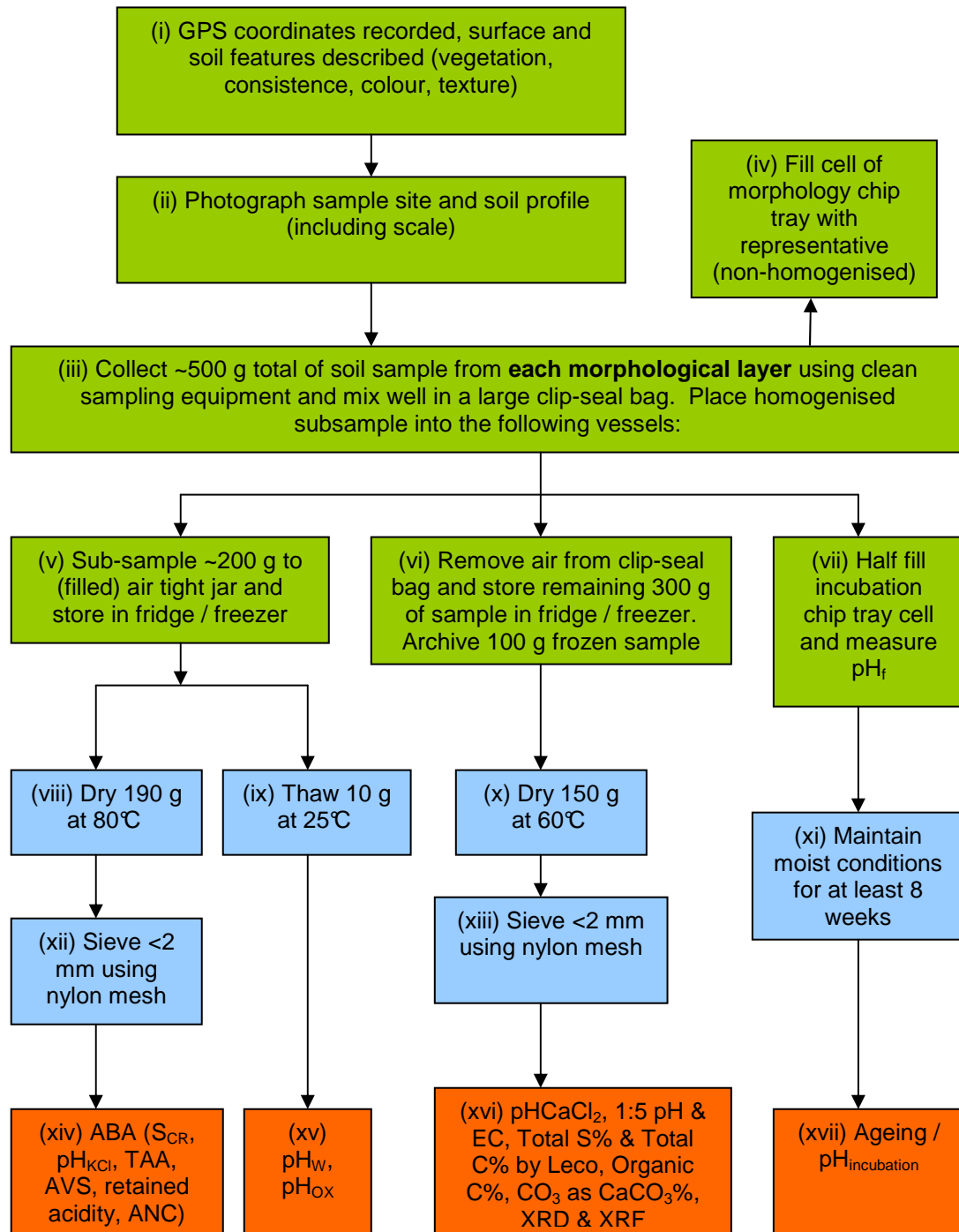


Figure 4-1 Generalised flow diagram of field procedures used for soil sample collection and storage (green boxes), sample preparation (blue boxes), and analytical methods (orange boxes) applied. Abbreviations used: GPS – Global Positioning System, ABA – acid base accounting using the Chromium reducible Sulfur (S_{CR}) suite (Ahern *et al.* 2004), EC – electrical conductivity, pH_f – field measured soil pH (paste), pH_W – soil pH measured in 1:1 solution in water, pH_{OX} – soil pH after treatment with hydrogen peroxide, $pH_{incubation}$ – soil pH after ageing under moist conditions in a chip tray for at least 8 weeks, Total S% and Total C% by LecoTM, Organic C%, CO_3 as $CaCO_3\%$, XRD and XRF.

4.2. Soil descriptions

Morphological descriptions were made on all soil materials sampled following the conventions of the USDA Field book for describing and sampling soils (Schoeneberger *et al.* 2002) and the Australian Soil and Land Survey Field Handbook (McDonald *et al.* 1990). Soil morphological descriptions are extremely important tools for assessing soil conditions (Bingham and Ciolkosz 1993; Richardson and Daniels 1993; Schwertmann 1993). Soil properties such as colour, consistency, structure, porosity, texture, organic matter type and content, redoximorphic features and carbonate content are very useful when interpreting acid sulfate soil conditions (Brouwer and Fitzpatrick 2002; Fitzpatrick *et al.* 1996b; Fritsch and Fitzpatrick 1994; Vepraskas and Caldwell 2008).

Pedogenic soil layers (horizons) were denoted using standard horizon designations of the United States Natural Resources Conservation Service (US NSRC), (e.g. A, B or C), indicating their position in the soil profile and suffix notations to denote special features (Schoeneberger *et al.* 2002). Soil colour was determined on moist samples using Munsell Soil colour notation (Munsell 1994). Acid base accounting and soil analytical results were also used to classify acid sulfate soil materials according to the classification scheme proposed by Sullivan *et al.* (2010) and summarised in Table 4-2.

A complete set of soil morphological data for all the samples describing the sample depth, field texture and soil consistence are provided in Appendix B. In addition, analytical results (EC, pH_f , pH_w , pH_{OX} , $\text{pH}_{\text{Incubation}}$, Total S%, Organic C%, $\text{CaCO}_3\%$ and Acid Base Accounting using the S_{CR} suite) for all samples analysed are also presented in Appendix B and Appendix C. However, to assist the reader, key results and discussion that focus on a selected group of soil profiles that best represent soil process conditions within each of the twelve “map units”, which are located within each of the four focus areas are described in Chapters 5 and 6 (e.g. see Table 6-1 and Figure 6-1).

Table 4-2 Acid sulfate soil materials have been classified using the following definitions. These definitions were explained in detail in Chapter 2.

Descriptive terminology	Definition
Sulfuric materials	soil materials with a $\text{pH}_w < 4$ as a result of sulfide oxidation
*Sulfidic materials	soil materials containing detectable sulfide minerals ($\geq 0.01\%$ reduced inorganic S)
Hypersulfidic materials	sulfidic material that has a field pH of 4 or more and experiences a drop in pH by ≥ 0.5 units to 4 or less after ≥ 8 weeks of incubation
Hyposulfidic materials	sulfidic material that has a field pH ≥ 4 and does not experience a drop in pH by ≥ 0.5 units to 4 or less after ≥ 8 weeks of incubation
Monosulfidic materials	soil materials with an acid volatile sulfur content of 0.01% or more

**This term differs from previously published definitions in various soil classifications (Isbell 2002).*

4.3. Soil sampling and analysis

Soil samples were collected using clean, stainless steel equipment to decrease the risk of cross-contamination. At each sampling site, global positioning system (GPS) coordinates were recorded and digital photographs taken of the site characteristics, soil profiles and the finer soil features (e.g. salt efflorescences and soil mottle patterns). Site features were described and sketched and soil morphological descriptions were recorded on a layer-by-layer basis. Soil samples were routinely collected from zero to five centimetres and then from each observed morphological layer down the profile. Soil morphology was described in the field to include, for example colour, consistency, structure and texture according to McDonald *et al.* (1998). Soil colour, texture, structure and consistency are valuable field indicators for soil identification and assessment, indicating soil type and potential impacts from acid sulfate soil processes, and likely products of oxidation based on acid generating and acid neutralising characteristics. Sampling depth ranged from about 3 m to less than 30 cm and was usually limited by the water table. Soil Munsell colour notation was used to determine the matrix and mottle colours with particular focus on redoximorphic features (Soil Survey Staff 2010). Multiple samples from each soil layer were taken for the various analytical requirements (refer to Figure 4-1). Soil bulk density and moisture content was determined on volumetric samples, collected from main soil layers of 'type' profiles, according to methods described by Rayment and Higginson (1992). A range of secondary minerals, such as jarosite, sideronatrite

and schwertmannite may form in acid sulfate soil landscapes, which act as stores of acidity, i.e. they may produce acidity upon dissolution (rewetting). Samples of bright yellowish and reddish-brown coloured salt efflorescences, coatings and mottles were described in the field and carefully collected for mineralogical analyses using X-ray diffraction (XRD), light microscopy and scanning electron microscope (SEM).

4.4. Acid sulfate soil analyses

An important consideration for acid sulfate soil hazard assessment is the mineralogical make-up of the soils, which may either enhance or neutralise acid generating potential. These also need to be combined with field observations and placed into the geological and hydrogeological setting, so that laboratory-scale data can be extrapolated and interpreted at the larger landscape scale. To determine the presence and extent of acid sulfate soil types and associated hazards, including existing acidity, acid generation potential and potential for metal mobilisation and de-oxygenation, comprehensive analysis using a set of established and tested field and laboratory methods is required. The most effective methodology for assessing acid sulfate soil hazards may vary according to the local environment and associated mineralogy. This study incorporated the most generally accepted methodologies for acid sulfate soil testing: (i) pH testing in water (pH_W) and after treatment with hydrogen peroxide (pH_{OX}) (approximately 1:1 soil solution slurry; hydrogen peroxide pH adjusted to 5), and soil incubation experiments ($\text{pH}_{\text{Incubation}}$) (ii) acid-base accounting (ABA). These methods are analytical techniques developed to assess coastal acid sulfate soils (Ahern *et al.* 1998; Ahern *et al.* 2000; Ahern *et al.* 2004; Sullivan *et al.* 2000; Sullivan *et al.* 2009).

4.4.1. Soil sample preparation

Fifty grams of wet sample was archived in a freezer. Ten grams of wet sample was used for pH_W and pH_{OX} measurements. Approximately 150 g of sample was dried at 80° C, sieved (<2 mm) and large shell fragments removed. This sample was then milled in a Cr-free ring mill (nominal 90% passing through a 160 μm sieve) and used for acid sulfate soil analyses / characterisation (Ahern *et al.* 2004). Representative

subsamples were analysed for total carbon using LecoTM (Merry and Spouncer 1988), XRF and XRD. Chip tray samples were incubated moist at room temperature for at least 8 weeks (nominally 19 weeks) before checking soil pH_{Incubation}. Morphology chip trays were allowed to air dry at room temperature and archived.

4.4.2. Methodologies used to assess acid sulfate soil properties

Peroxide oxidation analysis

This method is a useful screening tool for acid sulfate soil assessments (Ahern *et al.* 2004). Hydrogen peroxide (H₂O₂) is a strong oxidising agent and is used to rapidly oxidise sulfide minerals (principally pyrite: FeS₂) producing acid and hence providing an estimate of the maximum potential production of acidity from this source. Since peroxide is a very strong oxidising agent, it can be argued that the resultant pH measured is a worst-case scenario as under field conditions, oxidation, and thus acidification, is rarely complete. Under field conditions, the presence of carbonate minerals such as calcite (CaCO₃) may neutralise acid produced. However, in some cases the carbonate may not fully dissolve due to slow dissolution rates or the formation of protective mineral coatings (e.g. gypsum or iron oxides) and the peroxide pH measurement may reflect this. The dissolution rates of individual minerals may be controlled by a number of factors, hence additional tests to measure the carbonate content are recommended.

Soil incubation (ageing)

The soil incubation (pH_{Incubation} or pH on ageing) method is the standard method used in Australian Soil Classification (Isbell 2002) and Soil Taxonomy (Soil Survey Staff 2010), which is often considered to represent a more realistic field scenario for this acid sulfate soil test is based on allowing the soil to “speak for itself” (Dent 1986). The method has been described in more detail by (Sullivan *et al.* 2009) and (Fitzpatrick *et al.* 2010c) where the method has been used and refined. However, all are based on keeping the sample moist for a specified period (at least 8 weeks). Incubation allows oxidation of sulfide minerals to occur slowly. Although this may mimic nature more closely and does not force reactions to occur (as with the peroxide pH test) it can be argued that the complex processes occurring in the field are not

adequately reproduced, e.g. factors such as exchange with sub-surface waters (containing ANC) or biogeochemical reactions. These factors should also be taken into consideration wherever possible, but require a thorough understanding of water movement (e.g. groundwater), and are often site and scenario specific.

Sulfur chemistry

In soils or sediments, the “total sulfur” test is an inexpensive, convenient method to screen acid sulfate soil samples for acid generation potential (Ahern *et al.* 2004). However, this technique also measures non-acid generating sulfur; therefore, the total sulfur determination may greatly over-estimate the potential acidity hazard, so that when a trigger value is exceeded, more detailed analysis techniques are usually adopted. Interpretation is complicated by the presence of sulfate salts (containing oxidised S) such as gypsum, which do not produce acidity. Directly measuring the amount of reduced inorganic sulfur in a sample has therefore become the accepted standard for estimating acid generation potential for acid sulfate soils.

Acid-base accounting

Acid-base accounting (ABA) is used to assess both the potential of a soil material to produce acidity from sulfide oxidation and also its ability to neutralise any acid formed. The standard ABA applicable to acid sulfate soil as described in (Ahern *et al.* 2004) is shown below.

$$\text{Net Acidity} = \text{Potential Sulfidic Acidity} + \text{Existing Acidity} - \frac{\text{Acid Neutralising Capacity}}{\text{Fineness Factor}}$$

The components in this ABA are discussed below.

Potential Sulfidic Acidity

The Potential Sulfidic Acidity (PSA) is most easily and accurately determined by assessing reduced inorganic sulfur (S_{CR}). This method was developed specifically for analysing acid sulfate soil materials to, among other things, assess their Potential Sulfidic Acidity (PSA) also known as the ‘acid generation potential’ (AGP). The approach is described in (Ahern *et al.* 2004). They describe the chromium reducible

sulfur method and its conversion to PSA and AGP. Chromium reducible sulfur is a component of the acid generating potential of a soil or sediment, and is one component of the net acidity, along with existing acidity and acid neutralising capacity (ANC). The difference between reduced inorganic sulfur and total sulfur is generally the quantity of sulfate plus organic sulfur in the sample.

Chromium reducible sulfur analysis

In this study, selected soil and sediment samples collected from type profiles within the focus areas or from spot sampling locations were tested for reduced inorganic sulfur content. Samples were dried at 80°C and ground in a Cr-free ring mill or by hand in a mortar and pestle. The powder samples were weighed into a reaction flask and hot, acidic CrCl₂ was added, following “Method Code 22B” described by Ahern *et al.* (2004) and Sullivan *et al.* (2000). Reduced inorganic sulfur within the sample is converted to H₂S by the hot acidic CrCl₂ solution. The evolved H₂S is transported via slow nitrogen gas to a beaker filled with zinc acetate. As the H₂S bubbles through the zinc acetate solution it precipitates as ZnS. The ZnS precipitate is then re-dissolved by adding HCl to the zinc acetate to enable sulfide concentration (assuming negligible elemental S) to be determined using an iodimetric titration, using a starch indicator.

Acid Volatile Sulfide (AVS) was determined using the same laboratory equipment and a similar procedural method, but where the use of CrCl₂ is omitted (refer to Method Code 22A of Ahern *et al.* (2004)). Qualitative pyrite sulfur concentration (as %S_{CR}) was also determined on selected samples using an XRF based method, developed by Fritz *et al.* (2004). Although this method is not as accurate and has a higher limit of detection than the wet chemistry method described above, it can provide a comparatively cheap and rapid alternative for the measurement of S_{CR}.

Existing Acidity

This is the sum of the Actual Acidity and the Retained Acidity (Ahern *et al.* 2004). Total Actual Acidity (TAA) is a measure of the actual acidity in acid sulfate soil materials that have already oxidised. TAA measures the sum of both soluble and exchangeable acidity. Retained acidity is the acidity ‘stored’ in minerals such as

jarosite, schwertmannite and other hydroxysulfate minerals. Although these minerals may be stable under acidic conditions, they can release acidity to the environment when these conditions change. The methods for determining both TAA and Retained Acidity are given by Ahern *et al.* (2004). Total Actual Acidity was measured on soil samples for which measured pH_{KCl} were below 6.5. In this study, TAA was estimated by the method (23F) described by Ahern *et al.* (2004). Retained Acidity was measured on soil samples for which pH_{KCl} was below 4.5, or where secondary sulfate minerals, such as jarosite, sideronatrite and schwertmannite, were identified in the sample by either field identification in hand specimen, using light microscopy, scanning electron microscopy or by X-ray diffraction. In this study, retained acidity was estimated by method (20J) described by Ahern *et al.* (2004).

Acid Neutralising Capacity (ANC)

If pH_{KCl} values of a soil are > 6.5 the soil potentially has acid neutralising capacity (ANC), usually in the form of carbonate minerals, principally of calcium, magnesium and sodium. By accepted definition (Ahern *et al.* 2004), any acid sulfate soil material with a $\text{pH}_{\text{KCl}} < 6.5$ has a zero ANC. An estimate of ANC can be made from: the inorganic carbon, (e.g. by LecoTM furnace on acid pre-treated samples), by back-titration of unreacted acid following soil digestion with added acid, or by determination of alkali cations concentrations if non-calcite forms of neutralising (e.g. dolomite / magnesite) are suspected. The methods for determining ANC are given by Ahern *et al.* (2004). In this study, ANC was estimated by the back-titration method (19A2) described by Ahern *et al.* (2004). The neutralising capacity of the soil is expressed as $\% \text{CaCO}_3$ equivalents. In the ABA equation, any measured ANC is moderated by the use of a fineness factor (using a minimum of 1.5) to take into account the fineness of the acid neutralising material, reactivity, incomplete mixing, coatings, etc.

4.5. Spatial and temporal variability

An understanding of the detailed behaviour of various Acid Sulfate Soil materials (e.g. hypersulfidic, hyposulfidic or sulfuric) and features (e.g. salt efflorescences) in layers, horizons and deep regolith is fundamental to successful characterisation and mapping of coastal acid sulfate soils in the Barker Inlet region. This section provides a brief summary of how conceptual soil-regolith models are constructed and used to describe, explain and predict the spatial heterogeneity of acid sulfate soil properties. These models help to describe and predict soil-regolith processes that occur as a consequence of fundamental shifts in the “environmental equilibrium” brought about by the impact of past (i.e. construction of bund walls) and current (e.g. excavation of drains with sulfuric material in a fluctuating water environment between summer and winter) management practices. These systems are not stable and therefore may undergo rapid change depending on whether water levels are dropping or rising. Acid sulfate soil materials change, depending on the water status of the soil (saturated or unsaturated), which controls whether chemical processes are oxidising or reducing and its acidity status.

4.5.1. Soil-regolith models

To aid in understanding the spatial heterogeneity of acid sulfate soil properties, especially when bund walls or drains are constructed, soil landscape cross-sections in the form of conceptual soil-regolith toposequence models are constructed from field and laboratory data and surveyor knowledge. Conceptual soil-regolith process models enable workers to develop and present a mechanistic understanding of complex spatial and temporal soil-regolith environments (Fritsch and Fitzpatrick 1994). The regolith is the unconsolidated earth material present above bedrock or sediment and includes the upper soil layers. These models are cross-sectional representations of soil-regolith-bedrock profiles that illustrate vertical and lateral changes that occur across wetland hydro-toposequences. They also tell a story explaining the complex soil, hydrological and biogeochemical interactions that have led to the development of an acid sulfate soil problem (Fitzpatrick *et al.* 2010b; Fitzpatrick and Merry 2002; Fitzpatrick and Shand 2008).

To support management of acid sulfate soils in the Barker Inlet area an understanding of the variation both spatially and with time is required. The understanding is presented here in the following three categories:

- Descriptive soil-regolith models.
- Explanatory soil-regolith models.
- Predictive soil-regolith models.

The descriptive soil-regolith models (see Chapters 5 and 6) are used as the precursor or framework for: (i) developing explanatory soil-regolith models shown in Chapter 7 through to Chapter 11, (ii) construct soil maps and (iii) practical solutions for ameliorating soils; Chapter 12.

Descriptive Conceptual Soil-regolith Models

Descriptive soil-regolith models characterise the lateral and vertical spatial variability of current soil-regolith layers, horizons, materials (e.g. transition of hypersulfidic and sulfuric) and features (salt efflorescences) occurring in the unsaturated sands on the water margins, and subaqueous hypersulfidic material occurring below water (tidal and streams). In summary, descriptive soil-regolith models are able to group similar soil features into fewer soil layers, which are linked down the toposequence and mapped in cross-section. Soil layers are linked to hydrological processes (water flow paths and other morphological, chemical and mineralogical indicators) and hydrology measurements.

Explanatory Conceptual Soil-regolith Models

Descriptive soil-regolith toposequence models are used to help construct explanatory soil-regolith process models to explain contemporary redox (Chapter 8), geochemical (Chapter 9) and mineralogical (Chapter 10 and Chapter 11) processes in key representative toposequences. These models essentially explain the formation and degradation of acid sulfate soils in a single diagram that illustrates the micromorphological, pedological, geological, hydrological, biogeochemical and mineralogical processes occurring in key transects in Barker Inlet.

Predictive Conceptual Soil-regolith Models

Predictive soil-regolith models (four dimensional) are constructed to illustrate specific tidal or wetland transects and scenarios using a collage of figures, which illustrate several stages of soil-regolith condition in response to natural or human induced (e.g. management) changes over time. These conceptual models can be used to predict processes and potential consequences but not the timing of events, which will depend on weather, changes in water level and land management. Construction of predictive conceptual soil-regolith models are based on detailed knowledge from repeated site visits over time. These models can illustrate complex and varied distribution of acid sulfate soil Subtypes in contrasting systems due to the temporal variation caused by: bund wall construction, drains, and tidal fluctuating water levels.

As our knowledge and understanding improves, predictive soil-regolith models can be prepared to illustrate potential changes in the future. The acid sulfate soil maps (Chapter 7) together with the conceptual soil-regolith toposequence models can be used to predict acid sulfate soil changes and generate “interpretive maps” and data sets to support management planning. To extract value from these maps, data sets and conceptual models, professional people with knowledge who understand maps and acid sulfate soil process should be consulted. Depending on the situation it is likely that additional information would need to be collected for incorporation into the models.

While the maps and data produced from this study are static for the time when the field work for the study was conducted (Table 4-1), there is a very good opportunity to extract and provide information from acid sulfate soil maps, which can be used to support decision making.

4.6. Soil map units

The surface features identified from aerial photography (e.g. vegetation, bare salt scalded areas, scoured areas and pooled water) were grouped according to their position in the landscape (e.g. within or adjacent to drainage lines). These map units were also linked to surficial geology mapped by Belperio and Rice (1989) and others, and to vegetation types mapped by Fotheringham (1994). These surface features were used as surrogates or contributors to the development of soil map units. The map units were verified by conducting field investigations in focus areas using toposequence transects and by spot sampling across the study sites.

Four focus areas, encompassing toposequence transects, were assessed in detail at the Gillman study site (Table 4-3).

Three focus areas, encompassing toposequence transects, were assessed in detail at the St Kilda study site (Table 4-4).

In total, ten soil profiles were assessed at the St Kilda study site and 40 soil profiles were assessed at the Gillman study site to relate soil morphology and acid sulfate soil characteristics to each of the map units.

The following two chapters describe the landscape features and soil morphology in each of the focus areas, describe and characterise each of the soil profiles located along the toposequence transects.

The St Kilda study site is described in Chapter 5. The Gillman study site is described in Chapter 6. Acid sulfate soil characteristics are also described in these chapters. In Chapter 7 acid sulfate soil hazards are developed for the map units.

Table 4-3 Summary of the major map units (landscape, vegetation, salt efflorescence and surface soil) at the Gillman study site.

Map unit no. (description)	Surface Cover <i>Landscape, salt efflorescence soil surface and *vegetation</i>	Soil Surface Description <i>Soil morphology (0-5 cm)</i>	Landform	Surficial geomorphology	Water state, ponding and drainage	Focus areas
Disturbed / reclaimed tidal areas						
1. Water	Obvious depression of at least 0.5 m below surrounding land surface and permanently inundated. Channels >1 m wide and often contain suspended filamentous algae. Monosulfidic material commonly present at the sediment-water interface. The channels are lined by bare salt scalded areas or by dense mat plants (<i>Disphyma crassifolium</i>) and low heath (<i>Halosarcia pergranulata</i>). Some excavated depressions and drains are included in this category.	Soft yellowish brown (10YR 5/6) sludge (subaqueous gel) at the surface (0-1 cm) comprising of mostly reddish brown stained organic matter (fibric to sapric). Black (2.5Y 2.5/1) monosulfidic material (ooze) with much organic matter below 1 cm.	Erosional channel – stranded tidal creek channel	Intertidal mud and sand flats	Wet, poorly drained – permanently inundated >5 cm, (subaqueous soils)	Gillman: B & C
2. Benthic mat and bare salt scalded mud flats	Obvious depression of at least 0.3 m below surrounding land surface. Bare, salt scalded channels >1 m wide with seasonal (summer) salt efflorescence (predominately halite and gypsum) often with a thin benthic organic mat (algal mat) at the surface. Channels are periodically inundated during winter, enabling monosulfidic material to accumulate. The channels are lined by dead mangrove tree (<i>Avicennia marina</i>) stumps, salt scalded areas or by dense mat plants (e.g. <i>Disphyma crassifolium</i>) and low heath (<i>Halosarcia pergranulata</i>). Some excavated depressions and drains are included in this category.	Soft pale yellowish brown (10YR 5/6) algal mat at the surface (0-2 cm) with areas of strong brown (7.5 YR 5/6) stained (sapric) organic matter. Below 2 cm, black (2.5Y 2.5/1) monosulfidic material (gel) with much (sapric) organic matter.	Erosional channel stranded tidal creek channel	Intertidal mud and sand flats	Wet (winter), poorly drained – seasonally inundated > 2 cm (and following storm event)	Gillman: B & C
3. Bare salt scalded mud flats	Slight depression of less than 0.2 m below surrounding land surface. Predominantly bare, permanent salt scalds with limited covering by purple flowering round-leaf pig face (<i>Disphyma crassifolium</i>). Salt efflorescence (halite and gypsum) commonly form during summer months. These scalds are lined by dense mat plants (<i>Disphyma crassifolium</i>), low heath (<i>Halosarcia pergranulata</i>) and other samphire shrubs (e.g. <i>Tecticornia spp.</i>). Numerous dead mangrove (<i>Avicennia marina</i>) stumps protrude from the surface.	Firm, dark reddish brown (5YR 3/4) sandy clay with reddish brown stains – mottles. Below 2 cm is dark greyish brown (10 YR 3/2) sandy clay with abundant dark grey (7.5YR 5/1) and black (2.5Y 2.5/) mottles (monosulfidic rich material).	Open depression - transition from stranded tidal creek to open, flat plain	Intertidal mangrove woodland	Wet (winter), poorly drained – rarely inundated	Gillman: B & C
4. Dense low heath - samphire shrublands	Flat landscape with subtle undulations covered by dense, low heath / samphire shrublands dominated by <i>Sclerostegia arbuscula</i> , <i>Halosarcia pergranulata</i> and rarely <i>Halosarcia flabelliformis</i> (Bead Glasswort) occurring in the wetter areas. Salt marsh grasses such as <i>Puccinellia stricta</i> and weeds (e.g. <i>Suaeda australis</i> and scattered <i>Sarcocornia quinqueflora</i>) also occur.	Firm, dark greyish brown (10 YR 4/2) silt loam to sandy clay loam with coarse subangular blocky structure, abundant fine roots and minor strong brown (7.5 YR 5/6) mottles along ped surfaces and root channels.	Open flat plain – lower former intertidal floodplain	Supratidal marsh	Moist (winter), moderately well drained	Gillman: B, C & D
5. Open low scrub and grasses	Flat landscape covered by a dense ground layer of herbs (e.g. yellow-flowering bower spinach - <i>Tetragonia implexicoma</i>) and grasses such as wallaby grass (<i>Danthonia spp.</i>), curly ryegrass (<i>Parapholis incurve</i>) and salt marsh grasses (e.g. <i>Puccinellia stricta</i>). Low heath and samphire shrubs are common (e.g. <i>Halosarcia pergranulata</i> and <i>Wilsonia humilis</i>). Taller shrubs (weeds) up to 2 m tall African Boxthorn (<i>Lycium ferroissimum</i>) sporadically form a very sparse upper stratum.	Firm, dark greyish brown (10 YR 4/2) silt loam to sandy clay loam with coarse subangular blocky structure, abundant fine roots and minor strong brown (7.5 YR 5/6) mottles along ped surfaces and root channels.	Open flat plain – upper former intertidal floodplain	Stranded sandy shore	Moist (winter), moderately well drained	Gillman: B & C
6. Open grass plain and scrub	Flat landscape covered by a dense ground layer of halophytes and non-halophyte plant species. E.g. sedges, herbs (<i>Tetragonia implexicoma</i>) and grasses such as wallaby grass (<i>Danthonia spp.</i>), curly ryegrass (<i>Parapholis incurve</i>) and salt marsh grasses (e.g. <i>Puccinellia stricta</i>). Samphire shrubs (<i>Halosarcia pergranulata</i>) are less common. Taller shrubs (weeds) up to 2 m tall African Boxthorn (<i>Lycium ferroissimum</i>) sporadically form a very sparse upper stratum.	Firm, dark greyish brown (10 YR 3/2) silt loam with coarse subangular blocky structure with abundant fine roots and without mottles.	Open flat plain – former supratidal zone	Stranded sandy shore face	Moist (winter), well drained	Gillman: A & B
7. Bare, scalped, salt scalded sand flats	Obvious depression of up to 0.5 m below surrounding land surface. Predominantly bare, with permanent salt scalds limiting vegetative cover. Salt efflorescence (halite and gypsum) commonly form during summer months. The depressions are generally lined by low heath and samphire shrubs and grasses	Loose, light grey (10 YR 7/2) medium sand with some coarse shell fragments and strong brown (7.5 YR 5/6) mottles along shell surfaces.	Open depression – scalped / mined former supratidal zone	Stranded sandy shore	Moist (winter), moderately well drained	Gillman: B & C
8. Artificially filled areas and embankments	Obvious embankment or raised (filled) areas of between 0.3 m and 4 m above the surrounding land surface. Bund walls are usually constructed by obtaining sediment from the landward side of the embankment, creating borrow pits adjacent to the wall. Filled areas are often reclaimed by hydraulic placement of dredged sediments, creating playas. Embankments are predominantly covered by grasses such as wallaby grass (<i>Danthonia spp.</i>), curly ryegrass (<i>Parapholis incurve</i>) and salt marsh grasses (e.g. <i>Puccinellia stricta</i>). Coastal salt bush (<i>Atriplex cinerea</i>) and taller shrubs (weeds) up to 2 m tall African Boxthorn (<i>Lycium ferroissimum</i>) occur sporadically along the mid section of embankments and on filled platforms	Fill material is generally firm layers of pale yellow (2.5Y 8/4) silt to fine sand, often containing fragments of crushed calcareous rubble. Soft light greenish grey (5GY 7/1) clay fill material, with minor strong brown (7.5YR 5/8) mottles occurs in wetter, low lying areas or at depth. Fragments of red clay bricks and other building rubble is commonly observed. Bunds are lined with a rock armour on the seaward side.	Embankments and raised (filled) former intertidal to supratidal zone	Filled using borrowed soil from adjacent to the embankment, using dredge spoil or waste fill material	Dry to moist (winter), moderately to poorly drained	Gillman: B & C St Kilda: C

*Sourced from: (Fotheringham 1994; Fotheringham and Coleman 2008).

**This species is listed as vulnerable under the *Environment Protection and Biodiversity Conservation Act 1999*(EPBC Act 1999).

Table 4-4 Summary of landscape features (landscape, vegetation, salt efflorescence and surface soil) used to develop map units for the St Kilda study and Gillman site.

Map unit no. (description)	Surface Cover <i>Landscape, salt efflorescence soil surface and *vegetation</i>	Soil Surface Description <i>Soil morphology (0-5 cm)</i>	Landform	Surficial geomorphology	Water state, ponding and drainage	Focus areas
Undisturbed intertidal to supratidal areas						
9. (Water)	Pools in tidal creek channels that form obvious depression of at least 0.3 m below surrounding land surface and are permanently inundated. (i.e. this unit does not include the subtidal zone). Channels / depressions are >1 m wide and often contain algal mat and rafts of sea lettuce (<i>Ulva sp</i>) and dead seagrass. Monosulfidic material is sometimes present at the sediment-water interface. The channels are lined by low dense samphire and heath (e.g. <i>Sclerostegia arbuscula</i> and <i>Halosarcia pergranulata</i>). Some excavated depressions and drains are included in this category.	Subaqueous, soft black (5Y2.5/1) peat (predominantly hemic material) with many very coarse roots and medium roots. H ₂ S smell.	Erosional channel - tidal creek channel	Intertidal mud and sand flat and mangrove woodland	Wet, poorly drained	St Kilda: A & C. Gillman: D
10. (Mangrove woodlands)	Flat landscape covered by dense mangrove woodland (<i>Avicennia marina</i>).	Soft, very dark brown (10YR 2/2) clayey peat (predominantly hemic material) with abundant, very coarse roots and medium roots. H ₂ S smell.	Open flat – intertidal zone	Intertidal mangrove woodland	Wet, moderately to poorly drained	St Kilda: A, B & C. Gillman: D
11. (Low growing salt marsh plants)	Flat landscape dominated by low heaths and samphire shrubs (e.g. <i>Sclerostegia arbuscula</i> , <i>Halosarcia pergranulata</i> and rarely ** <i>Halosarcia flabelliformis</i> (Bead Glasswort)). Mangrove communities replace salt marsh where tidal flooding is almost daily.	Soft, very dark greyish brown (10YR3/2) clayey peat (predominantly fibric material) with many coarse and medium roots.	Open flat – intertidal floodplain	Supratidal marsh	Wet, moderately to poorly drained	St Kilda: A. Gillman: D
12. (Bare chenier ridge - shell-based)	Subtle, open mound, predominantly bare, permanent with limited covering by low heath (<i>Halosarcia pergranulata</i>) and other samphire shrubs. Salt efflorescence (halite and gypsum) form on the surface during summer months on the less frequently flooded areas.	Loose, dark grey (5Y 4/1) peaty clay loam with few medium roots, abundant broken shells and predominantly sapric matter.	Open mound – intertidal to supratidal floodplain	Stranded sandy shore face	Wet, very well drained	St Kilda: B.

*Sourced from: (Fotheringham 1994; Fotheringham and Coleman 2008)

**This species is listed as vulnerable under the *Environment Protection and Biodiversity Conservation Act 1999 (EPBC Act 1999)*.

Chapter Five

5. Soil Morphology, properties and classification for the intertidal St Kilda floodplain

5.1. Introduction

The prime objective of this chapter is to describe and characterise soil-regolith processes within the intertidal floodplain at St Kilda by summarising key soil morphological and classification information across representative toposequences.

To keep the chapter length manageable, only one soil profile from each of the map units (defined in Table 4-3 and Table 4-4) is described in detail in the text. The other ‘type’ soil profiles located along toposequences are summarised, and full morphological descriptions are provided in Appendix B.

St Kilda is located on the north-eastern side of the Barker Inlet (see Figure 3-1), and is about 10 kms north of the Gillman study site. The St Kilda study site has essentially remained under tidal influence although in some adjacent localised tidal areas low bund walls were constructed in the past to reclaim tidal areas. These localised reclaimed areas are landward of the St Kilda study site. The study site consists of unconsolidated Holocene coastal marine sediments of the St Kilda formation, predominantly featuring light grey, shelly and often silty or clayey materials or sediments.

The St Kilda study site was subdivided into **three focus areas** that best represent the hydrological and pedological characteristics of the area, and that were also clearly discernable using aerial photography. **Focus area A** was located close to open water in Barker Inlet and is strongly influenced by tidal waters. Focus area A contained map units 9 (Water) and 10 (Mangrove woodland) (Table 5-1). **Focus area B** was located on a slightly elevated, north-south striking shell grit (chenier) ridgeline that was intermittently traversed by meandering tidal creeks. Focus area B contained map units 10 (Mangrove woodlands) and 12 (Bare chenier ridge) (Table 5-1). **Focus area C** was

located landward of the other two areas and included map units 11 (Supratidal samphire vegetation) and 10 (mangrove woodland), and a permanently flooded tidal creek depression (map unit 9) (Table 5-1).

In all, four of the 12 map units identified in the study were found at the St Kilda study site.

Table 5-1 Soil profiles located within focus areas that are representative of the map units. Soil profile numbers marked in **red** text are type sections described in detail in the following section.

Soil profile numbers	Focus area	Map unit no.	Landform	Water State, ponding and drainage
Undisturbed intertidal to supratidal areas (St Kilda study sites)				
BSK 5, 8	A, C	9 (Water)	Erosional channel - tidal creek channel	Wet, poorly drained
BSK 4, 1, 2, 7, 600, 2610	A, B, C	10 (Mangrove woodlands)	Open flat –intertidal floodplain	Wet, moderately to poorly drained
BSK 6	C	11 (Low growing salt marsh plants)	Open flat – intertidal to supratidal zone	Wet, moderately well drained
BSK 3	B	12 (Bare chenier ridge; shell-based)	Open mound –intertidal to supratidal floodplain	Wet, very well drained

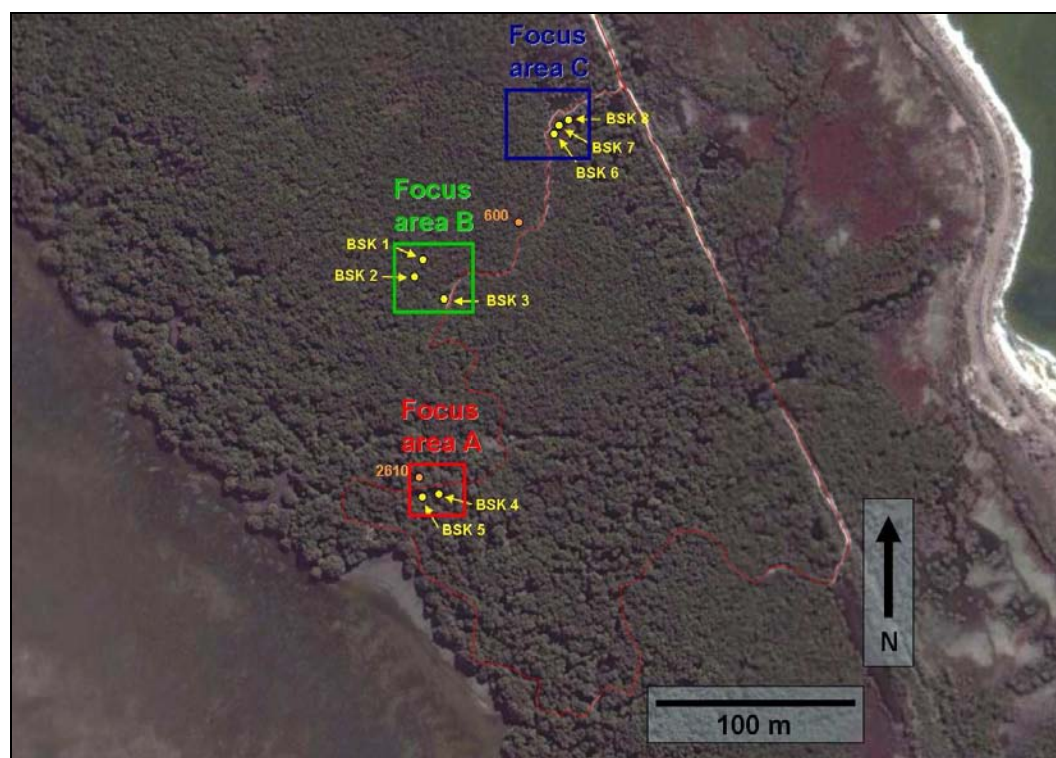


Figure 5-1 St Kilda study site. Focus area – A is located close to the seaward extent of the mangrove woodland and transects a well defined tidal creek. Focus area B – is located on a topographical high and transects from mangrove woodland to a bare patch on the shell based chenier ridge. Focus area – C is located near the upper extent of the intertidal zone and transects samphire marsh, mangrove woodland and permanently inundated tidal creek soils. Soil profile numbers refer to Table 5-1.

5.2. Descriptive soil-regolith toposequence process model with strong tidal influence

5.2.1. St Kilda Focus area A with strong tidal influence

Focus area A is situated within mature mangrove woodland, about 50 m from the low tide mark at the seaward fringe of the mangrove forest. This area is close to the exposed seagrass beds of Barker Inlet and has a strong tidal influence (Figure 5-2).

Focus Area A encompasses a toposequence that traverse from relatively high (elevation of about 0.6 m AHD) intertidal floodplain covered by thick mangrove pneumatophore root masses, to lower lying (elevation of about 0.3 m AHD) permanently inundated, eroded tidal creek (Figure 5-3). Two soil profiles (BSK 4 and BSK 5) are located on the toposequence and are representative of map units 10 (Mangrove woodland) and 9 (Water) respectively (Table 5-2).

Table 5-2 Soil profiles selected to be representative of map units occurring within focus area A, located on toposequence transect A-A' in Figure 5-2.

Soil profile numbers	Elevation	Map unit no.	Landform	Water State, ponding and drainage
Intertidal zone				
BSK 5	0.3 m AHD	9 (Water)	Erosional channel - tidal creek channel	Wet
BSK 4	0.6 m AHD	10 (Mangrove woodlands)	Open flat –intertidal floodplain	Wet, moderately to poorly drained

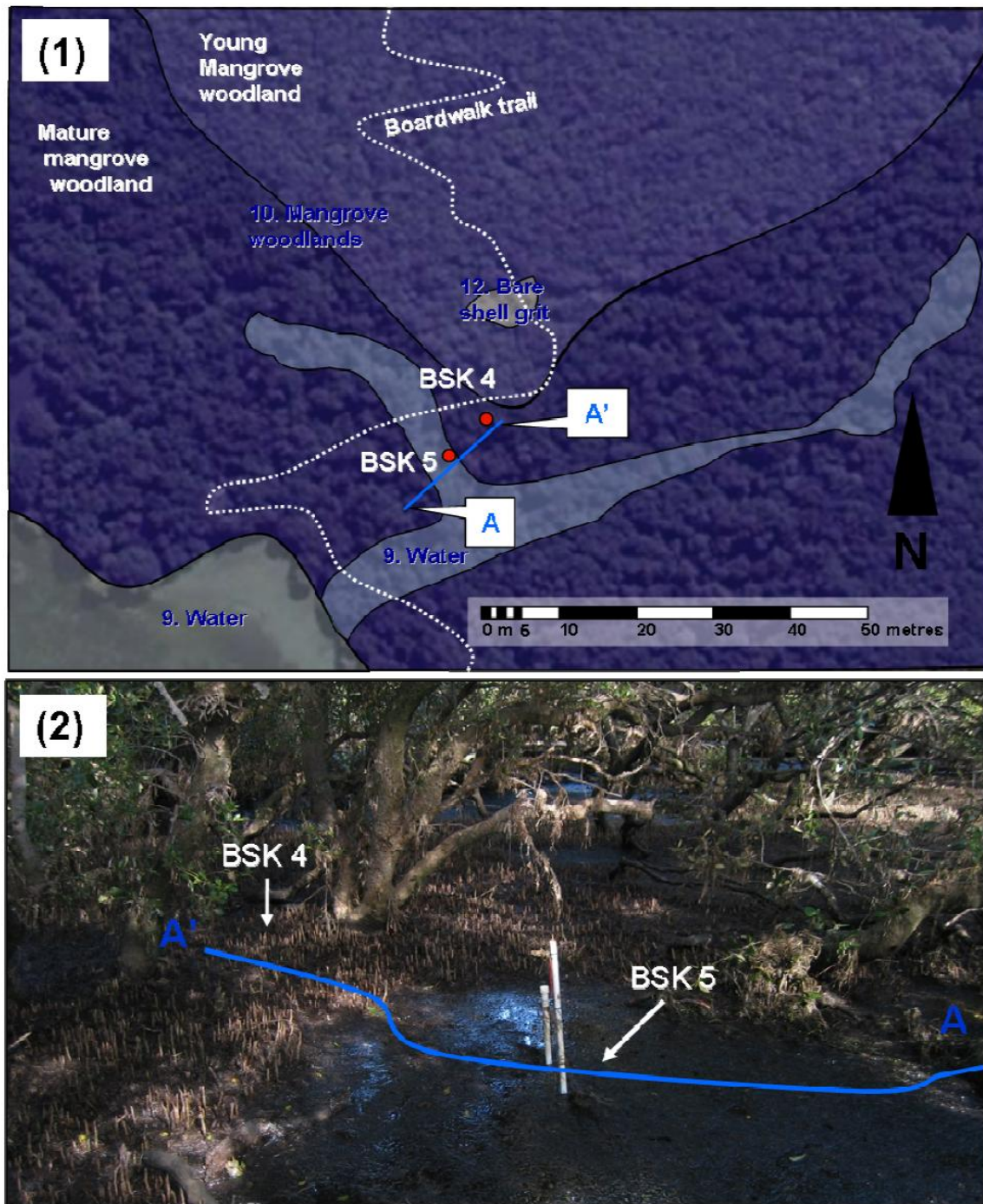


Figure 5-2 Map (1) showing map units in Focus area A and location of toposequence transect A-A' with soil profiles BSK 4 and BSK 5. The St Kilda boardwalk is indicated by the white dotted line. Landscape photo (2) showing the relative positions of soil profiles along the toposequence transect and contrasts between map units.

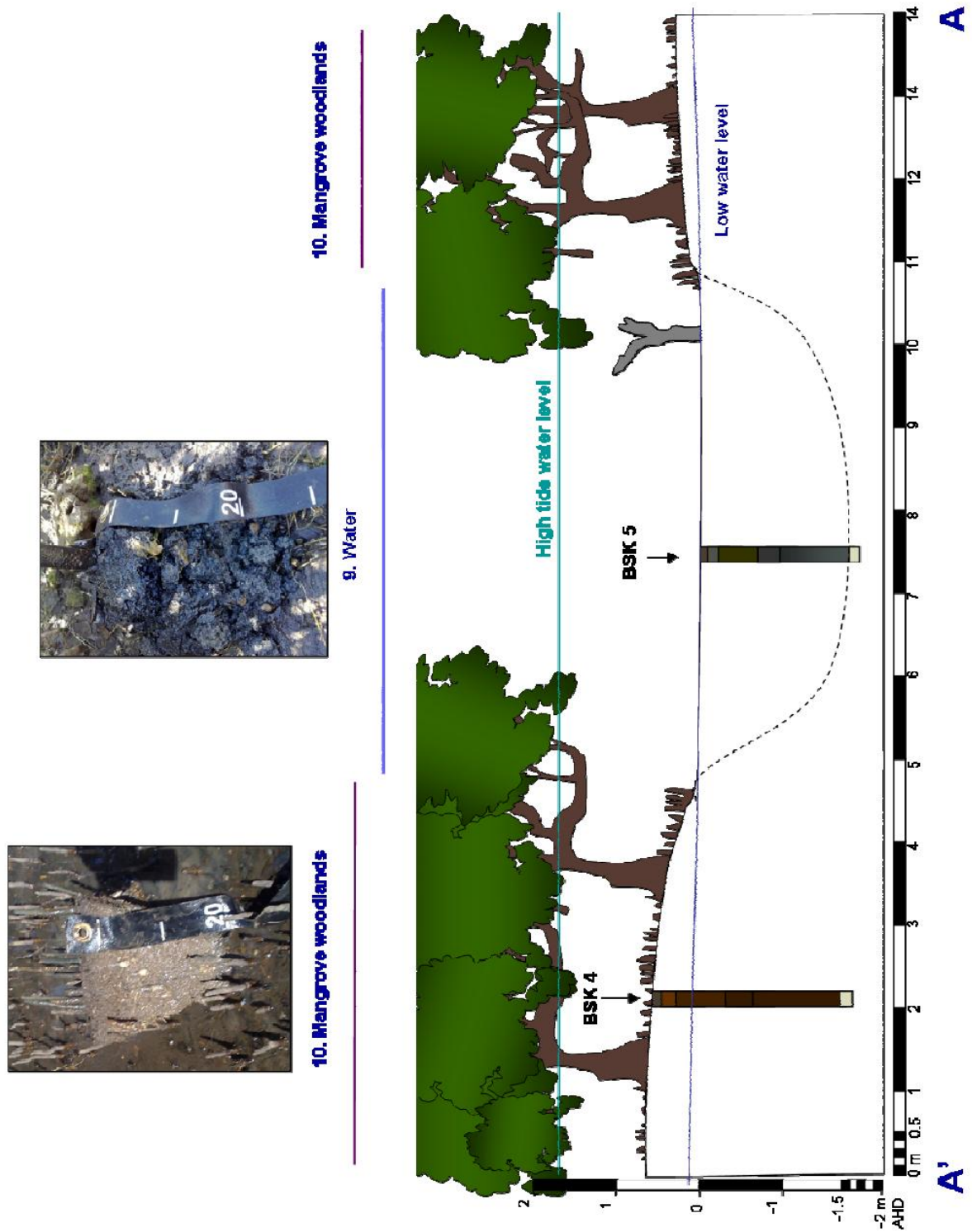


Figure 5-3 Descriptive soil-regolith toposquence model (cross section A-A' as shown Figure 5-3) indicating map units and position of representative soil profiles with colour photograph and average water table depths during low and high tide. The dotted line indicates the shape of the filled tidal creek depression at profile BSK 5. Refer to Table 5-3 and Table 5-4 for soil profile descriptions.



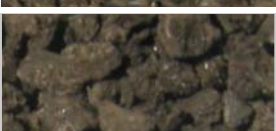
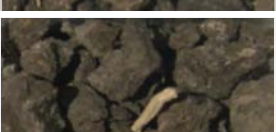


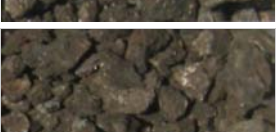

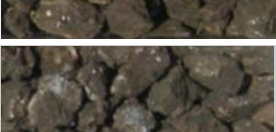

Map unit 10 - *Wet: moderately to poorly drained, open flat intertidal flood plain covered by mangrove woodland (mature trees). Profile BSK 4* – (Figure 5-3).

Soil profile BSK 4 occurs within map unit 10 (Mangrove woodland). A detailed summary of the key soil morphological features together with a corresponding close-up photograph of soil fragments are provide in Table 5-3. Profile BSK 4 developed in a lower, intertidal regime, with tidal flooding generally occurring twice a day. Soil material consists of a thick (2 m) peat deposited under mangrove vegetation overlying shell grit (buried chenier ridge). A detailed explanatory soil-regolith toposequence model of St Kilda is outlined in Chapter 9, which shows variable redox status and hydrology (tidal) together with vegetation, geology and soil types.

The surface horizon (Oe/W1) occurred from 0 to 5 cm depth and was moist due to tidal inundation. The upper ten soil layers (0 to 110 cm) comprised several Oe/W horizons consisting of very dark brown to black peat with slightly varying degrees of organic matter types, in various states of decomposition. The upper six Oe horizons generally contained live roots with little mineral content (5%) and no redoximorphic features (Table 5-3). The three underlying Oe/W7 to Oe/W10 horizons (110 to 190 cm) contained highly decomposed (sapric) organic matter and had slightly more mineral (clay) content (10% to 20%) than the Oek/W11 horizon. The lower Oek/W11 horizon (190 to 210 cm) was a grey clayey peat containing 60% sapric material and abundant broken shell fragments. The entire profile was devoid of redoximorphic features although a slight hydrogen sulfide smell was evident from the lowest two soil horizons (Table 5-3). The soil morphology for profile BSK 4 is summarised in Table 5-3.

Soil EC was very high for the entire profile, with the top 190 cm recording an EC of > 66.4 dS/m. EC ranged from a maximum of 93.3 dS/m in the Oe/W7 horizon to a minimum of 25.2 dS/m at the base of the profile in the Oek/W11 horizon (Figure 5-4). The very high EC is likely due to evapoconcentration of seawater during low tide (when soil samples were collected) and from sample drying.

Table 5-3 Summary of soil morphology for profile BSK 4: *Wet: saturated (permanent), very poorly drained wetland*. Soil colour was determined on moist samples and consistence on dry samples. Photos show dried samples.

Horizon (ID)	Depth	Soil morphology	Sample (5 x 2.5 cm)
Oe/W1 (BSK 4-68)	0-5 cm	Very dark brown (10YR2/2) peat (5% mineral, 95% fibric and hemic material); abundant coarse live roots; diffuse boundary	
Oe/W2 (BSK 4-69)	5-10 cm	Very dark brown (10YR2/2) peat (5% mineral, 95% hemic material); abundant coarse live roots; diffuse boundary	
Oe/W3 (BSK 4-70)	10-20 cm	Very dark brown (10YR2/2) peat (5% mineral, 95% sapric and hemic material); abundant coarse live roots; diffuse boundary	
Oe/W4 (BSK 4-71)	20-50 cm	Black (5Y2.5/1) peat (5% mineral, 95% sapric and hemic material); some coarse live roots; diffuse boundary	
Oe/W5 (BSK 4-72)	50-90 cm	Black (5Y2.5/1) peat (5% mineral, 95% sapric and hemic material); no roots; diffuse boundary	
Oe/W6 (BSK 4-73)	90-110 cm	Very dark brown (10YR2/2) clayey peat (10% mineral, 90% sapric and hemic material); no roots; diffuse boundary	
Oe/W7 (BSK 4-74)	110-130 cm	Very dark brown (10YR2/2) clayey peat (10% mineral, 90% sapric material); no roots; diffuse boundary	
Oe/W8 (BSK 4-75)	130-150 cm	Very dark brown (10YR2/2) clayey peat (10% mineral, 90% sapric material); no roots; diffuse boundary	
Oe/W9 (BSK 4-76)	150-170 cm	Very dark brown (10YR2/2) peaty clay (15% mineral, 85% sapric material); no roots; diffuse boundary	
Oe/W10 (BSK 4-77)	170-190 cm	Very dark grey (10YR3/1) peaty clay (20% mineral, 80% sapric material); no roots; slight H ₂ S smell; clear wavy boundary	
Oek/W11 (BSK 4-78)	190-210 cm	Grey (10YR5/1) peaty clay (40% mineral, 60% sapric material); no roots; slight H ₂ S smell; some medium to coarse broken shell fragments.	

Soil pH (1:5) was near neutral at the top and bottom of the profile and was slightly acidic in the middle two horizons, due to oxidation on oven drying of the samples. Soil pH (1:5) ranged from 8.4 to 5.8, with a median of pH of 7.2. $\text{pH}_{\text{CaCl}_2}$ values were very similar to pH (1:5) measurements which is expected due to the high ionic strength of the salty soils. Total organic carbon content generally decreased with depth, ranging from 23.1% in the surface Oe/W1 horizon to 4.2% at the base of the profile, in the Oek/W11 horizon. Total sulfur contents increased slightly with depth (ranging from 1.23% S in the near surface Oe/W1 horizon to 2.2% in the lower Oe/W10 horizon at 70 to 190 cm depth). The Oek/W11 horizon at the base of the soil profile recorded the lowest total S content of 0.75%. Carbonate content ranged between 1.2% and 7.6% CaCO_3 within the upper 190 cm of the profile, and was very high at the base of the profile (46.7% CaCO_3), below 190 cm depth.

Soil profile BSK 4 classifies as: Sulfic Haplowassists, and a Sapric, Histic-Sulfidic, Intertidal Hydrosol (Isbell 2002).

[Acid sulfate soil characteristics:](#)

Soil pH testing (pH_W , pH_{OX} and $\text{pH}_{\text{Incubation}}$)

Soil pH measurements were determined on all samples in a 1:1 soil-water mixture (pH_W), after treatment with peroxide (pH_{OX}) and after 19 weeks of ageing ($\text{pH}_{\text{Incubation}}$) the soil in a moist environment. pH_W indicates whether the soils is acidic and is used to assess whether a soil contains sulfuric material (i.e. $\text{pH}_W < 4$). Peroxide oxidation tests (pH_{OX}) were performed on all samples to determine the likely presence of sulfidic materials.

Soil-water pH (pH_W) data range from near neutral to slightly acidic, with a median of 6.45 (Figure 5-4). Soil pH_{OX} values were appreciably lower for most soil layers suggesting that they have moderate S_{CR} contents. Only soil layer Oe/W10 (170 to 190 cm) recorded a $\text{pH}_{\text{OX}} < 2$ (dropping from a pH_W of 6.32 to pH_{OX} of 1.95) suggesting that it contains significant S_{CR} (Figure 5-4). Following incubation soil $\text{pH}_{\text{Incubation}}$ dropped by more than 0.5 pH unit to below 4 in 3 samples from layers Oe/W7, Oe/W8 and Oe/W10 (between 90 and 190 cm). Net acidity results supported both the pH_{OX} results and $\text{pH}_{\text{Incubation}}$ results.

Titrateable actual acidity (TAA)

pH_{KCl} testing was performed on six representative soil samples with all results measuring > pH 6.5, indicating they did not contain Existing Acidity as TAA or retained acidity. pH_{KCl} results ranged between 6.6 and 9.3.

Acid Volatile Sulfur (AVS)

Four samples from below 50 cm depth were analysed for AVS because of their dark grey to black matrix colour and saturated moisture state. AVS contents ranged from 0.01% to 0.02%.

Chromium Reducible Sulfur (S_{CR})

Reduced inorganic sulfur was determined for six representative samples which ranged from 0.09% S_{CR} at the near surface (0 to 5 cm), to 0.91% S_{CR} in the lower Oe/W10 horizon (170 to 190 cm), with a median of 0.40% S_{CR}, indicating that all soil layer samples tested contained Potential Sulfidic Acidity (Figure 5-4).

Acid Neutralising Capacity (ANC)

ANC was determined on six samples and ranged from 1.2% to 12.2% CaCO₃, with a median of 5.8% CaCO₃.

Net Acidity

Net Acidity values were negative for 4 of the 6 soil layers tested. The upper three layer samples tested had negative net acidity values ranging from -947.0 mole H⁺/tonne at the near surface layer (0 to 5 cm) to -258.5 mole H⁺/tonne in the Oe/W6 horizon (90 to 110 cm). Net acidity was positive for the two layer samples tested between 110 and 170 cm depth (measuring 236.0 and 314.5 mole H⁺/tonne respectively). Net acidity was very negative for the lower Oek/W11 horizon, measuring -1583.1 mole H⁺/tonne (Figure 5-4).

Acid sulfate soil classification: In accordance with the acid sulfate soil terminology adopted (refer to Table 4-2), soil profile BSK 4 classifies as an acid sulfate soil, containing; hypersulfidic and hyposulfidic materials with minor monosulfidic material. Soil profile BSK 4 does not contain sulfuric material.

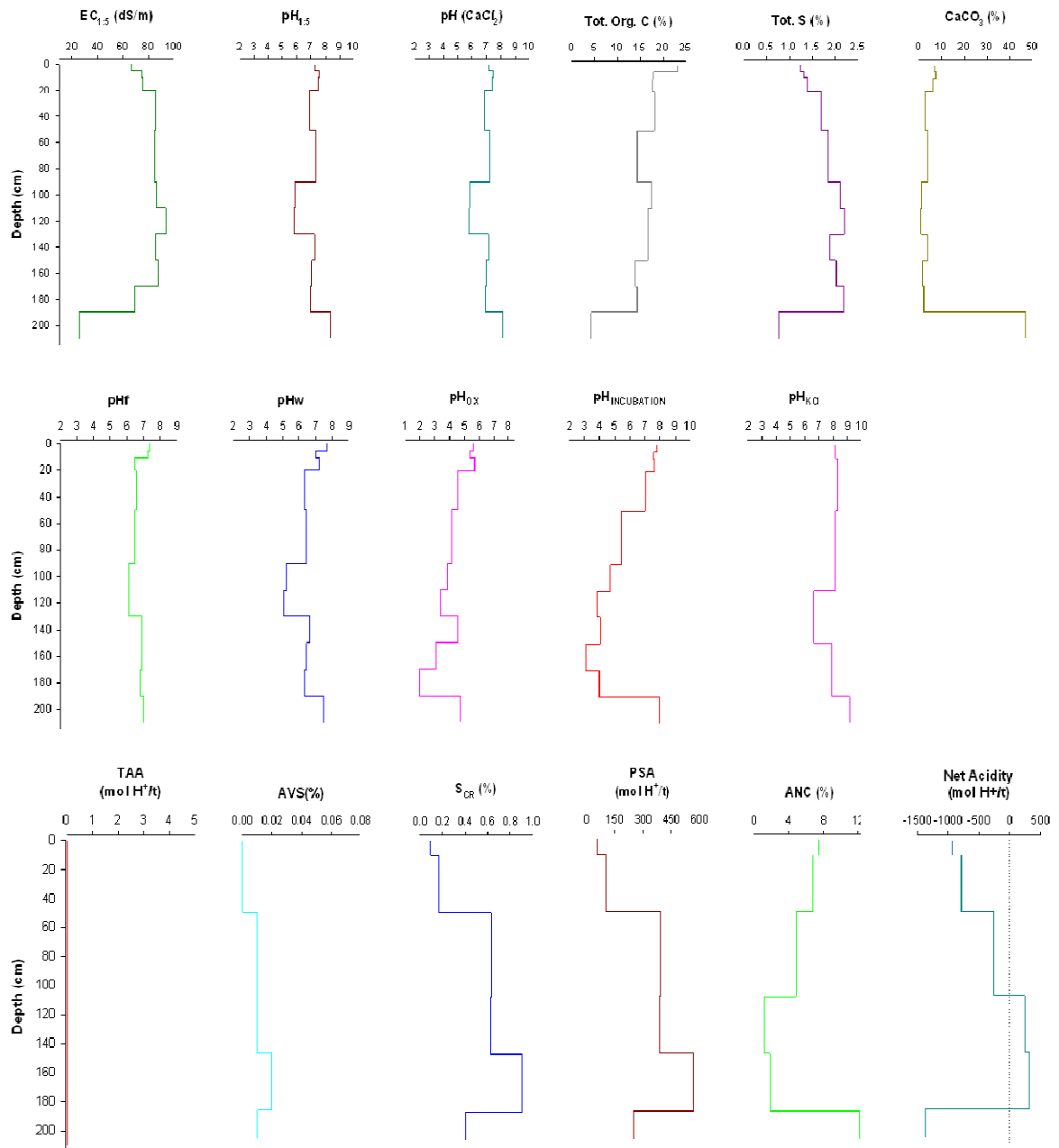


Figure 5-4 Down profile soil chemistry and acid sulfate soil characteristics of profile BSK 4. All soils analytical data are tabulated in Appendix C.

Map unit 9 – Wet: poorly drained, erosional tidal creek depression covered by water.**Profile BSK 5 – (Figure 5-2)**








Soil profile BSK 5 occurs within map unit 9 (Water). A detailed summary of the soil morphological features together with a corresponding close-up photograph of soil fragments are provided in Table 5-1. Profile BSK 5 has developed in a tidal creek depression that is filled with thick organic matter derived from mangrove trees, seagrass (*Pasidonia* sp.) and rafts of sea lettuce (*Ulva* spp.). The soil material consists of a thick (1.5 m) peat / organic wrack deposited under mangrove vegetation and overlying shell grit (a buried chenier ridge). A detailed explanatory soil toposequence model of St Kilda displaying in schematic soil-landscape cross section format displaying vegetation, geology, hydrology, redox states and soil types is shown in Chapter 9.

Seven soil layers were distinguished and sampled from the 150 cm thick profile. The surface horizon (Oe/W1) was wet and occurred from 0 to 10 cm depth. It consisted of very dark brown, slightly decomposed seagrass, mangrove foliage and sea lettuce. A white filamentous mat or slick, likely to be the filamentous sulfur-oxidising bacterium (*Baggiatoa* spp.) (Coleman 2002, personal communication), was evident on the surface of water and wet soil. The upper six soil layers (0 to 190 cm) qualified as Oe/W horizons consisting of very dark brown peat with varying amounts of organic matter types and mineral content. The organic matter became more decomposed with depth. The W/Oe horizons generally contained no roots, very little mineral content (<5%) and no redoximorphic features (Table 5-4). The lower Oe/W6 horizon (150 to 190 cm) contained highly decomposed (sapric) organic matter and had slightly more mineral (clay) content (10%) than the upper Oe/W horizons. Broken shell fragments were abundant at the base of the profile, in the Oek/W7 horizon (190 to 210 cm). The entire profile was devoid of redoximorphic features although a slight hydrogen sulfide smell was evident from the lowest two soil horizons (Table 5-4). The soil morphology for profile BSK 5 is summarised in Table 5-4.

Soil EC was very high for the entire profile and ranged from 98.5 dS/m to 53.5 dS/m, with a median of 80.7 dS/m (Figure 5-5). The high ECs were likely an artefact of drying during the sample preparation (i.e. evapoconcentration of saline pore waters (seawater) during sample preparation for lab measurement of EC 1:5 soil:water) for samples that

had very high moisture contents and low bulk densities. The Oe/W1 horizon had a field moisture content of 92% and bulk density of 0.1 t/DW/m³ and had to be partially dried to achieve a 1:5 soil:water ratio for measuring EC (Appendix C). Soil pH (1:5) was near neutral for the entire profile and ranged from 7.1 to 8.0, with a median of 7.6.

Table 5-4 Summary of soil morphology for profile BSK 5: *Wet: saturated (permanent), very poorly drained, inner wetland*. Soil colour was determined on moist samples and consistence on dry samples. Photos are of dry samples.

Horizon (ID)	Depth	Soil morphology	Sample (5 x 2.5 cm)
Oe/W1 (BSK 5-79)	0-10 cm	Very dark brown (10YR2/2) peat (2% mineral, 98% fibric, hemic and sapric material); no roots; very diffuse boundary. Thin (<1 mm) white striated slick / mat on water and moist soil surface)	
Oe2/W2 (BSK 5-80)	10-30 cm	Black (5Y2.5/1) peat (<5% mineral, >95% hemic and sapric material); no roots; very diffuse boundary	
Oe/W3 (BSK 5-81)	30-60 cm	Black (5Y2.5/1) peat (5<% mineral, >95% fibric, hemic and sapric material); no roots; diffuse boundary	
Oe/W4 (BSK 5-82)	60-110 cm	Very dark brown (10YR2/2) peat (5% mineral, 95% fibric, hemic and sapric material); no roots; diffuse boundary	
Oe/W5 (BSK 5-83)	110-150 cm	Very dark brown (10YR2/2) peat (5% mineral, 95% sapric and hemic material); no roots; some coarse shell fragments; diffuse boundary	
Oe/W6 (BSK 5-84)	150-190 cm	Very dark brown (10YR2/2) organic rich clay loam (40% mineral, 60% sapric material); no roots; some coarse shell fragments; diffuse boundary	
Oek/W7 (BSK 5-85)	190-210 cm	Grey (10YR5/1) organic rich clay (50% mineral, 50% sapric material); no roots; slight H ₂ S smell; some medium to coarse broken shell fragments.	

pH_{CaCl2} values were slightly lower (within 0.2 of a pH unit) than pH (1:5) measurements. Total organic carbon content decreased slightly with depth and ranged from 17.7% in the surface Oe/W1 horizon to 14.4% at the base of the profile, in the Oek/W7 horizon. Total sulfur content was also relatively consistent throughout the profile, ranging from 1.6% to 1.9%, with a median of 1.9%. Carbonate content generally increased with depth and ranged from 2.2% to 21.9% CaCO₃ (Figure 5-5).

Soil profile BSK 5 classifies as: Sapric Haplowassists (Soil Survey Staff 2010); Sapric, Histic, Intertidal Hydrosol (Isbell 2002).

Acid sulfate soil characteristics:

Soil pH testing (pH_W , pH_{OX} and $pH_{Incubation}$)

Soil-water pH (pH_W) data showed that all soil layers were circumneutral (Figure 5-5). The pH_{OX} results were about 2 pH units lower than pH_W , suggesting that they are likely to contain minor S_{CR} contents (Figure 5-5). $pH_{Incubation}$ remained above 6 for all samples. The relatively high pH_W , pH_{OX} and $pH_{Incubation}$ results were supported by the acid base accounting data, with all samples recording negative net acidities.

Titrateable actual acidity (TAA)

pH_{KCl} testing was performed on four representative soil samples with all results measuring >6.5 , indicating they did not contain Existing Acidity as TAA or retained acidity. pH_{KCl} results ranged from 8.1 to 8.5.

Acid Volatile Sulfur (AVS)

Three samples from below 30 cm depth were analysed for AVS because of their very dark brown to black matrix colour and saturated moisture state. AVS contents ranged from 0.01% to 0.02%.

Chromium Reducible Sulfur (S_{CR})

S_{CR} was determined for four samples and ranged from 0.17% at the near surface (0 to 10 cm), to 0.83% at the base of the soil profile (190 to 210 cm), with a median of 0.43%. All samples contained Potential Sulfidic Acidity (Figure 5-5).

Acid Neutralising Capacity (ANC)

ANC was determined on four samples and ranged between 3.1% and 8.5% $CaCO_3$, with a median of 6.6% $CaCO_3$.

Net Acidity

Net acidity values were negative for all samples tested, ranging from -236 mole H^+ /tonne to -769 mole H^+ /tonne (Figure 5-5).

Acid sulfate soil classification: According to the acid sulfate soil terminology adopted (refer to Table 4-2), soil profile BSK 5 classifies as an acid sulfate soil, containing; hyposulfidic materials with minor monosulfidic materials. Soil profile BSK 5 does not contain sulfuric soil materials.

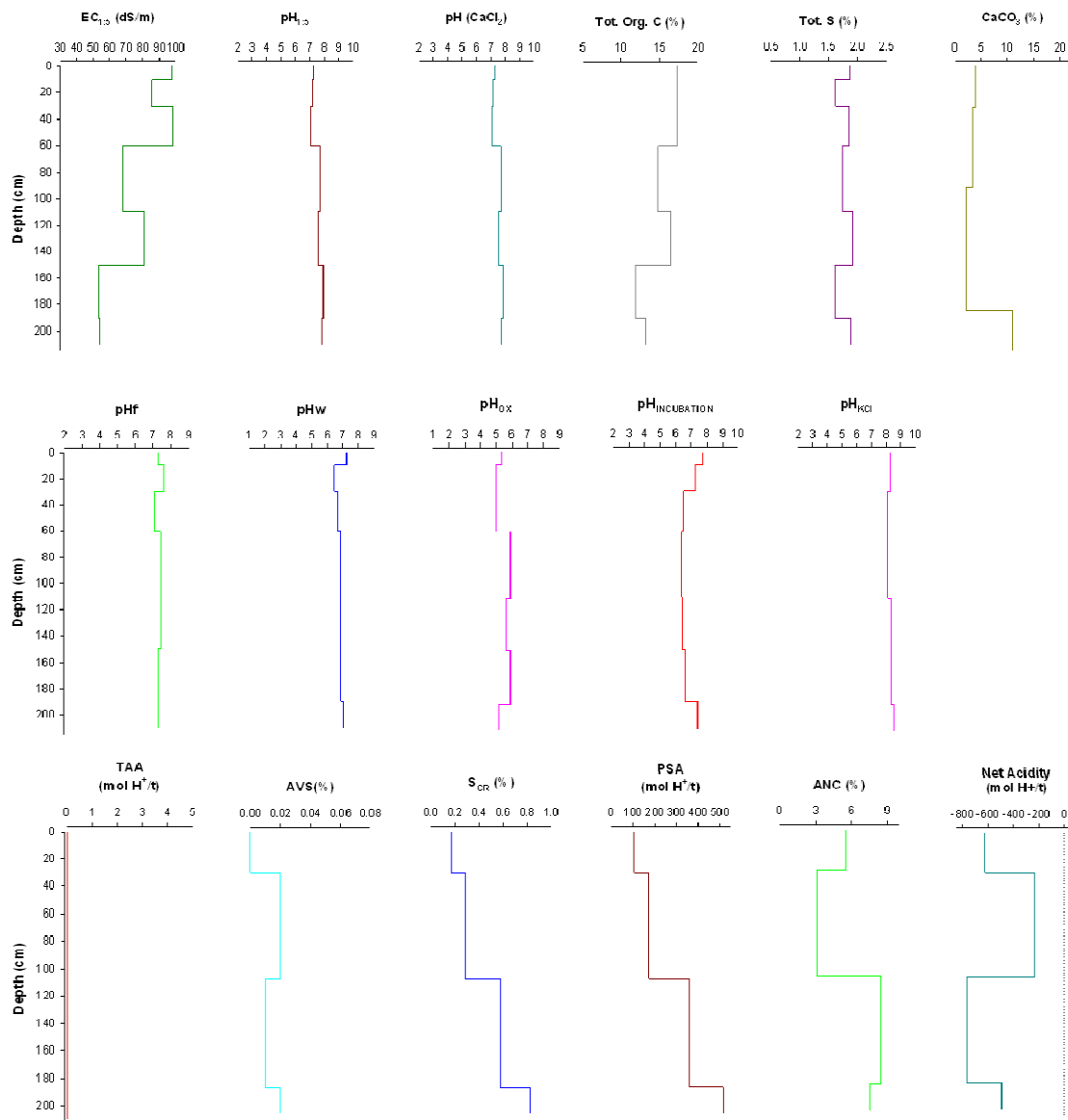


Figure 5-5 Down profile soil chemistry and acid sulfate soil characteristics of profile BSK 5. All soils analytical data are tabulated in Appendix C.

Summary – St Kilda Focus area A

Soil map units within St Kilda Focus area A have been characterised according to i) geomorphology, ii) landscape position, iii) erosional regime, iv) vegetative cover, v) surface soil morphology and vi) water state / drainage. Soil profiles have been classified morphologically; according to Australian Classification (Isbell 2002) and Soil Taxonomy (Soil Survey Staff 2010), and using the recent acid sulfate soil terminology (Sullivan *et al.* 2010) (Table 5-5). Classifications were based on field morphological observations and laboratory data. Soil profile BSK 4 occurs within the intertidal zone and classifies as a Sulfic Haplowassists (Soil Survey Staff 2010), and a Sapric, Histic-Sulfidic, Intertidal Hydrosol (Isbell 2002) containing hyposulfidic and hypersulfidic materials, and minor monosulfidic material. Soil profile BSK 5 is located in a tidal creek channel and classified as a Sapric Haplowassists (Soil Survey Staff 2010), and an Sapric, Histic, Intertidal Hydrosol (Isbell 2002) containing hyposulfidic material and minor monosulfidic material.

Reduced inorganic sulfur contents were slightly higher in profile BSK 4 (maximum AVS of 0.02% and S_{CR} of 0.91%) than in the profile BSK 5 (maximum AVS of 0.02% and S_{CR} of 0.83%). Soil profile BSK 4 has similar total organic C, slightly higher total S and lower carbonate contents than profile BSK 5. These differences can be attributed to these respective profiles occurring at different positions in the landscape, which has influenced: (i) the amount of organic matter (thickness) that can build up above the carbonate rich layers of the Glanville Formation, (ii) different drainage characteristics and redox conditions, and (iii) different organic matter types that are in varying states of decay.

Table 5-5 St Kilda Focus area A soil profiles are classified according to Australian Soil Classification (Isbell 2002), Soil Taxonomy (Soil Survey Staff 2010) and using acid sulfate soil terminology (Sullivan *et al.* 2010).

Soil profile no.	Map unit no.	Aust. Soil Classification (Isbell 2002)	Soil Taxonomy (Soil Survey Staff 2010)	Acid Sulfate Soil materials	Significant net acidity occurrence
Intertidal zone					
BSK 4	10 (Mangrove woodlands)	Sapric, Histic-Sulfidic, Intertidal Hydrosol	Sulfic Haplowassists	Hyposulfidic, hypersulfidic, monosulfidic	40 cm @ 275 mole H^+ /t from 110 cm depth and 0.02% AVS
BSK 5	9 (Water)	Sapric, Histic, Intertidal Hydrosol	Sapric Haplowassists	Hyposulfidic, monosulfidic	210 cm @ -531 mole H^+ /t from 0 cm depth and 0.02% AVS

5.2.2. St Kilda Focus area B – on an elevated, bare, shell grit chenier ridgeline

Focus area B is situated on a slightly elevated shell grit ridgeline (chenier) that is flanked by mangrove woodlands. This area is about 250 m from the low tide mark (Figure 5-1). Focus area B encompasses a toposequence that transects from a relatively high, bare chenier ridge with an elevation of about 1.3 m AHD, to low-lying intertidal mangrove woodlands with an elevation of about 0.8 m AHD. Two soil profiles (BSK 1 and BSK 3) are located on the toposequence and are representative of map units **10** (Mangrove woodland) and **12** (Bare chenier ridge) (Table 5-6). Both profiles are inundated during high tide.

Table 5-6 Soil profiles selected to be representative of map units occurring within focus area A, and along toposequence transect B-B' in Figure 5-6.

Soil profile no.	Elevation	Map unit no.	Landform	Water State, ponding and drainage
Intertidal zone				
BSK 1	0.8 m AHD	10 (Mangrove woodlands)	Open flat –intertidal floodplain	Wet, moderately to poorly drained
BSK 3	1.3 m AHD	12 (Bare chenier ridge; shell-based)	Open mound –intertidal to supratidal floodplain	Wet, very well drained

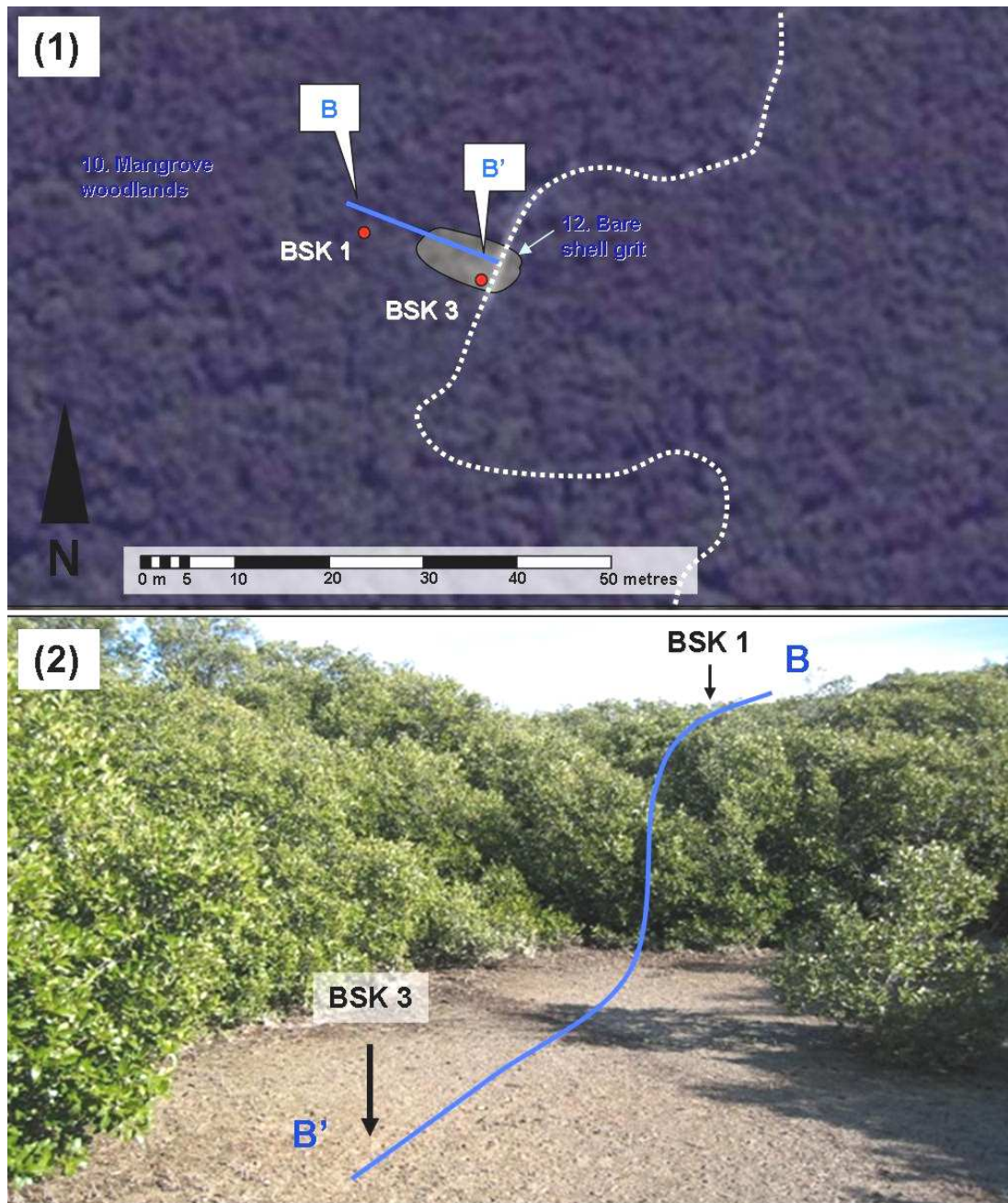


Figure 5-6 Map (1) showing map units in Focus area B and the location of toposequence transect B-B' with soil profiles BSK 1 and BSK 3. The St Kilda boardwalk is indicated by the white dotted line. Landscape photo (2) shows the relative positions of soil profiles along the toposequence transect and contrasts between the map units.

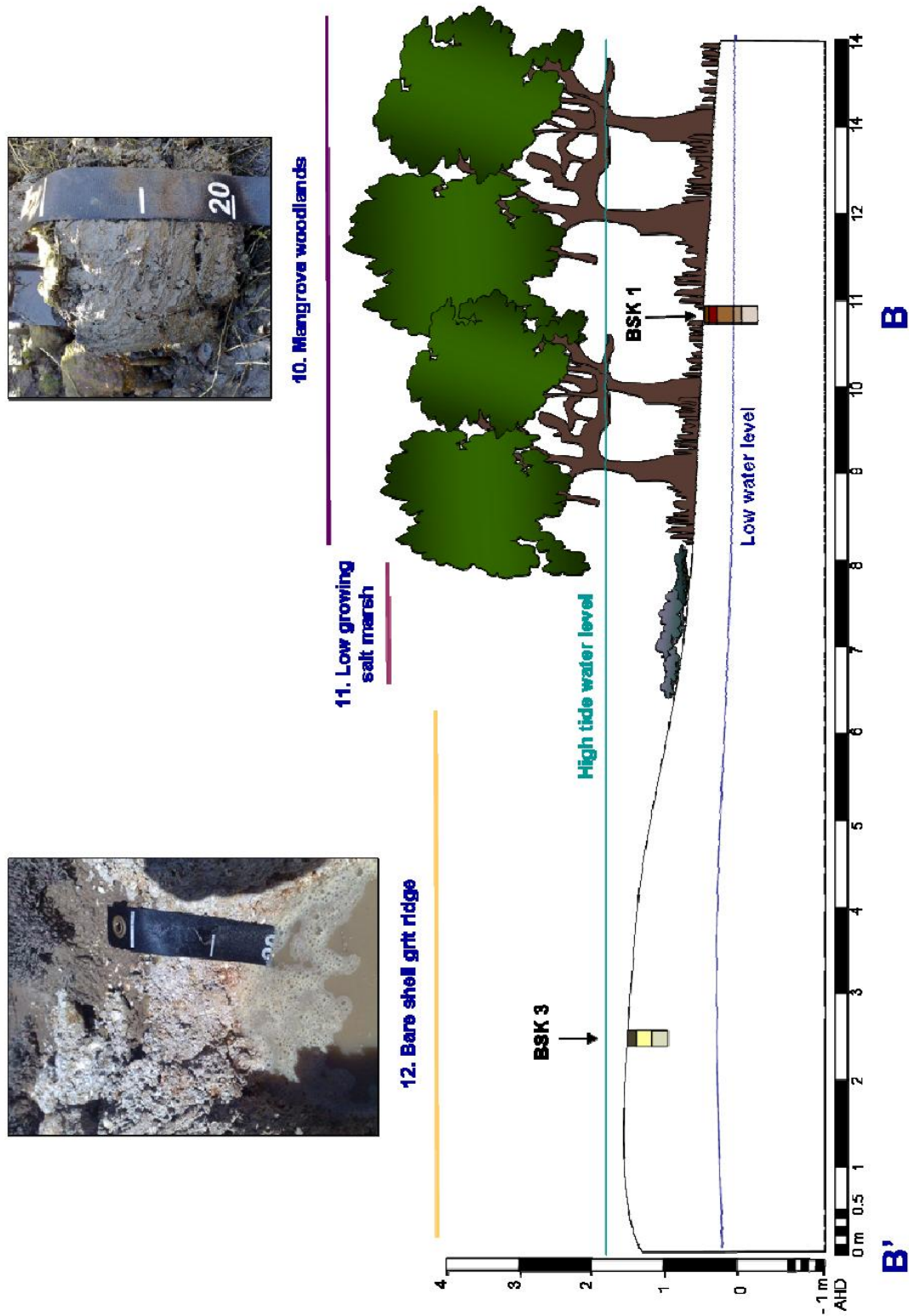


Figure 5-7 Descriptive soil-regolith toposequence model (cross section B-B' as shown in Figure 5-6) indicating map units and position of representative soil profiles with colour photograph and average water table depths during low and high tide.






Map unit 12 - *Wet: very well drained, open mound in an intertidal floodplain covered by a bare, shell-based, chenier ridge. Profile BSK 3* – (Figure 5-7)

Soil-sediment profile BSK 3 occurs within map unit 12 (Bare chenier ridge, shell grit based). A detailed summary of the soil morphological features together with a corresponding close-up photograph of soil fragments are provide in Table 5-6. Profile BSK 3 has developed in an upper intertidal regime, with tidal flooding generally occurring twice a day, however dodge tides occur about twice every month, where the diurnal tidal fluctuation is less than 5 cm. During dodge tides profile BSK 3 may remain exposed for 5-6 consecutive days (refer to Chapter 8). The soil material consists of a 70 cm thick profile dominated by shell hash with a thin clayey layer at the surface (Figure 5-7). A detailed, schematic cross section of the soil-landscape of St Kilda displaying vegetation, geology, hydrology, redox state and soil types is shown in Chapter 8. The near surface soil layer (Oa1 horizon) was wet due to recent tidal inundation and consisted of very dark brown clay and abundant broken shell fragments. The underlying Oa2 horizon (5 to 15 cm) has slightly more broken shell fragments than the near surface layer. The Oa horizons displayed redoximorphic features as strong brown coatings on some shell surfaces (Figure 5-7). The underlying B horizons (15 to 70 cm) predominantly consisted of broken shell fragments with some highly decomposed (sapric) organic and minor redoximorphic features (strong brown mottles along shell surfaces). Shell fragments became coarser with depth (Table 5-7).

Soil EC was reasonably high for the entire profile and generally decreased with depth. The highest EC of 40.8 dS/m was determined for the near surface Oe1 horizon while the lowest EC of 22.0 dS/m was measured in the B/W1 horizon (15-30 cm) (Figure 5-8). Soil pH (1:5) was slightly alkaline for all layer samples and ranged from pH 8.6 at the near surface to pH 9.5 at the base of the profile. Soil pH (1:5) had a median of pH 9.0. $\text{pH}_{\text{CaCl}_2}$ values were about 0.2 pH units lower than pH (1:5) measurements. Total organic carbon contents generally decreased with depth and ranged from 4.8% in the near surface Oa1 horizon to 1.4% at the base of the profile, in the B/W3 horizon. Total sulfur contents were consistent throughout the soil-sediment profile, ranging from 0.42% S in the near surface Oa1 horizon to 0.32% in the underlying Oa2 horizon. Carbonate content was very high for all layer samples and generally increased with depth, ranging from

46.5% CaCO₃ in the near surface layer to 77.2% CaCO₃ at the base of the soil-sediment profile. The median carbonate content measured 65.9% CaCO₃. The soil morphology for profile BSK 3 is summarised in Table 5-7.

Table 5-7 Summary of soil morphology for profile BSK 3: *Wet: saturated (permanent), very poorly drained, inner wetland*. Soil colour was determined on moist samples and consistence determined on dry samples. Photos are of dried bulk samples.

Horizon (ID)	Depth	Soil morphology	Sample (5 x 2.5 cm)
Oa1 (BSK3-63)	0-5 cm	Very dark brown (10YR2/2) clay (10% mineral, 50% hemic material); many coarse and medium live roots; material; some coarse carbonate fragments with strong brown coatings (<5% volume); clear smooth, wavy boundary	
Oa2 (BSK3-64)	5-15 cm	Very dark greyish brown (10YR3/2) clay (30% mineral, 70% sapric material); many coarse and medium roots; minor H ₂ S smell; gradual wavy boundary. Some shell surfaces have strong brown coatings (<5% volume)	
B/W1 (BSK3-65)	15-30 cm	Light grey (10YR7/1) shell hash with some sapric material and some live roots. Minor strong brown (7.5YR 5/8) mottles on shell surfaces (5% volume). Carbonate shell fragments are coarse; diffuse boundary	
B/W2 (BSK3-66)	30-55 cm	White (10YR8/1) shell hash with abundant coarse broken shells. Few strong brown (7.5YR 5/8) mottles on shell surfaces (2% volume). Diffuse boundary	
B/W3 (BSK3-67)	55-70 cm	White (10YR8/1) shell hash with abundant very coarse broken shells.	

Soil profile BSK 3 classifies as: Typic Endoaquents (Soil Survey Staff 2010) and an Epicalcareous, Intertidal Hydrosol (Isbell 2002).

[Acid sulfate soil characteristics:](#)

Soil pH testing (pH_W, pH_{OX} and pH_{Incubation})

Soil pH measurements were determined on all five layer samples in a 1:1 soil-water mixture (pH_W), after treatment with peroxide (pH_{OX}) and after ageing (pH_{Incubation}) the soil for up to 19 weeks in a moist environment. Soil-water pH (pH_W) data show that all soil layers are near neutral to slightly alkaline, with a median pH_W of 7.7 (Figure 5-8).

The pH_{OX} results dropped only marginally (about 1 pH unit) for all soil layers suggesting that they are likely to contain only minor amounts of reduced inorganic sulfur, and have high buffering capacity. The lowest pH_{OX} of 6.2 was obtained by the surface Oa1 horizon (0 to 5 cm) (Figure 5-8).

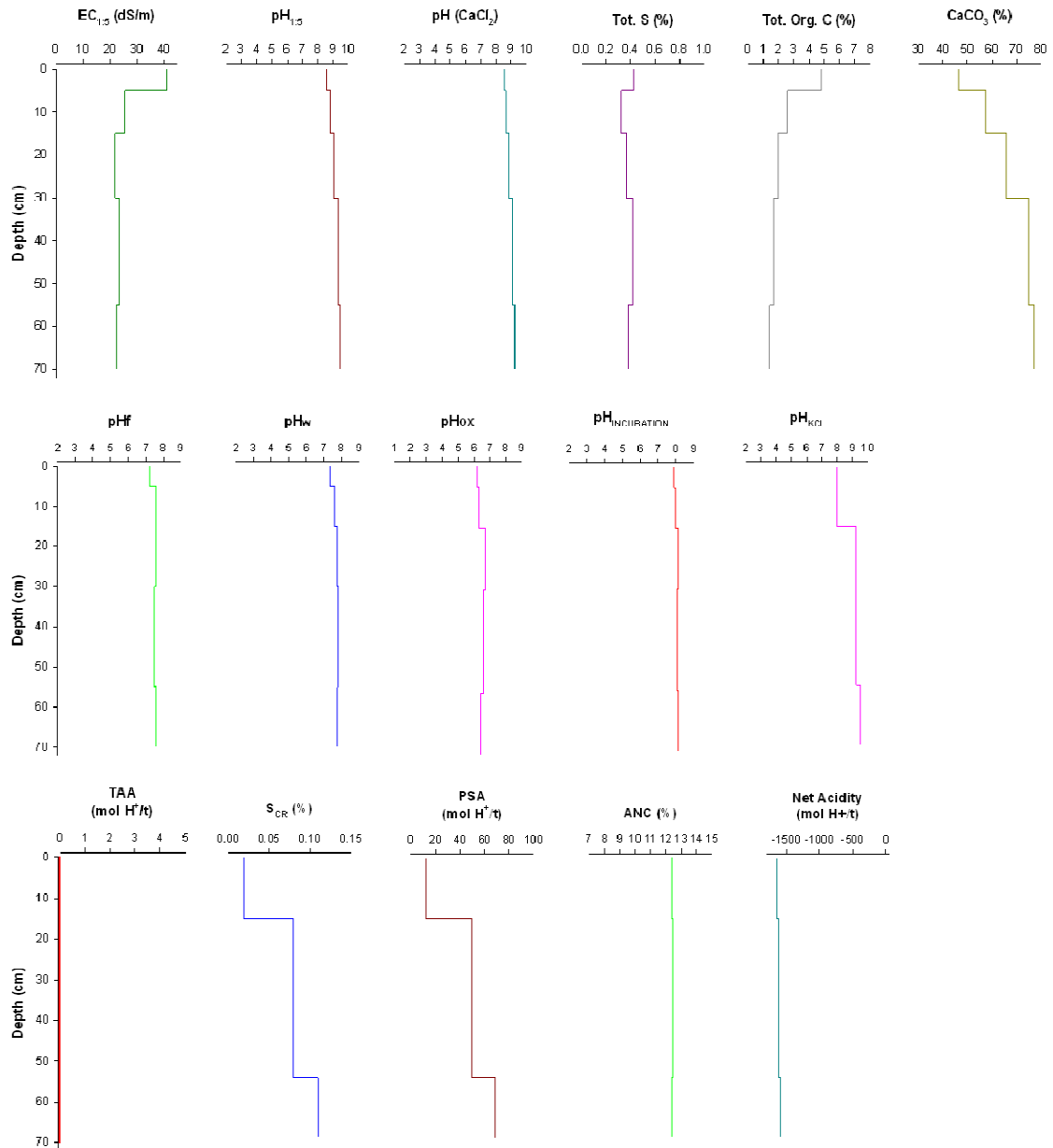


Figure 5-8 Down profile soil chemistry and acid sulfate soil characteristics of profile BSK 3.

Titrateable actual acidity (TAA)

pH_{KCl} results for all three layer samples analysed were >6.5, indicating they did not contain Existing Acidity as TAA or retained acidity. pH_{KCl} results ranged between 8.0 and 9.6, with a median of 9.2 (Figure 5-8).

Chromium Reducible Sulfur (S_{CR})

Reduced inorganic sulfur was determined for three representative layer samples within soil profile BSK 3. S_{CR} values increased with depth, ranging between 0.02% S_{CR} in the near surface layer (0 to 5 cm) and 0.11% S_{CR} at the base of the profile (55 to 70 cm) indicating that all soil layer samples tested contain Potential Sulfidic Acidity (Figure 5-8). No samples were analysed for AVS due to there being no occurrence of dark grey to black soil material or mottles.

Acid Neutralising Capacity (ANC)

Three layer samples were determined to contain abundant effective ANC, with values ranging from 12.0% CaCO₃ to 12.5% CaCO₃ indicating that a high percentage of carbonate is unlikely to be an effective neutralising material. This could be due to armouring and or the coarse grain size of shells.

Net Acidity

Net Acidity values are very negative for all layer samples analysed. Net acidity measurements range from -1583 mole H⁺/tonne at the base of the profile to -1639 mole H⁺/tonne in the surface Oa1 horizon (Figure 5-8).

Acid sulfate soil classification: According to the acid sulfate soil terminology adopted (refer to Table 4-2), soil profile BSK 3 classifies as an acid sulfate soil, containing; hyposulfidic material.

Summary – St Kilda Focus area B

A full description of profile BSK 1 is contained in Appendix B, and is summarised briefly here. Soil profile BSK 1 occurred within the intertidal zone and was located about 10 metres from BSK 3 amid thick mangrove woodland (Figure 5-7). Profile BSK 1 was classified as a Typic Hydrowassents (Soil Survey Staff 2010) and Hemic, Epicalcareous, Intertidal Hydrosol (Isbell 2002) containing hyposulfidic material. Soil profile BSK 3 was located on a slightly elevated shell grit ridgeline and classified as a Typic Endoaquents (Soil Survey Staff 2010) and an Epicalcareous, Intertidal Hydrosol (Isbell 2002), containing hyposulfidic material.

Reduced inorganic sulfur contents were slightly higher in profile BSK 1 (maximum S_{CR} of 0.15%) than in the profile BSK 3 (maximum S_{CR} of 0.11%). Soil profile BSK 1 had a total organic C content of 21.6% in the surface Oa1 horizon which decreased with depth to 2.3% at the base of the profile (Appendix B). Total S was also elevated at the surface of profile BSK 1 (1.1%) (Appendix B). Carbonate content in profile BSK 1 was lowest at the surface (2.0%) and increased with depth to 69.5% at a depth of 55 cm (Appendix B). Organic carbon and total S contents were lower for soil layers of profile BSK 3, but the down profile trends were similar. Carbonate content in profile BSK 3 also increased with depth but values were higher than in profile BSK 1 and measured 46.6% in the surface Oa1 horizon (Appendix B). These differences can be attributed to the prominent positions of profile BSK 3, located on the shell grit ridge, which has very little vegetation cover compared to the mangrove woodland Figure 5-7 and drains considerably faster following tidal inundation.

Table 5-8 St Kilda Focus area B soil profiles are classified according to Australian Soil Classification (Isbell 2002), Soil Taxonomy (Soil Survey Staff 2010) and using acid sulfate soil terminology (Sullivan *et al.* 2010).

Soil profile no.	Map unit	Aust. Soil Classification (Isbell 2002)	Soil Taxonomy (Soil Survey Staff 2010)	Acid Sulfate Soil materials	Significant net acidity occurrence
Intertidal Zone					
BSK 1	10 (Mangrove woodlands)	Hemic, Epicalcareous, Intertidal Hydrosol	Typic Hydrowassents	Hyposulfidic	12 cm @ -234 mole H^+ /t from 0 cm depth
BSK 3	12 (Bare chenier ridge)	Epicalcareous, Intertidal Hydrosol	Typic Endoaquents	Hyposulfidic	70 cm @ -1610 mole H^+ /t from 0 cm

5.2.3. St Kilda Focus area C comprising a scalped depression with intertidal samphire shrublands and mangrove woodlands

An old bund wall was constructed at St Kilda in the 1890s from scalping nearby intertidal sediments and forms the eastern boundary to the St Kilda study site (Figure 5-1). A permanently inundated depression runs parallel to either side of the bund wall as a relic of its construction. The bund wall dammed meandering tidal creeks but was breached and abandoned in the early 1900s. The scalped depressions act as tidal creeks and enabled mangroves to colonise areas previously dominated by samphire vegetation (Burton 1984). St Kilda Focus area C covers a portion of this modified area (Figure 5-9). It encompasses three soil profiles located on a 20 m long northeast trending toposequence that transects across intertidal samphire shrublands, mangrove woodlands and low lying permanently inundated tidal creek channel soils. The toposequence crosses the following three map units: **11** (Low growing salt marsh plants), **10** (Mangrove woodlands) and **9** (Water). Each map unit is represented by the following soil profiles BSK 6, BSK 7 and BSK 8 respectively (Table 5-9).

Table 5-9 Soil profiles selected to be representative of map units occurring within focus area C, and along toposequence transect C-C' in Figure 5-9.

Soil profile numbers	Elevation	Map unit	Landform	Water State, ponding and drainage
Intertidal to supratidal areas				
BSK 6	1.2 m AHD	11. Low growing salt marsh plants	Open flat – intertidal to supratidal zone	Wet, poorly to moderately well drained
BSK 7	0.9 m AHD	10. Mangrove woodlands	Open flat –intertidal floodplain	Wet, moderately to poorly drained
BSK 8	0.0 m AHD	9. Water	Erosional channel - tidal creek channel	Wet, poorly drained

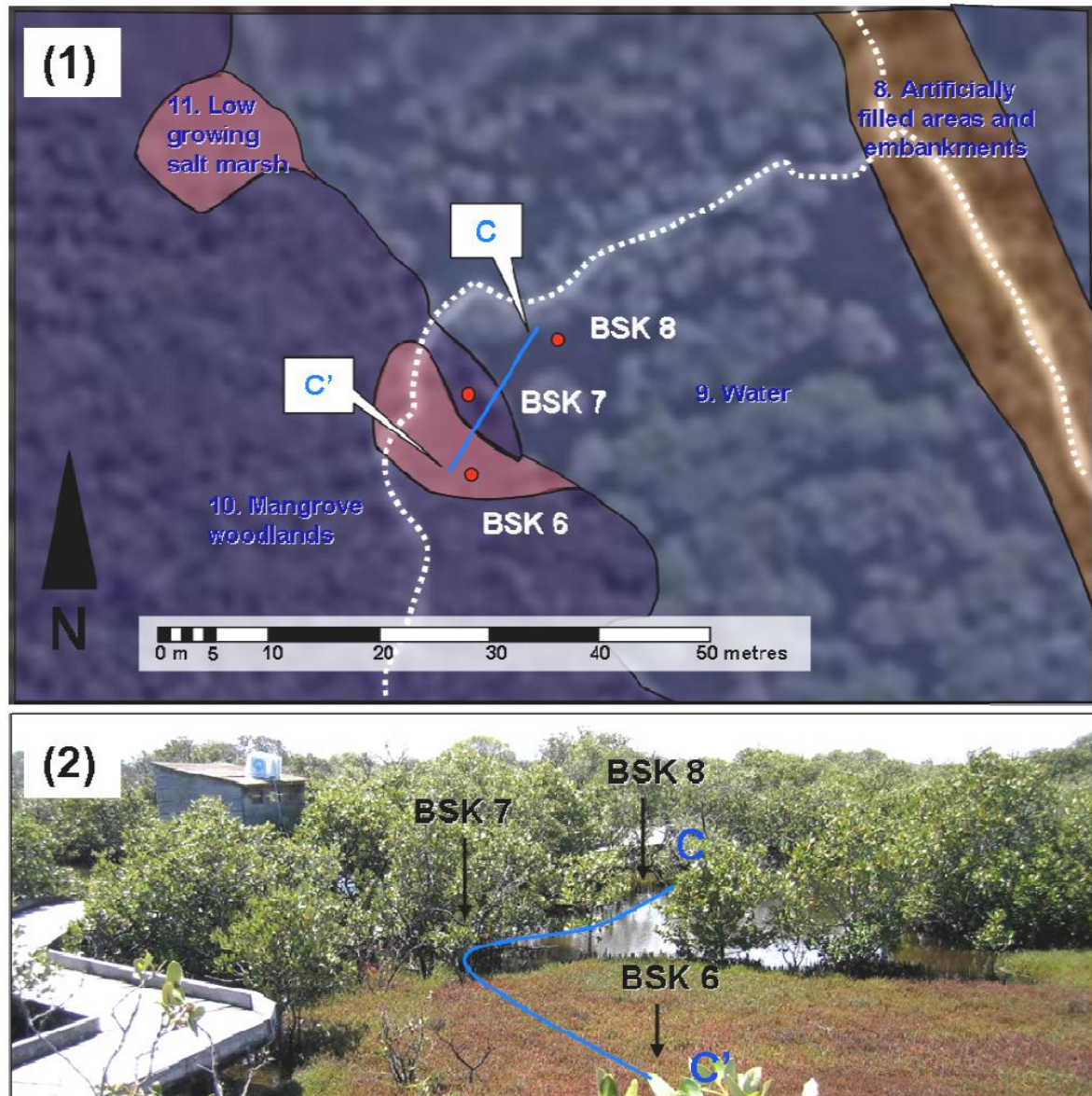


Figure 5-9 (1) Figure showing the map units in Focus area C and the location of toposequence transect C-C' and soil profiles BSK 6, BSK 7 and BSK 8. The St Kilda boardwalk, which also runs along the top of the old bund wall, illustrated as map unit 8 (Artificially filled areas and embankments), is indicated by the white dotted line. (2) Landscape photo showing the relative positions of soil profiles along the toposequence transect and contrasts between the map units. A redox data logger was located in the white box on top of the grey wooden bird-hide and recorded soil redox conditions at depth increments within these three soil profiles.

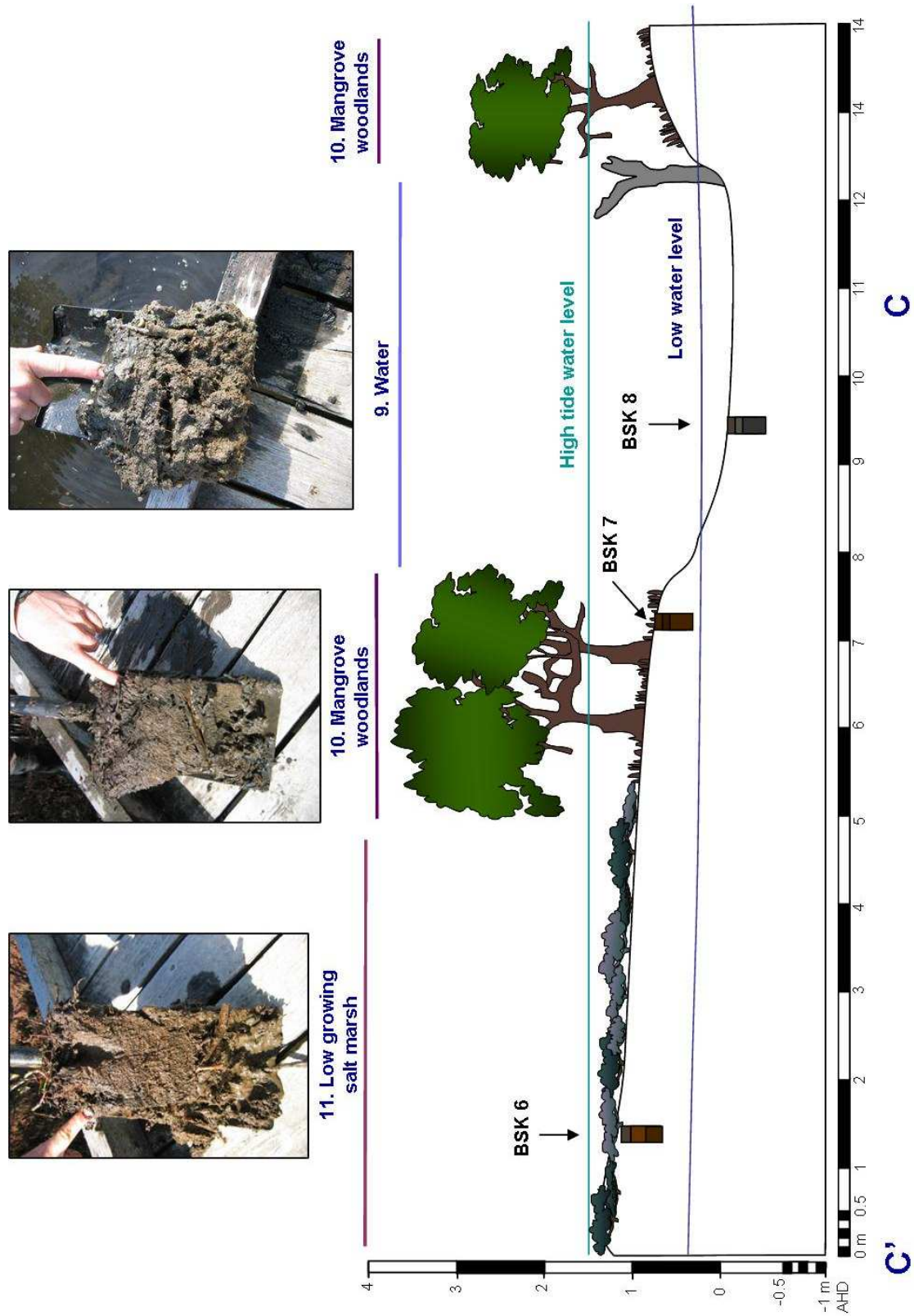





Figure 5-10 Descriptive soil-regolith toposquence model (cross section C-C' as shown in figure 5-9) indicating map units and position of representative soil profiles with colour photograph and average water table depths during low and high tide.

Map unit 11 – Wet: poorly to moderately well drained, open flat intertidal floodplain covered by low growing salt marsh plants. Profile BSK 6 – (Figure 5-10)

Soil profile BSK 6 occurs within map unit 11 (Low growing salt marsh plants). A detailed summary of the soil morphological features together with a corresponding close-up photograph of soil fragments are given in Table 5-9). Profile BSK 6 has developed in an upper intertidal regime, with tidal flooding generally occurring twice a day. The soil profile consists of a 30 cm thick clayey peat that was deposited under samphire vegetation. The clayey peat overlays shell grit (buried chenier ridge) and the carbonate rich Glanville Formation. An explanatory soil toposequence model of St Kilda displaying in schematic soil-landscape cross section format, displaying vegetation, geology, and soil redox conditions is shown in Chapter 8. Three soil layers were distinguished and sampled from the upper 30 cm of the clayey peat. The surface horizon (Oe/W1) occurred from 0 to 5 cm depth and was wet at the time of sampling due to recent tidal inundation. The layer was predominantly a root mat with abundant live roots, had very little mineral content (5%) and minor strong brown mottles coating live root channels. The underlying Oe/W2 horizon (5 to 15 cm) had slightly more mineral content (10%), and few strong brown mottles along root channels. The lower Oe/W3 horizon (15 to 30 cm) contained slightly less roots and more mineral (clay) content than the upper two soil layers, and no redoximorphic features. Hemic material was the principal organic matter type within these soil layers (Table 5-10).

Soil EC was reasonably high and consistent throughout the profile, measuring 46.8 dS/m in the lower Oe/W3 horizon. Soil pH (1:5) was near neutral for each of the soil layers (ranging from 7.3 to 7.9) and were very similar to both $\text{pH}_{\text{CaCl}_2}$ and field pH measurements (Table 5-10). Total organic carbon measured 18.3% in the surface Oe/W1 horizon, 18.5% in the Oe/W2 horizon and 12.6% in the lower Oe/W3 horizon. Total sulfur was similar between upper and lower soil layers, measuring 1.2%, 2.2% and 1.9% respectively. Carbonate content was surprisingly low, measuring 1.8% CaCO_3 in the surface Oe/W1 horizon, and 0.60% and 0.90% CaCO_3 in the underlying horizons respectively. The soil morphology for profile BSK 6 is summarised in Table 5-10.

Table 5-10 Summary of soil morphology for profile BSK 6: *Wet: satiated (subaqueous), poorly drained, intertidal wetland*. Soil colour was determined on moist samples and consistence on dry samples. Photos shown here are of wet samples.

Horizon (ID)	Depth (cm)	Soil morphology	Sample (5 x 2.5 cm)
Oe/W1 (BSK 6-86)	0-5 cm	Very dark brown (10YR2/2) clayey peat (5% mineral, 95% fibric and hemic material); abundant coarse and medium live roots; minor strong brown (7.5YR5/8) mottles coating live root channels (<5% volume); diffuse boundary	
Oe/W2 (BSK 6-87)	5-15 cm	Very dark brown (10YR2/2) clayey peat (10% mineral, 90% fibric and hemic material); abundant coarse and medium live roots; few strong brown (7.5YR5/8) mottles coating live root channels (<2% volume); gradual wavy boundary	
Oe/W3 (BSK 6-88)	15-30 cm	Very dark grey brown (10YR2/3) peaty clay (20% mineral, 80% hemic material); many medium live roots; slight H ₂ S smell.	

Soil profile BSK 6 classifies as: Typic Sulfiwassists (Soil Survey Staff 2010), and a Hemic, Histic-Sulfidic, Intertidal Hydrosol (Isbell 2002).

[Acid sulfate soil characteristics:](#)

Soil pH testing (pH_W, pH_{OX} and pH_{Incubation})

Soil pH measurements were determined on all three samples in a 1:1 soil-water mixture (pH_W), after treatment with peroxide (pH_{OX}) and after 19 weeks of ageing (pH_{Incubation}) the soil in a moist environment. Soil-water pH (pH_W) data show that all soil layers are near neutral, with a median pH_W of 7.7 (Figure 5-11). The pH_{OX} results were low (<2.5) for all soil layers suggesting that they contain appreciable amounts of reduced inorganic sulfur (Figure 5-11). After incubating all three samples showed a substantial drop in pH to less than pH 4, and ranged from pH_{Incubation} of 1.8 to 2.5. The S_{CR} analysis data supports that this drop in pH is due to sulfide oxidation.

Titrateable actual acidity (TAA)

pH_{KCl} results for all three samples were >6.5, indicating they did not contain Existing Acidity as TAA or retained acidity. pH_{KCl} results ranged between 7.1 and 8.1, with a median of 7.5 (Figure 5-11).

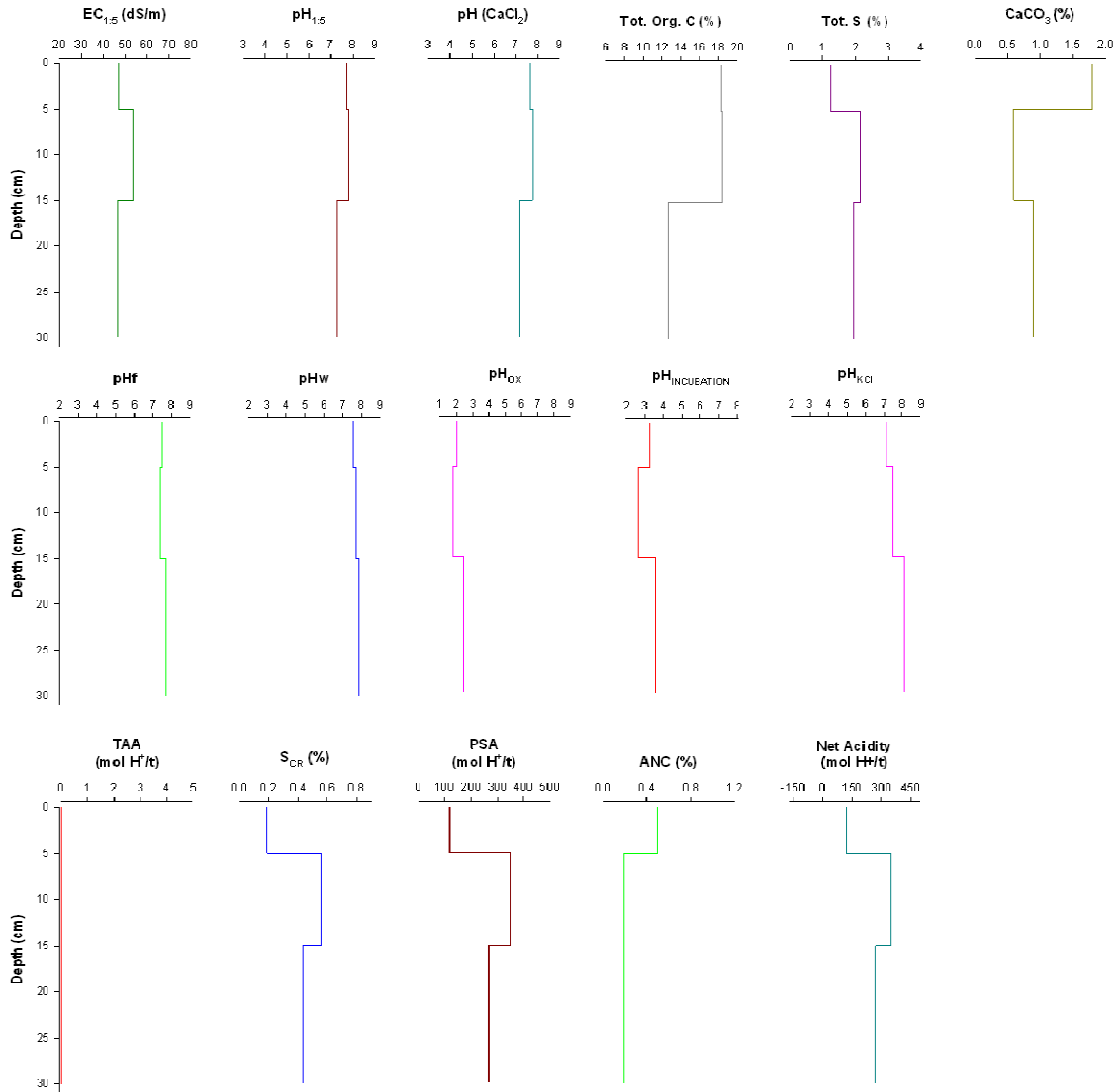


Figure 5-11 Down profile soil chemistry and acid sulfate soil characteristics of profile BSK 6.

Chromium Reducible Sulfur (S_{CR})

Reduced inorganic sulfur was determined for all three layer samples within soil profile BSK 6. S_{CR} values measured 0.19 at the surface (0 to 5 cm), 0.56% from 5 to 15 cm and 0.43% from 15 to 30 cm depth, indicating that all soil layer samples contain Potential Sulfidic Acidity (Figure 5-11). No samples were analysed for AVS due to the absence of black mottles.

Acid Neutralising Capacity (ANC)

All three samples were determined to contain negligible effective ANC, even though CaCO₃ content measured 1.8% in the surface Oe/W1 horizon, 0.6% in the underlying Oe/W2 horizon and 0.8% in the Oe/W3 horizon.

Net Acidity

Net Acidity values were positive for all three layer samples. The net acidity of the measured 119 mole H⁺/tonne in the surface Oe/W1 horizon, 349 mole H⁺/tonne in the Oe/W2 horizon and 269 mole H⁺/tonne in the Oe/W3 horizon (Figure 5-11).

Acid sulfate soil classification: According to the acid sulfate soil terminology adopted (refer to Table 4-2), soil profile BSK 6 classifies as acid sulfate soil with hypersulfidic material. Soil profile BSK 6 did not contain sulfuric soil material.

Summary – St Kilda Focus area C

Descriptions of soil profiles BSK 7 and BSK 8 are contained in Appendix B, and are discussed briefly here. Map units within St Kilda Focus area C have been characterised according to i) geomorphology, ii) landscape position, iii) erosional regime, iv) vegetative cover, v) surface soil morphology and vi) water state / drainage. Soil profiles have been classified morphologically; according to Australian Classification (Isbell 2002) and Soil Taxonomy (Soil Survey Staff 2010), and using acid sulfate soil terminology (Sullivan *et al.* 2010) (Table 5-11). Classifications were based on field morphology and laboratory data.

Soil profiles BSK 6 and BSK 7 occur within the intertidal zone and both classify as Typic Sulfiwassists (Soil Survey Staff 2010), and as Hemic, Histic-Sulfidic, Intertidal Hydrosols (Isbell 2002). BSK 6 contained hypersulfidic material while BSK 7 contained both hypersulfidic and hyposulfidic materials. Soil profile BSK 8 was located in a tidal creek channel and classified as a Typic Hydrowassents (Soil Survey Staff 2010), and an Sapric, Epicalcareous, Intertidal Hydrosol (Isbell 2002) containing, hyposulfidic materials and minor monosulfidic materials.

Reduced inorganic sulfur contents recorded in the St Kilda Focus area C were highest in subaqueous soil profile BSK 8 (with a maximum AVS of 0.18% and S_{CR} of 1.24%). These values were considerably higher than S_{CR} contents found in subaqueous soil profile BSK 5 (with a maximum AVS of 0.02% and S_{CR} of 0.82%), which is subjected to more vigorous tidal flushing and open water of the Barker Inlet.

Soil profiles BSK 6 and BSK 7 occur within map units 11 and 10 respectively, and are very similar to each other in soil type and acid sulfate soil characteristics and are comparable to soil profiles BSK 1 and BSK 4, from map unit 10 (Appendix B). Soil profiles BSK 8 and BSK 5 both occur within map unit 9, however BSK 8 has higher total S and net acidity contents. These differences can be attributed to the profiles occurring at different positions in the intertidal landscape which has influenced: (i) the amount (thickness) of organic matter that can build up above the carbonate rich layers of the Glanville Formation, (ii) different organic matter types and their state of decay and (iii) different tidal flushing strengths (i.e. stability of redox conditions).

Table 5-11 St Kilda Focus area C soil profiles are classified according to Australian Soil Classification (Isbell 2002), Soil Taxonomy (Soil Survey Staff 2010) and using acid sulfate soil terminology (Sullivan *et al.* 2010).

Soil profile no.	Map unit	Aust. Soil Classification (Isbell 2002)	Soil Taxonomy (Soil Survey Staff 2010)	Acid sulfate soil materials	Significant net acidity occurrence
Intertidal Zone					
BSK 6	11. Low growing salt marsh plants	Hemic, Histic-Sulfidic, Intertidal Hydrosol	Typic Sulfiwassists	Hyposulfidic, hypersulfidic	30 cm @ 246 mole H^+ /t from 0 cm depth
BSK 7	10. Mangrove woodlands	Hemic, Histic-Sulfidic, Intertidal Hydrosol	Typic Sulfiwassists	Hyposulfidic, hypersulfidic	30 cm @ 459 mole H^+ /t from 0 cm depth
BSK 8	9 Water	Sapric, Epicalcareous, Intertidal Hydrosol	Typic Hydrowassents	Hyposulfidic, monosulfidic	15 cm @ 42 mole H^+ /t from 10 cm depth and a max 0.18% AVS

5.3. Summary

From the seven soil profiles assessed within the three focus areas at the St Kilda study site, 37 soil samples were collected for description and laboratory analysis. Soil-water pH (pH_w) ranged from 5.08 in soil profile BSK 4, to 7.88 in profile BSK 6, and indicated that no soil profiles contained sulfuric materials. Reduced inorganic sulfur

contents $> 0.01\%S_{CR}$ were detected in all soil samples analysed, indicating they all contained some potential sulfidic acidity. The highest S_{CR} content of 1.24% was measured in soil profile BSK 8, located within map unit 9 (Water). Profile BSK 8 also had the highest AVS content, measuring 0.18%, indicating it contained monosulfidic material. Minor occurrences of monosulfidic material were detected in soil profiles BSK 4 and BSK 5, which were located in map units 10 (Mangrove woodlands) and 9 (Water) respectively. Soil incubation experiments indicated that only three soil profiles (BSK 4, BSK 6 and BSK 7) contained hypersulfidic material and these represented map units 11 (Low growing salt marsh plants) and 10 (Mangrove woodlands). All soil profiles contained hyposulfidic material. The spatial variability within the four map units identified at the St Kilda study site was linked to vegetation type and hydrological and pedological characteristics of the area, which are controlled by micro-elevation and ultimately by geomorphology. The use of surface cover types (e.g. vegetation types, bare mud flats, water) on aerial photographs was therefore a good surrogate for mapping acid sulfate soils within the St Kilda study site. Associations between map units and soil types are presented in Table 5-12. The correlations between these map units and acid sulfate soil hazards have been explored further in Chapter 7.

Table 5-12 Map units located within the St Kilda study site (Focus areas A, B and C) combined with soil profiles classified according to Soil Taxonomy (Soil Survey Staff 2010), the Australian Soil Classification (Isbell 2002) and acid sulfate soil terminology (Sullivan *et al.* 2010).

Map unit no. (map unit colour)	Soil profile No	Australian Soil Classification (Isbell 2002)	Soil Taxonomy (Soil Survey Staff 2010)	Acid sulfate soil materials
9. Water	BSK 5	Sapric, Histic, Intertidal Hydrosol	Sapric Haplowassists	Hyposulfidic, monosulfidic
	BSK 8	Sapric, Epicalcareous, Intertidal Hydrosol	Typic Hydrowassents	
10. Mangrove woodlands	BSK 1	Hemic, Epicalcareous, Intertidal Hydrosol	Typic Hydrowassents	Hyposulfidic, hypersulfidic, monosulfidic
	BSK 4	Sapric, Histic-Sulfidic, Intertidal Hydrosol	Sulfic Haplowassists	
	BSK 7	Hemic, Histic-Sulfidic, Intertidal Hydrosol	Typic Sulfiwassists	
11. Low growing salt marsh plants	BSK 6	Hemic, Histic-Sulfidic, Intertidal Hydrosol	Typic Sulfiwassists	Hypersulfidic
12. Bare chenier ridge (shell-based)	BSK 3	Epicalcareous, Intertidal Hydrosol	Typic Endoaquents	Hyposulfidic