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The influence of soil genesis, type and composition on constraints to plant growth in salt-affected soils in Upper South East South Australia

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ABSTRACT

This thesis documents the physicochemical, mineralogical, geochemical and morphological characteristics of two major soil types present on the interdunal Avenue Plain in the Upper South East of South Australia. Their evolution in the landscape is hypothesised. The district has historically been affected by dryland salinity and seasonal flooding; artificial drainage has been adopted in some areas to ameliorate these constraints. The study was instigated in collaboration with members of the Keilira Farm Management Group (KFMG) in response to a perceived decline in pasture growth since the establishment of the Fairview Drain in the Keilira District in 1997.

A preliminary study was conducted on three properties at Keilira; two included drains (South and Central sites) and one was un-drained (North), with the aim of investigating the effects of artificial drainage on soil physicochemical condition. Annual rainfall and standing water levels (SWL) in a series of observation wells were assessed. Results showed that groundwater levels have fallen both with a decline in annual rainfall and the implementation of artificial drainage. The lowering of SWL has facilitated the leaching of salts, often resulting in the expression of sodicity. Comparison with 1950 (pre-drainage) data confirmed that a change in soil physicochemical condition has occurred at both drained and un-drained sites. Poor plant growth was prevalent when the soils were both chemically hostile and structurally unstable. Soil type and mineralogy were found to vary both across and within study sites; smectite-dominant soils located at the un-drained North site exhibited the most hostile chemical conditions for plant growth.

Subsequent studies at the South site used geophysical tools and soil survey to determine the extent of soil physicochemical variability, whereas mineralogical investigations were performed to identify their cause. Data from the geophysical surveys were used to locate the position for a representative soil trench. Soil samples were collected both across the survey area and within the trench. X-ray Diffraction, X-ray Fluorescence and Transmission Electron Microscopy analyses were conducted both on whole soil samples and the separated clay-size fraction. Petrographic analysis of indurated carbonates was conducted using thin-sections. Carbon and oxygen isotopic analysis was performed to determine the type and origin of the carbonates present.

Two distinct soil types were detected at the site, a Chromosol overlying indurated carbonate that supported good pasture growth and species diversity, and a deep saline-sodic Vertosol that supported only poor pasture growth. The electromagnetic induction survey revealed discrete conductive zones that most likely relate to the depth of the groundwater capillary fringe and presence of clay-rich horizons. Ground Penetrating Radar detected the isolated patches of deep, extremely saline and strongly sodic Vertosols, in addition to numerous indurated carbonate horizons.

Results confirmed that the variability of soil types and carbonate morphology is related to position in the landscape and historic oscillations in ground and surface water levels. Chromosols are predominately found on the eastern side of the Avenue Plain and within the shorelines of lunettes where calcareous lacustrine sediments were periodically exposed and modified, resulting in the development of highly indurated palustrine limestones. These soils are dominated by illite and kaolinite clay minerals that are stratified above the palustrine barrier; they respond well to artificial drainage and chemical amelioration.

The Vertosols are located predominately on the western side of the interdunal plain in the lowest parts of the landscape, such as in the basins of lunettes and throughout natural drainage lines. These soil types are particularly prone to the development of high pH, extreme salinity and strong sodicity and can be difficult to ameliorate. One particularly degraded Vertosol was dominated in surface horizons by the Mg-rich clay mineral saponite, whereas other horizons contained montmorillonite, sepiolite and palygorskite, in addition to Mg-rich calcite and ankerite.

In addition to this work the KFMG instigated on-farm research (OFR) to investigate amelioration strategies. Extension activities were conducted to improve farmer knowledge and facilitate management change. A survey conducted with the three farmers intimately involved in the project confirmed that the combination of off-site research, OFR and regular extension activities improved their knowledge of dryland salinity, sodicity and soil variability on their farms. Management practices have been affected as a result.

It is concluded that the decline in pasture growth observed is due primarily to the sporadic presence of Vertosols that are extremely saline, strongly sodic and very strongly alkaline. Poor plant growth may also be observed on Chromosols when sodic.

STATEMENT OF DECLARATION

This work contains no material that has been accepted for the award of any other degree or diploma in any university or other tertiary institution to Melissa Fraser and, to the best of my knowledge and belief, contains no material previously published or written by another person, except where due reference has been made in the text.

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Melissa Fraser Date

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Financial assistance for this research was provided by the University of Adelaide, School of Earth and Environmental Science, the CRC for Plant Based Management of Dryland Salinity, the Future Farm Industries CRC, the Keilira Farm Management Group and South East Natural Resources Management Board. I am very grateful for the personal and professional development opportunities that were provided by both the University and the CRC and would particularly like to thank Daryll Richardson (CRC) and Dr Ron Smernik (U of A) for their continued enthusiasm for enhancing the PhD experience.

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THESIS STRUCTURE

This PhD project came to fruition in 2005 when a group of farmers from South Australia's Upper South East approached the University of Adelaide to help them investigate a problem they observed on their farms. I was looking for a new challenge and came on-board, intrigued by the nature of their concerns and excited about working with a group of growers and the prospect of incorporating an extension component into my research project. This thesis documents the studies and activities that were conducted to help the Keilira farmers understand the cause of declining plant growth across their farms and the factors that lead to its development. Each Chapter contained herein has been written as an independent document in a format appropriate for publication in scientific journals; some degree of repetition therefore occurs since journal articles must be self-contained.

Chapter 1 introduces the problems encountered by the farmers and gives an overview of the environmental setting for the study. As this environment was/is affected by dryland salinity, a review of literature follows focusing on saline and sodic soils. As the degree of structural degradation in sodic soils is affected by clay mineralogy, a review of soil clay minerals is also included.

Chapter 2 investigates the flux of groundwater levels throughout the study area, with particular reference to the effect of deep artificial drains. Three core study sites were selected and the current soil condition is compared to historic data for two key soil types identified.

Chapter 3 explains how geophysical equipment was used to identify the location for a large study trench that was subsequently excavated. Physicochemical data collected within the trench and from other sampling points allowed inferences to be made about the features that were detected in the geophysical surveys.

Chapter 4 investigates the study trench in more detail, with particular reference to the clay mineral and carbonate types and variability present. Based on these data, hypotheses explaining the evolution of the landscape and the soil types are formulated.

Chapter 5 is an evaluation of the project and its outcomes, including how the knowledge and skills of the participating growers has changed since the projects inception.

Chapter 6 summarises and discusses the findings from this thesis and makes recommendations for future research arising from the work presented.

CHAPTER 1

INTRODUCTION

Soils that are affected by sufficient levels of either soil solution or exchangeable sodium to limit economic and environmental sustainability are broadly categorised as saline, sodic, or saline-sodic soils (Northcote and Skene 1972). Saline soils contain high concentrations of soluble salts, impacting on plant growth through osmotic effects (Keren 2000). A different but equally significant threat to plant production is seen in sodic soils. Sodicity occurs when the concentration of sodium ions on the exchange complex reaches a level where it disrupts soil structure by swelling and dispersion, severely affecting soil-water and soil-air relations (Rengasamy and Olsson 1991). Sodicity often occurs when clay rich saline soils are leached of salts, with dispersion occurring once the electrolyte concentration falls below a threshold level (Rengasamy and Olsson 1991). Hence, the expression of sodicity may occur following the amelioration of salinity.

In South Australia's Upper South East region up to 40% of the land is affected by dryland salinity alone (National Land and Water Resources Audit and National Heritage Trust 2001). To help combat this problem, the Upper South East Dryland Salinity and Flood Management Program (USE DS&FMP) was implemented throughout parts of the region. The expansion of a deep artificial drainage network was one of the strategies employed in the program, with the aim of lowering soil salinity and intercepting surface flood waters; in 1997 the Fairview drain was one of the major systems excavated. Since this time, local land managers have noticed patches of declining pasture growth on the Avenue Plain and were of the opinion that these areas were increasing annually, coinciding with the extension of the drains and the subsequent reduction of groundwater levels.

The area of concern is situated on the Avenue Plain in the Upper South East (USE) of South Australia (SA), in an area locally referred to as the Keilira District (Fig. 1.1). At an average 22 m above sea level, the inter-dunal plain (approximately 8 km wide at Keilira) was investigated by Blackburn in 1952 and he is the only researcher to have extensively studied the soils in this area (Hundreds of Minecrow & Townsend). In this study, 20 soil profiles were collected in late summer and autumn of 1950; 77 soil samples were subsequently analysed for pH, total soluble salts (%), NaCl (%), $CaCO_3$ (%), C, N & P (%), and particle size distribution. Blackburn's observations of the typical soil physicochemical condition in the Kingston-Avenue Drainage area concluded:

- The soils are mainly alkaline and generally saline as well;
- Calcium carbonate is present in all sampled profiles, though in many it was absent from the top 7 cm of soil;
- Great variability in the salinity and organic matter occurred in the soils of the plains;
- Colour was less variable; most of the soils of the plains were either grey or black;
- The vast majority of the soils on the plains were shallow, approximately 7.5 – 45 cm deep, but more commonly between 15 – 30 cm, overlying limestone.

Blackburn's investigations confirm that the soils at Keilira were once saline, however, little scientific data on the soils of this region has been collected since the implementation of broad-scale artificial drainage, despite growing concerns over declining plant growth.

NOTE:
This figure is included on page 3
of the print copy of the thesis held in
the University of Adelaide Library.

Fig. 1.1 Map depicting the South East of South Australia, overlaid with current and proposed drainage alignments. The blue square highlights the Upper South East Region, and the small blue rectangle identifies the Keilira District. Source: SECWMB (2003)

Given the relationship between salinity and sodicity, the implementation of the drainage schemes and the purported reduction in groundwater levels and soil salinity, it is possible that the degrading effects of sodicity are now being expressed across this landscape, and are having a detrimental impact on pasture growth.

The farmers also noticed that the affected areas were confined mostly to the western side of the plains, within 2-3 km of the major drainage alignments. Their fear at that time was that all of the land parallel to the drains would succumb to the same problem. Because of the farmers' observations, the current and future planned expansion of the drainage schemes and the lack of recent soil investigations, the need to conduct new research in the region arose. The aim of this study therefore was to investigate the current physicochemical condition of the soils at Keilira and to identify the cause of variable plant growth and proliferation in this environment. To undertake such investigations, it was important to first gain an understanding of the relationship between salinity and sodicity and the physical and chemical constraints that may be encountered in this environment; the factors that influence their development and expression, such as clay mineralogy, also needed to be identified. The following review of the literature is intended to meet this purpose; it was written at the outset of the project. As the project progressed it became evident that the review of additional literature was required (principally on continental carbonates); the literature of interest is contained within the relevant chapters.

1.1 ENVIRONMENTAL SETTING

The area referred to in this thesis as the ‘Keilira District’ is located in the USE of SA on the Avenue Plain. The land is mainly used for meat and fibre production, grazing livestock on improved pastures; some cereal cropping is also performed. Geologically, the USE region is characterised by three key features, the Padthaway Ridge, Murray Basin and Otway Basin (South East Catchment Water Management Board 2003). Flanked on the western side by the ocean and the State of Victoria to the east (Appendix 1.1), most of this area is characterised by dune fields of reworked riverine and littoral deposits (Butler *et al.* 1983). Within the Murray Basin more specifically, the Keilira district (36^{0} 42’ 32.38”S 140^{0} 09’ 46.46”E) is situated 30 km inland from the coastal township of Kingston. Part of the Bridgewater Formation (Firman 1973), the East and West Avenue Ranges that flank Keilira belong to a series of stranded coastal dunes that are aligned parallel to the current coastline. The suite of ridges reportedly contain deposits of calcareous sands, including fragments of marine organisms, with varying proportions of quartz, resulting in the development of *Podzols*[1] and *Terra rossa* soils (Blackburn *et al.* 1965; Butler *et al.* 1983). Rising from 26 – 30 m above sea level, thermoluminescence dating suggests that the East and West Avenue ranges formed in the Middle Pleistocene, some 414,000 ± 29 and 342,000 ± 32 years ago respectively (Huntley *et al.* 1993).

The numerous inter-dunal plains of the south-east region are more recent and are generally formed of grey fluviatile silts, sands and gravels, resulting in *Solodized solonetz*

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[1] Australian Soil Classification (Great Soil Group classification): Podosol (Podzol); Chromosol (Terra rossa); Sodosol (Solodized solonetz) and Vertosol (Rendzina)

and *Rendzina soils*, the latter being restricted to areas of fine textured estuarine or lacustrine sediments (Blackburn 1983). Limestone is generally found within 0.2 to 0.4 m of the soil surface, and ranges in form from hard and flinty to fairly soft weathered types and grey cemented calcareous material underlain by marly material and hard stone (Blackburn 1952).

The character of the landscape, soils and geology of the South East combined with a relatively high annual rainfall (climate is further discussed in Chapter 2) has historically led to annual surface water inundation (flooding) across much of the region (South East Catchment Water Management Board 2003), including the Avenue Plain. There is a gentle gradient downwards from east to west on the Avenue Plain, causing surface waters to gently drain to the west before being intercepted by the eastern side of the West Avenue Range, directing the flow north-westwards (Appendix 1.2). These features make the USE prone to frequent and sometimes prolonged surface water inundation during the winter and spring months (Appendix 1.3). In 1866 Goyder reported accounts of floodwaters rising 0.3 - 1.8 m above the surface of the soil in this region, with some areas never drying out completely (England 1993). Before European settlement in this area it is believed that the floodwaters gradually travelled north, feeding into Salt Creek, eventually supplying fresh water from the USE to the south lagoon of the Coorong (England 1993).

The nature of the landscape and surface water inundation therefore leads to a rapid vertical recharge of a shallow unconfined aquifer within the Murray Group Limestone in the Murray Basin and the Gambier Limestone of the Otway Basin which is approximately

20 m deep (Holmes and Waterhouse 1983). Some recharge of this aquifer may also occur through upward leakage of water from the confined aquifer in areas where the confining layer permits movement (South East Catchment Water Management Board 2003). Unconfined aquifer salinity in the Keilira district is reported to range between 1500 – 7000 mg/L.

The second major groundwater system in the USE is a deep confined aquifer that flows in a westerly and south-westerly direction from its eastern edge in the Victorian Grampians. This regional aquifer is primarily recharged by lateral inflow in the eastern parts of the Murray Basin, flowing through the Dilwyn Formation in the Otway Basin and the Renmark Group in the Murray Basin. An upper confining layer of clay and marl forms the aquitard that separates the two aquifers (Holmes and Waterhouse 1983).

Widespread settlement throughout the South East of SA first occurred in the mid 1800’s and the land was quickly developed for agricultural production, capitalising on the availability of good quality water and the openness of native vegetation. However, seasonal inundation was a problem, hence artificial drainage was first constructed near Millicent from 1864 - 1883 to overcome this problem, ensuring agricultural productivity, transport routes and communications were not compromised by the annual floodwaters. However, with no natural relief for the water to escape to the coast, much of the drain water was channelled to the northwest, increasing the volume of water travelling throughout the USE region. Over time, artificial drainage networks have gradually expanded, with an estimated 2,400 km of shallow and deep drains now intercepting surface floodwater and shallow groundwater across the South East. During the 1950’s the

Blackford and Jacky Whites drains were excavated, allowing the waters of the Keilira district to be discharged to the ocean just north of Kingston. In 1997 extensive development of the drainage network in the USE was conducted, with the establishment of the 55 km long Fairview drain further aiding the removal of waters from Keilira.

1.2 SALT-AFFECTED SOILS IN AUSTRALIA

Salt-affected soils are widespread in the arid to semi-arid regions of the world, with much of this land exhibiting limitations to agricultural productivity; they include saline, sodic, magnesium, gypsiferous and acid sulphate (Szabolcs 1989) types. Salinity is a widespread and well known problem in Australia, however Rengasamy and Olsson (1991) highlight that Australia exhibits the highest ratio of sodic to saline soils across several continents of the world (Table 1.1). More recently it has been reported that over 60% of soils in Australian agricultural zones are sodic in comparison to the 16% of agricultural soils affected by water table induced salinity (Rengasamy 2006).

Table 1.1 The comparative distribution of areas of saline and sodic soils on several continents (10^3 Km^2). Source: Rengasamy and Olsson (1991).

NOTE:
This table is included on page 8
of the print copy of the thesis held in
the University of Adelaide Library.

The map shown in Fig. 1.2 depicts Northcote & Skene's predicted distribution of saline and sodic soils in Australia in 1972. The soils in the South East of South Australia are shown here to be of an alkaline, strongly sodic nature. Given this information, it is therefore likely that sodicity also occurs in the Keilira District in addition to salinity and may further suppress plant growth and proliferation through the effects of dispersion.

NOTE:
This figure is included on page 9
of the print copy of the thesis held in
the University of Adelaide Library.

Fig. 1.2 Distribution of Saline and Sodic soils in Australia.

1.3 SOIL SALINITY

Salt can occur naturally in the regolith of agricultural land due to rock mineral weathering, from deposits of oceanic derived atmospheric salts and through submergence by seawater. It is generally believed that prior to agricultural development salt accumulations on the surface of the soil were leached through the profile by percolating rain, accumulating below the root zones of native vegetation. Leaching potential was not great enough to allow the transport of salts into the deep groundwater (Rengasamy 2002^{a}) and environmental degradation was limited as the landscape was vegetated by tolerant species and the hydrological cycle was in equilibrium. However, in Australia, rising shallow groundwater levels have resulted from the disturbance to the equilibrium in the hydrological cycle (Ghassemi *et al.* 1995), principally brought about by the extensive clearing of native vegetation since European settlement for agricultural purposes. The reduction in perennial and deep-rooted vegetation and increase in production of annual shallow rooted species has resulted in a reduction of water usage. In places, this has enabled excess water to recharge aquifers, resulting in increases in the volume of groundwater in these areas. Such rising groundwater levels enable the mobilisation of stored salts from deep in the regolith, transporting soluble salts back to the surface. These salts can concentrate and accumulate in the root zone and on the soil surface as evaporation of soil moisture from depths of up to 2 m (Rengasamy 2002[a]) can occur.

Salinisation is identified as the process whereby the concentration of total dissolved solids in water and soil is increased due to natural or human-induced processes (Ghassemi *et al.* 1995); these are termed as *primary* and *secondary* salinity respectively. Primary or naturally saline soils occur in regions where accumulations of salts occur naturally, and are expressed in the landscape due to naturally shallow groundwater, unaffected by European land use changes (Fitzpatrick 2003). Salt lakes, saltpans, salt marshes and salt flats are all examples of naturally occurring saline areas (Shaw *et al.* 1997). Secondary saline soils are caused by rising saline groundwater and characteristically possess high salt accumulations due to evaporative water loss in saline seeps (Fitzpatrick 2003) and this is commonly identified as dryland or seepage salinity. Figure 1.3 demonstrates some of the processes of induced salinisation.

Fig. 1.3 Causes and effects of induced land salinity. Source: (EPA 2000)

Secondary irrigation-induced salinity can also occur as a result of water applied during irrigation. Poor management of irrigated crops can lead to an excess of water leaching past the root zone, aiding recharge to the groundwater (Shaw *et al.* 1997). The rising groundwater can again mobilise salts, bringing them to the surface and into the root zone where the increased salt concentration can have detrimental osmotic effects on the irrigated crop.

Another form of salinisation occurs from accumulations of salts derived from wind and rain and soil weathering reactions. Salt that is deposited in this way can accumulate in soils with poor hydraulic conductivity (such as sodic soils), in low rainfall dryland areas, in areas of high vegetative transpiration and climates that induce high evaporation during summer months. It is known as dry saline land or transient salinity, can be subsoil or surface-expressed, and is not associated with groundwater fluctuation (Rengasamy 2002[a]).

1.3.1 Salinity in the USE

Soil surveys conducted by Blackburn in the Kingston-Avenue area in 1950 identified areas of saline soils and the presence of salt tolerant vegetation. Attention was drawn to the spread of salt-water tea tree populations across the Avenue plains, possibly indicating an increase in dryland salinity throughout this area. Northcote and Skene's map of saline and sodic soils categorise the soils in this area as being AS1; having alkaline strongly sodic and sodic clay soils intergrading to saline forms or to normal forms.

In the Upper South East it is estimated that primary salinity currently affects 22,500 ha of land while secondary salinity affects over 250,000 ha (Barnett 2000) accounting for 40% of the total land area. Another 409,500 ha of land is at risk of becoming salt-affected by 2050 if no further management strategies are implemented throughout the region (National Land and Water Resources Audit and National Heritage Trust 2001). It is estimated that an average of 700,000 tonnes of rain-borne salt is deposited in the South East catchment (including the Keilira district) annually, and 710, 000 tonnes of salt are removed from the catchment in the drainage networks throughout the region.

1.3.2 Effects of salts on plants and soils

Osmosis, or the diffusion of water across a membrane, is the process by which plants take up water from soil (Raven and Johnson 1996). Detrimental effects on plant growth due to osmotic processes occur when the concentration of salts in the soil solution affects the osmotic gradient of plant roots. In non-saline environments, an osmotic gradient is set up by the plant with a higher concentration of solutes in the core of the root relative to soil water. As the plant uses water, suction is created in the plant and water is able to pass through the root cell membrane to deliver water in an attempt to achieve equilibrium between the root and soil solutions. When a soil is saline, the concentration of solutes in the soil is higher and the gradient between the soil solution and the root solution is reduced, making it harder for the plant to extract water. If soil salt loads are highly elevated, the osmotic potential of the soil decreases to a point where the plant can no longer extract water from the soil. As dehydration of the plant cells occur, stomata begin to close, resulting in a reduction of photosynthesis, detrimentally affecting plant growth, and plant death may occur (Buck *et al.* 2004). Prolonged exposure of plants to saline environments can lead to the uptake and accumulation of toxic ions such as Na, Cl and HCO_3. This accumulation may lead to the interference of normal cell function, disrupting plant growth, also potentially causing plant death. Electrical Conductivity of a 1:5 soil:water solution ($EC_{1:5}$) however, does not give an accurate indication of the salt load that plant roots are exposed to *insitu*, so soil texture has to be accounted for (Adcock *et al.* 2007). The guidelines (Shaw 1999) presented in Table 1.2 are proposed for soils with differing clay contents.

Table 1.2 Soil salinity ratings for Electrical Conductivity of a 1:5 soil:water solution in dSm^{-1} for different soil textures as determined by Shaw (1999), *in* Hazelton and Murphy (2007)

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The effects of salts on soil are wide and varied, depending on soil type and chemistry, salt type and concentration and position in the landscape. Saline conditions generally have detrimental effects on plant growth, as previously discussed, and they can in some cases result in a total loss of plant growth and resultant soil cover. Bare salt scalds can develop, leaving vast tracts of land exposed to the degrading effects of wind and water erosion, dependant on their position in the landscape. Unprotected saline soils on hill slopes and in gullies are prone to a loss of soil with the development of blowouts and deep rills.

The most commonly reported effect of salts on soils is the development of sodicity while other degradational effects are not well reported. The presence of salt in coarse textured soils (dominated by sand) has very little effect on soil structure or chemistry, because quartz minerals do not possess charge and their structural development is minimal. Salt accumulation in clay soils, however, can have significant impacts on soil physicochemical properties. Clays have a net negative charge and can therefore attract cations, predominately calcium, magnesium, sodium and potassium. In environments where saline waters are rich in sodium chloride, the presence of excess sodium ions can dominate exchange sites, displacing calcium and magnesium. Smectite clay minerals in particular naturally possess the ability to shrink and swell during changing moisture regimes and this process is enhanced by the presence of sodium, which attracts water into the clay minerals. Depending on the total concentration of electrolytes in solution, clay particles will either flocculate or disperse. Soils that disperse due to the presence of sodium ions are identified as being sodic and are discussed in detail in section 1.4.

1.4 SODICITY

Sodic soils have historically been defined by their exchangeable sodium percentage value (ESP); a soil is considered to be sodic when the ESP is >6 and those with an ESP >15 as strongly sodic (Northcote and Skene 1972). The later is the value proposed by the United States Salinity Laboratory Staff (1954) above which soils are considered to exhibit adverse properties. Rengasamy (2003), however, states that a soil may also be considered sodic when the exchangeable sodium reaches a concentration where it disrupts soil structure through a breakdown of soil aggregates, due primarily to the dispersion of clay particles. All sodic soils are dispersive, whereas all dispersive soils need not be sodic. Because of enhanced dispersion, sodicity causes major soil structural decline, principally a loss of porosity that results in poor soil-water and soil-air relations and leads to adverse affects on plant growth and crop production (Rengasamy 2002^{b}). Sodic soils often exhibit surface sealing, crusting and hardsetting which commonly cause restricted infiltration, waterlogging, increased runoff and erosion to occur (Naidu *et al.* 1995). Such soil constraints limit the availability of water and nutrients to plants and can have dire consequences for agricultural productivity.

1.4.1 Exchangeable Sodium Percentage

Soils with sodic properties are characterised by moderate to high exchangeable sodium. The percentage of negative charge occupied by sodium is known as the exchangeable sodium percentage (ESP). ESP is often used as a measure of sodicity and is determined by analysing the solid phase of the soil.

$$ESP = (\text{exchangeable sodium} / \text{cation exchange capacity}) \times 100$$

Northcote and Skene (1972) proposed a classification for Australian sodic soils (Table 1.3), whereby soils with an ESP greater than 6 are considered to be sodic. However, it has been found that the extent of soil structural degradation by dispersion varies depending on electrolyte concentration (EC) and ESP, the nature and content of organic matter, soil pH, clay content and mineralogy, dominance of calcium vs. magnesium and soil biology (Rengasamy *et al.* 1984; Chorom *et al.* 1994; Churchman *et al.* 1995; Barzegar *et al.* 1997; Nelson and Oades 1997; Grieger 1999).

Table 1.3 Sodicity ratings and ESP proposed for Australian Soils by Northcote and Skene (1972).

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An alternative determination of the content of exchangeable sodium in soils can be calculated by measuring the Na, Ca and Mg in a soil solution, obtained from either a 1:5 soil:water extract or from a saturation extract. Cations in soil solution move freely between the soil solution and exchange sites, maintaining equilibrium between adsorbed ions and those in solution, however, divalent ions are adsorbed more strongly than monovalent ions. Based on this concept, sodium adsorption ratio is defined as follows (Rengasamy 2003):

$$SAR = Na^{+} / \sqrt{(Ca^{2+} + Mg^{2+}) / 2}$$

Where Na^{+}, Ca^{2+} and Mg^{2+} refer to soluble ionic concentrations in meq L^{-1}

It has been found that the SAR measured from saturation extracts often is approximately equal to the ESP of a soil and while the relationship may vary depending on several factors, SAR can be considered to be a measure of sodicity (Rengasamy 2003).

1.4.2 The deterioration of soil structure by dispersion

Dispersion occurs when the electrical double layers of two soil clay particles over-lap or interact. The diffuse double layer refers to the alternate layers of negative and positive charges that exist between a clay particle surface and the soil solution. As the distance from the soil particle face increases, there are progressively more anions in the solution until the electrical neutrality of the bulk solution is reached, in which the number of cations equals the number of anions (Buck *et al.* 2004). The diffuse double layer, in effect, occupies the space between the clay surface and the soil solution and has a thickness less than one-millionth of a centimetre, governed by two main factors, the ionic strength (electrolyte concentration) of the solution and the cation valence. The thickness of the diffuse double layer decreases with an increase in the ionic strength, it is then said to become compressed. The diffuse double layer further compresses when the exchange sites are dominated by polyvalent cations such as calcium and magnesium. The double layer expands when the exchange sites are dominated by monovalent ions such as sodium (Quirk 1968).

When two clay particles with a high concentration of monovalent sodium counter ions come close together, the double layers can overlap or interact, resulting in the total concentration of ions mid way between the two particles to be greater than in the soil solution in which the particle is immersed (Buck *et al.* 2004). The resultant change in osmotic pressure draws water between the particles, causing them to move further apart. In smectitic soils particularly, the expansion may be reversible for high soild:solution ratios, and the effect if known as swelling. In the presence of low electrolyte water, a sodic soil may move one stage further towards disruption so that the particles become dispersed completely from one another, severely affecting soil physical characteristics.

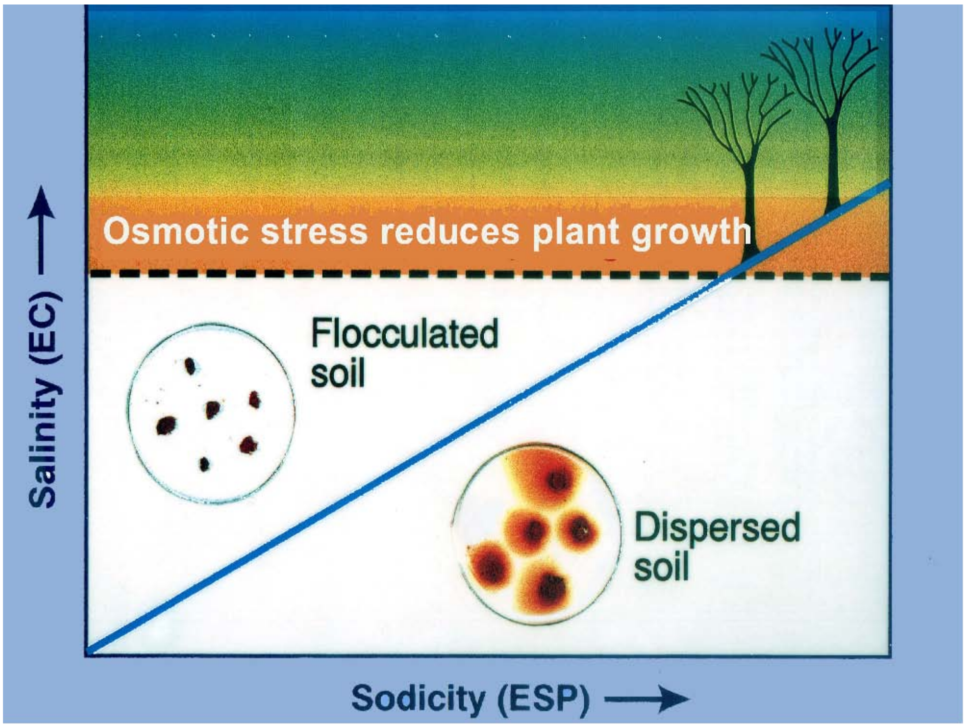

Fig. 1.4 Dispersion and flocculation of soils as affected by EC and ESP.
Source: (Pichu Rengasamy, The University of Adelaide, pers. comm. March 2006)

If the electrolyte concentration of the soil solution is high enough, the osmotic potential between soil solution and the inter-clay spaces is reduced enough to prevent dispersion and enhance flocculation, even in soils dominant in sodium (Fig. 1.4). The deleterious effects of sodium are therefore often only evident once salts have been leached below a threshold level (Rengasamy 2002[b]). Soils that are affected by salinity therefore have a tendency to express sodic behaviour after amelioration strategies to lower soil EC have been implemented.

1.4.3 The nature and content of organic matter and clay dispersion

Organic matter and its various fractions commonly contribute to both the formation and the stabilisation of soil aggregates but, under some circumstances, specific fractions of organic matter can also destabilise aggregates and increase the dispersibility of clay and silt sized materials (Kay and Angers 2000). The effect of organic matter in sodic soils is complex and is only discussed briefly here, the reader is referred to Churchman *et al.* (1995), Nelson and Oades (1997), Baldock and Nelson (2000) and Kay and Angers (2000) for a more detailed discussion on the role of organic matter in sodic soils.

Sodic soils often exhibit low organic matter contents as plant productivity is affected by the physical and chemical constraints generated by the presence of excess exchangeable sodium. Soil structure further degrades in the absence of the plant roots, polysaccharides and fungal hyphae (Tisdall *et al.* 1997) that generally stabilise macro-aggregates (Barzegar *et al.* 1997).

The presence of organic matter can both suppress swelling and enhance dispersion, often at the same time (Churchman *et al.* 1995). In the first instance, Churchman *et al.* (1995) conclude that in some soils swelling is probably suppressed as organic matter acts as a coating and linking agent, lowering the surface area of the soil minerals with which it is associated. In the second instance, humic substances, the more persistent components of organic matter, can aid dispersion in soils as organic anions decrease the activity of multivalent cations such as Ca through complexation (Barzegar *et al.* 1997), therefore increasing the SAR of the soil solution.

Nelson and Oades (1997) also note that an increase in organic matter in the soil can result in the production of weak acids that may lower the pH of the soil. Lowering the pH of the soil will lower the net negative charge of the clay minerals and will aid in suppressing dispersion. In contrast, however, the presence of some types of organic matter in clay soils can also increase the net negative charge of soil clay minerals, enhancing clay dispersibility, especially at high pH.

1.4.4 Soil pH and clay dispersion

Much of the behaviour of soils is governed by the nature of the surfaces of soil particles, particularly their surface area and charge (Rengasamy and Churchman 1999) and it is the presence of exchangeable cations on exchange sites that ultimately determines the degree of swelling and dispersion of clay minerals. Chorom *et al.* (1994) found that in a study of three soils, each dominated by one of three different soil minerals, all the soils exhibited a reduction in net negative charge when the $pH_{(water)}$ went below 6 and the percentage of dispersible clay reduced considerably. At lower pH values, mineral dissolution caused an increase in EC, further aiding flocculation in addition to the effect of the reduction in net negative charge. When the pH was increased, an increase in net negative charge was observed corresponding with an increase in dispersible clay percentage.

In addition to the constraints posed to plant production through salinity and sodicity, alkalinity is a common subsoil constraint observed in south-eastern Australian soils. In sodic soils, alkaline conditions (pH >8.5) are also often observed as sodium ions interact with carbonate and bicarbonate ions in the soil matrix and $NaCO_3^{2-}$ / HCO_3^- minerals are formed (Rengasamy 2002[b]). The hydrolysis of these minerals releases free OH^- ions into the soil solution, further increasing the pH, hence enhancing dispersibility. Highly alkaline conditions may also lead to plant deficiencies of P and N, micronutrient deficiencies (Zn, Cu, Mn, Fe) and/or toxicities of B and molybdenum (Adcock *et al.* 2007). The ratings presented in Table 1.4 are given as an interpretation of soil pH measured in water (1:5 soil:water).

Table 1.4 Soil pH ratings for neutral – very strongly alkaline soils, in Hazelton and Murphy (2007).

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1.4.5 Mineralogical composition and dispersion

Kaolinite, illite and smectite are the three most common aluminosilicate minerals found in the clay fractions of soils (Churchman *et al.* 1995). Kaolinites and illites exhibit very little swelling while smectites are capable of substantial swelling, especially in the presence of monovalent exchangeable cations in low EC solutions. The shrink - swell nature of smectitic clays can mask the degradative effects of sodicity, as the soils have the ability to ‘heal’ themselves through their self-mulching behaviour, aiding the break up of compacted layers. Kaolinitic soils are often acidic when they are not greatly affected by the presence of sodium, but kaolinitic soils can exhibit sodic behaviour under high pH conditions. Nonetheless, kaolinitic soils are often coarse-textured, which diminishes the effects of clay dispersion (Churchman *et al.* 1995). Illitic soils can exhibit severe degradation, as illites are highly susceptible to dispersion (Emerson 1983) when sodic because of their particle size and shape, but lack the ability to shrink and swell (Fanning *et al.* 1989).

1.4.6 Dominance of calcium vs. magnesium

High levels of exchangeable Mg in the soil have been shown to enhance the dispersion of some soils that also have high ESP's. A study by Rengasamy *et al.* (1986) found higher concentrations of magnesium salts than calcium salts were required to induce flocculation in a Red Brown Earth. Ca^{2+} and Mg^{2+} ions are both divalent and therefore bind more strongly to clay minerals than Na^{+} ions. Mg^{2+} ions, however, have a larger hydrated diameter than Ca^{2+} ions and therefore do not bind as strongly as Ca^{2+} ions. Since the repulsive force in an exchangeable calcium dominated clay is smaller, the aggregates in a calcium soil are more stable (Rengasamy *et al.* 1986) than those in an exchangeable Mg^{2+} dominated soil. Exchangeable Mg^{2+} does not however have the same level of influence over dispersive behaviours as does exchangeable Na^{+} (Buck *et al.* 2004).

1.4.7 Soil biology

Baldock and Nelson (2000) define resilience as the capacity of an ecosystem to return to its initial state after disturbance. Resilience is an important soil property and an indicator of how well a soil system is able to recover from external disruptions. Together with soil resistance (the inherent capacity to withstand disturbance) it ultimately defines the stability of a soil (Krull *et al.* 2005). There is a dearth of information relating to the role of soil biology in sodic soils. It is believed, however, that soils with a greater microbial diversity are more resistant to perturbations and more resilient than soils with less diverse communities.

1.4.8 Mechanical disturbance and clay dispersion

Mechanical disturbance (e.g. when aggregates of soils and clay minerals are disturbed when wet) can cause clay dispersion, even in the absence of sodium (Chorom *et al.* 1994). Mechanical dispersion commonly occurs when heavy machinery and agricultural implements are passed over or worked through the soil following a rainfall event. Areas that are affected by sodicity often suffer greater structural degradation as the lower hydraulic conductivity generates waterlogged conditions, enabling strong disturbance to occur during cropping operations.

1.4.9 Sodicity and clay dispersion, effects on soil permeability and water holding characteristics

So and Aylmore (1995) report that the hydraulic conductivity (HC) of a soil is an important parameter used to assess plant growth, soil aeration, soil water recharge, surface runoff, erosion and evapotranspiration. Factors that influence HC are numerous and include texture, structure, soil moisture, biological activity, electrolyte concentration of the soil solution and ESP (Coulombe *et al.* 1996). As HC reduces in a soil, rates of infiltration (IR), redistribution (or drainage) and evaporation are also reduced (So and Aylmore 1995). These conditions are conducive to the development of waterlogging, potentially having severe impacts on seed germination at planting, and reducing the amount of oxygen available to crop roots. Whereas an initial increase in evaporation may be observed in a waterlogged soil, the rate of drying often exceeds the HC of the soil, and the surface may dry rapidly, forming a surface crust. This crust subsequently reduces the evaporation of moisture from the soil, further enhancing the waterlogged conditions (So and Aylmore 1995).

In sodic soils, as ESP increases and EC decreases, the HC of the soil is significantly reduced (Shainberg and Letey 1984). There are various reasons why a decrease in HC is observed in sodic soils. In highly smectitic soils, swelling of particles may contribute to the initial reduction of HC as the high adsorption capacity of sodium ions for water causes swelling, possibly causing blockage to the surrounding water-conducting pores.

As previously discussed, as ESP increases and EC decreases, the potential for clay dispersion also increases, especially in illitic and smectitic soils. These mobile clay particles are then able to translocate throughout the soil matrix, often blocking soil pores, further reducing HC. Whereas the process of swelling is generally reversible with changing soil moisture regimes and electrolyte concentration, the movement and blocking of pores with dispersed clay is largely irreversible and can cause the formation of impermeable clay layers in the soil profile (Shainberg and Letey 1984). These layers can act as physical barriers to water movement and root growth, and can also aid the accumulation of salts in the root zone and resultant development of transient salinity.

Plant root growth and seedling emergence can also be affected due to the suppressing effects of high soil strength. Barzegar *et al.* (1995) conducted a study to investigate changes in tensile strength of Australian soils in relation to the properties of the soil clay. The results of this investigation led to the conclusion that soil strength was highly related to clay content, clay type, CEC of clay and the amounts of clay dispersed either spontaneously or mechanically. Clay soils dominated by smectite minerals of fine size and high CEC were found to result in the highest tensile strength compared to illitic and kaolinitic soils.

1.5 SOIL MINERALOGY

The texture of a soil is determined according to the proportions of different sized particles present in the soil. Particle size classes of soils recognised by the U.S.D.A system include gravel, very coarse sand, coarse sand, medium sand, fine sand, silt and clay (White 1997). The clay fraction of soils contains particles that are two micron (µm) in size and smaller and this fraction of the soil can contain a large assortment of minerals. The clay fraction of soils can be divided into two broad classes by type, the *crystalline clay minerals* (predominantly phyllosilicates) and the *accessory minerals* (non-phyllosilicates).

Minerals in the clay fraction have large surface areas that are chemically active and can hold a variety of cations and anions by various mechanisms. It is the presence of cations on clay mineral surfaces that give them many of their characteristic properties, including plasticity and the ability to absorb water and swell (Norrish and Pickering 1983).

This fraction is also responsible, along with organic matter, for holding nutrient elements and water for use by plants, and for reducing the susceptibility to leaching. The crystalline clay minerals found in the <2 µm fraction of the soil include the fine-grained layer lattice silicates (phyllosilicates) kaolinite, illite and smectite.

1.5.1 Kaolinite

Kaolin minerals, which include kaolinite and less commonly halloysite, are 1:1 layered aluminosilicates, with layers comprising one tetrahedrally coordinated silicon-based sheet combined with one octahedrally coordinated aluminium sheet via shared oxygen atoms. The lower surface of each layer consists of closely packed hydroxyl (OH) groups, and the upper surface of hexagonal rings of oxygen atoms, as seen in Figure 1.5. Layers are held together by hydrogen bonding between the hydrogen and oxygen atoms of adjacent layers. Kaolinite is a non-expanding mineral (in water) with a basal spacing of 7 Å (McLaren and Cameron 1996).

Compared to other clay minerals, the layer charge of kaolinite is extremely low (<0.005 mol of negative charge per unit cell), due primarily to the small amount of Al substitution for Si in the tetrahedral layer (McLaren and Cameron 1996). This amount of isomorphous substitution results in a low cation exchange capacity (CEC) to be observed, usually in the range of 1-10 cmol(+)/kg. Norrish and Pickering (1983) comment however, that at least part of the exchange capacity is pH dependent, indicating that some variable charge arises from dissociation of H^+ and OH^- ions at the crystal edges. Since the basal spacing of kaolinites does not leave room for interlayer cations, all of the charge-compensating cations are adsorbed on the exterior surfaces of a stack of layers (van Olphen 1977).

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Fig. 1.5 1:1 (Tetrahedral: Octahedral) layer Phyllosilicate, kaolinite (Grim 1962).

1.5.2 Illite

Illites are dioctahedral clay micas that have 2:1 (tet:oct) structures, consisting of a sheet based on octahedrally coordinated cations between two tetrahedrally coordinated silica sheets (Fig. 1.6). The unit layers have (non-exchangeable) K ions holding them together, these positive ions balancing the negative charge created by isomorphous substitution of Al for Si in one fourth of the tetrahedral sheet, and in some cases Mg for Al (Norrish and Pickering 1983). Some substitution of Mg and Fe for Al in the octahedral sheet is also possible, contributing to the average net negative charge of 1.6 mol per unit cell.

Illites are also non-expanding minerals with a basal interlayer spacing of about 10 Å (Norrish and Pickering 1983), however this spacing can increase as the mineral weathers and K is gradually replaced by cations of higher ionic potential, principally Ca and Mg (White 1997). In contrast to smectite minerals, only the external cations of illite clays are exchangeable as a consequence of the strong association of interlayer potassium with the layers, resulting in a smaller cation exchange capacity, despite the higher degree of isomorphous substitution and resultant layer charge. The CEC of illites is considered to be in the range of 20 – 40 cmol(+)/kg (Norrish and Pickering 1983).

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Fig. 1.6 2:1 layer Phyllosilicate, illite (Grim 1962).

1.5.3 Smectite

Smectites are a group of expansive 2:1 layer silicate minerals and as in micas (illite) the layer has a negative charge due to isomorphous substitution, giving rise to a variety of chemical compositions resulting in the formation of the different major minerals in this group (Table 1.5). Substitution of Al for Si in the tetrahedral sheet is sometimes observed, while Al is commonly replaced by Mg in the octahedral sheet (Fig. 1.7), but can also be replaced by Fe, Cr, Zn, and Li, creating a layer charge ranging between 0.4 - 1.2 mol of negative charge per unit cell (White 1997).

Table 1.5 Major smectite minerals found in soils.

Montmorillonite	Al in the octahedral sheet, with some Mg substitution for Al giving rise to the layer charge
Beidellite	Also Al in the octahedral sheet, but charge is derived from substitution of some Al for Si in the tetrahedral sheet
Nontronite	Ferric iron in the octahedral sheet
Saponite	Magnesium in the octahedral sheet, the charge originating in the tetrahedral sheet by substitution of some Al for Si

This negative charge is balanced by interlayer cations as in micas, however whereas illites are balanced typically by K, smectite interlayer cations are readily exchangeable and the charge on the silicate layer is fully expressed by the CEC of the clay, typically observed to be in the range of 80 – 150 cmol(+)/kg (Norrish and Pickering 1983). Due to the freely exchangeable nature of the interlayer cations, the basal spacings of smectites may vary from 15 – 40 Å, dependant on the nature of the exchangeable cations, their hydration diameters and electrolyte concentration (Quirk 1968). The presence of relatively large hydrated cations increases the interlayer spacing of smectites and Norrish and Pickering (1983) comment that smectites dominated with exchangeable Na may swell to at least several hundred Angstroms upon hydration.

Smectites in soil can either be derived from original rock material or can form as a result of neogenesis and transformations of primary minerals, however, these processes require specific micro-environmental conditions. Specifically, smectite development usually requires poor drainage, high concentrations of Ca and Mg and high pH (7 or higher) conditions to ensure the formation and preservation of such minerals (Borchardt 1989; Mermut *et al.* 1996). Smectites can also be formed through the transformation of mica through depotassication and dealumination and, finally, silication of the tetrahedral sheet

(Mermut *et al.* 1996). These conditions are so critical that smectites can transform to kaolinite plus iron oxide as a result of improved drainage.

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Fig. 1.7 2:1 layer Phyllosilicates with Al, Fe, Mg substituted for Si in Oct Sheet, smectite (Grim 1962).

Borchardt (1989) elaborates by commenting that the weathering rates of smectites can be increased to a rate where even intermediately stable minerals are not formed in the presence of drastically improved soil drainage. Smectite can be dissolved through simple hydrolysis, and the high acidity produced by the oxidation of pyrite (common in poorly drained sediments) further aids dissolution. Some smectites can tolerate low pH, but only in the presence of high concentrations of Si and Mg in solution and when leaching is restricted.

1.5.4 Non Phyllosilicate minerals

Other non clay minerals can also exist in the clay fraction of soils (<2 μm); they are known as the accessory minerals or non-phyllosilicates and some may contribute significantly to soil properties. These minerals are predominantly free oxides and hydroxides – compounds in which a single cation species is coordinated with O and/or OH, although carbonates and rock forming minerals can also exist in this fraction (White 1997) (Table 1.6).

Table 1.6 The most abundant non-clay minerals found in soils.

Oxides and Oxyhydroxides of Iron	Hematite
	Maghemite
	Goethite
	Lepidocrocite
Hydroxides and Oxyhydroxides of Aluminium	Gibbsite
	Boehmite
Silicon Oxides	Quartz
	Opaline Silica
	Disordered forms of silica
Carbonates	Calcite
	Dolomite
	Aragonite
Rock forming minerals	Feldspars Amphiboles

The oxides and oxyhydroxides of Fe and Al (*sesquioxides*) are considered the most important accessory minerals as they exhibit some pH dependant charge due to the reversible adsorption of potential-determining H^+ ions (White 1997). Such sesquioxides are positively charged up to pH 8, and contribute to the anion exchange capacity of the soil. Al and Fe oxides have a high affinity to fix phosphate and soils containing high oxide content can cause a deficiency of P in plants. Both Al and Fe oxides can coat other soil constituents and can influence soil physical properties such as aggregate stabilization

(Krishna Murti *et al.* 1977) and the swelling and dispersion characteristics of the soil (Taylor *et al.* 1983).

Oxides of manganese and titanium also exist in soils, but contribute little to the chemical and physical properties of the soil and thus are not discussed here. Carbonates such as calcite can also occur in soils formed on chalk and limestone and in high pH soils of arid regions. Carbonates affect soils mainly through their effects on altering pH.

1.6 CONCLUSION

Saline and sodic soils are both widespread across Australia's agricultural land and can cause major limitations to crop and pasture productivity. Salinity is known to occur in the Keilira District of USE SA and deep drainage schemes have been employed to help ameliorate this problem. In saline environments, however, sodic soils will only remain stable as long as the EC of the soil solution remains high enough to induce flocculation. Hence, the expression of sodicity has been found to occur following the remediation of saline soils, with high exchangeable sodium in the presence of low EC soil solutions facilitating the dispersion of clay particles, causing subsequent structural decline.

The purpose of the artificial drainage has been to intercept surface flood waters and to lower groundwaters to facilitate leaching, thereby reducing soil salinity levels. Northcote and Skene (1972) reported that the soils in the vicinity of the Keilira District were moderately to strongly sodic, and it is therefore possible that the effects of sodicity are now being seen across this landscape as the drains serve their purpose. Alkalinity is also a constraint in Australian soils that is known to occur in conjunction with sodicity. As the expression of sodicity is governed by many factors, such as pH, clay mineralogy and cation ratio, in addition to soil EC and ESP, it is therefore crucial that a thorough assessment of the soils in this region be conducted to determine the factors that are detrimentally affecting plant growth.

1.7 HYPOTHESES

Given these conclusions, the following hypotheses are proposed:

1. That the observed decline in pasture growth is the consequence of multiple soil physicochemical constraints, including salinity, sodicity and alkalinity.
2. That the physicochemical condition of the soil has been altered as a consequence of artificial drainage.
3. That the development of soil physicochemical variability is a function of:
    - i. Hydrology
    - ii. Position in the landscape
    - iii. Clay mineralogy
4. That farmer knowledge of the problem and how to manage it can be improved by interaction with researchers.

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CHAPTER 2

ARTIFICIAL DRAINAGE AFFECTS THE PHYSICOCHEMICAL PROPERTIES OF SALT-AFFECTED HEAVY CLAY SOILS IN THE UPPER SOUTH EAST OF SOUTH AUSTRALIA

2.1 INTRODUCTION

Salt-affected soils are widespread across Australia’s arable land, severely limiting agricultural productivity. In 2001 it was estimated that 250,000 hectares or 40% of the land in the Upper South East (USE) of South Australia (SA), comprising productive farmland, native vegetation and wetlands, had been degraded by salinisation caused by high groundwater levels and flooding (National Land and Water Resources Audit and National Heritage Trust 2001). The total cost to South Australia due to dryland salinity, through losses in agricultural production and maintenance to roads and infrastructure, was estimated to exceed $44 million per year and was expected to climb to almost $60 million by 2020 (Barnett 2000). Given the significance of this problem, great efforts have been made to reclaim the USE from the deleterious effects of dryland salinity. In 1995 ‘The Upper South East Dryland Salinity and Flood Management Program’ (USE DS&FMP) was developed to address community concerns about dryland salinity, waterlogging and ecosystem fragmentation and degradation in this region (Department of Water Land and Biodiversity Conservation 2009).

Artificial drainage networks had expanded rapidly in the 100 years that followed European settlement in South East SA, and the construction of a further 665 km of artificial drains was recommended in the new USE DS&FM program. This included the construction of the 55 km long, 3 m deep Fairview Drain, that intersected the inter-dunal Avenue Plain. The aim was to capture surface floodwaters that annually inundate the area, and to lower groundwater levels in the local unconfined aquifer, thereby lowering soil salinity. Nonetheless, since the implementation of the USE DS&FMP, a perceived decline in plant growth across an area of the Avenue Plain, known as the Keilira District, has led to growing levels of concern amongst members of the Keilira Farm Management Group (KFMG). In 2005, local land managers sought help after initially observing poor plant growth and bare patches of soil. They were of the opinion that the affected areas were increasing, coinciding with the extension of the drainage network and possible reduction of groundwater levels. However, there were also patches of declining plant growth occurring on farms that had not yet employed artificial drainage, so the need became evident to investigate the trends in groundwater levels and the possible effects of artificial drainage on soil physicochemical properties at both drained and undrained sites.

Despite the implementation of the USE DS&FMP and the subsequent construction of the Fairview Drain across the Avenue Plain in 1997/98, the only author to date who has conducted research and published data on the soils in this area is Blackburn (1952). In the vicinity of the Fairview Drain on the central - western side of the Avenue Plain, he identified two distinct soil associations. The first of these he called Soil Association J and characterised as variable grey and black clay rich soils that showed differentiation of colour, texture and structure and were mainly saline, occurring in the uneven lagoon – lunette areas. The soils were often relatively bare (Blackburn 1952). The Total Soluble Salt

% (TSS) in these soil types ranged from 0.026 – 9.1% and they were moderately to strongly alkaline throughout (Clarke 1955).

The second common soil type identified was Soil Association R, characterised by a surface horizon (<0.1 m) of loamy fine sand overlying a shallow black clay subsoil, with limestone occurring within 0.3 m (Blackburn 1952). The TSS % for these soils was significantly lower than for Soil Association J, ranging from 0.086 – 1.6% and the soils were strongly to very strongly alkaline throughout (Clarke 1955). The data collected by Blackburn (1952) and reported by Clarke (1955) confirm that historically the soils of this region were salt-affected and so the USE DS&FMP recommendation to expand the drainage network, lowering groundwater levels and hence soil salinity, seemed appropriate.

Lowering salinity levels can, however, have both positive and negative impacts on soils and plant growth depending on the soil texture and clay mineralogy. Whereas saline soils contain high concentrations of soluble salts, impacting on plant growth through osmotic effects (Keren 2000), a comparably important threat to plant production is seen in sodic soils. Sodicity occurs when the concentration of sodium on the exchange complex reaches a level where it disrupts soil structure through dispersion, severely affecting soil-water and soil-air relations (Rengasamy and Olsson 1991). Sodicity often occurs in clay rich saline soils that are leached of salts, with dispersion occurring once the EC falls below a threshold electrolyte concentration (Rengasamy and Olsson 1991). However, clay mineralogy can significantly affect the swelling and dispersion potential of sodic soils (Churchman *et al.* 1993) and other factors such as pH and OM can also aid or suppress the expression of sodicity (Chorom et al. 1994). Given that the USE DS&FMP was instigated to lower groundwater levels, and that Blackburn observed both heavy and light textured soils with varying degrees of salinity, it is possible that leaching has occurred, leading to the expression of sodicity. However, no recent studies have been published for the Keilira District identifying how the soil condition has changed since Blackburn's initial study and the extensive implementation of artificial drainage throughout the USE.

The primary aim of this study, therefore, was to determine the likely effects that artificial drainage has had on soil physicochemical properties in the Keilira District in South Australia and to identify whether the observed plant decline is being caused directly by the drainage schemes, as the farmers feared. This aim was achieved by: (i) determining the factors that influence the flux in standing water levels across this region and their trends over time, (ii) identifying the soil physicochemical constraints to plant production, comparing soils with differing drainage histories, and (iii) comparing current and historic data to identify the possible effects of artificial drainage on soil physicochemical properties and the consequences for pasture growth.

2.2 ENVIRONMENTAL SETTING OF THE STUDY

The USE of SA is characterised by a remarkable sequence of stranded dunes, deposited over the past 800,000 years (ka) as the result of the staged accession and recession of the ocean (Huntley *et al.* 1993). The dune systems run roughly parallel to the current coastline, creating a westerly barrier to surface waters, and historically caused seasonal inundation on the inter-dunal plains during winter and spring.

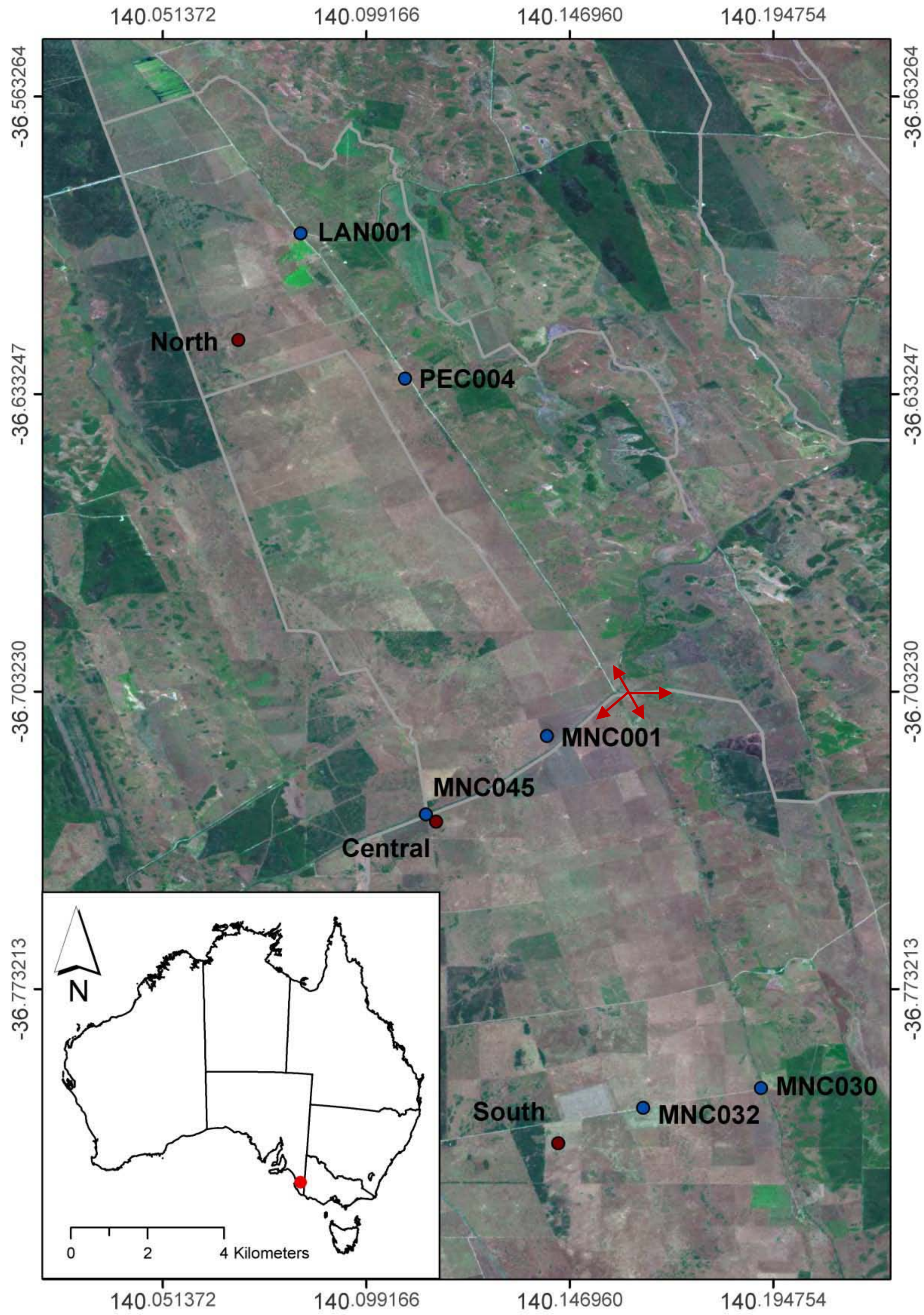

Fig. 2.1 Keilira District in the USE of SA, depicting the location of the study sites, South, Central and North, and the observation wells investigated in this study. The red arrows highlight the junction of the Rowney West road and the Keilira Avenue road.

The inter-dunal Avenue Plain is land-locked by two of the relic dunes, the East Avenue and West Avenue Ranges, with surface waters generally flowing from east to west and then travelling north-westerly. The area referred to here as the Keilira District on the Avenue Plain is intersected by the junction of the Rowney West and Keilira-Avenue Roads, near Keilira Station (36.71°S 140.16°E). The district encompasses agricultural land 15 km north and 15 km south of the Rowney West road, spanning an area of ~18,000 ha (Fig. 2.1).

2.2.1 Climate

The USE of SA has a temperate climate with warm dry summers and cold wet winters. Mean summer daily temperatures at Keith (36.10°S 140.36°E) range from a minimum 12.7° C to a maximum 29° C, whereas mean daily winter temperatures fall to a mean minimum of 5.7° C and reach a maximum of 15.3° C (Australian Bureau of Meteorology 2009). Mean winter rainfall at Keilira Station exceeds 230 mm and mean summer rainfall is generally <70 mm. Historic annual rainfall records for Keilira Station presented in Figure 2.2, show marked variability in rainfall over the record period. Data for the years 1945 – 2000 were sourced from the Australian Bureau of Meteorology (2009) and records for 2001 – 2008 from Keilira Station records (Shane Rook, Manager Keilira Station, pers. comm. March 2009).

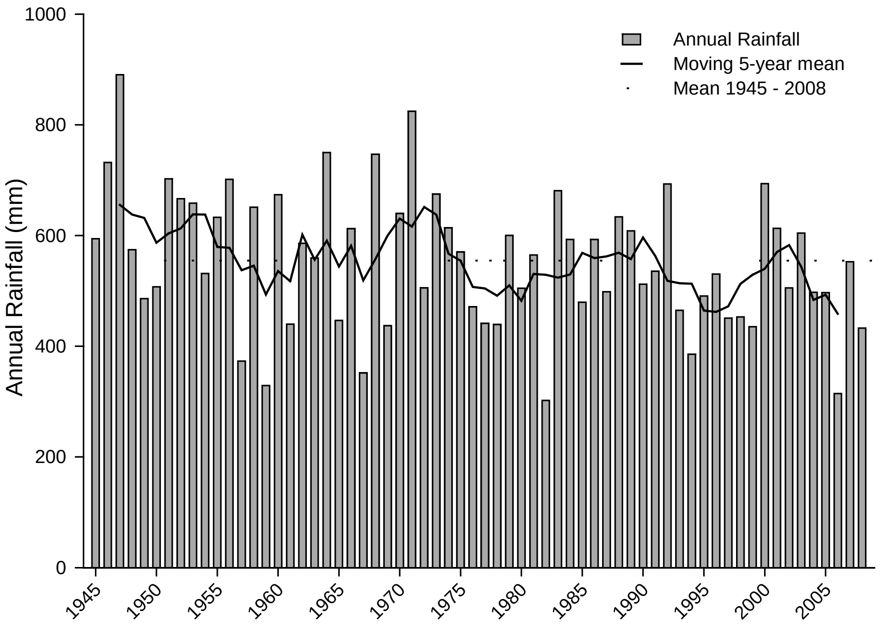

Fig. 2.2 Annual rainfall (mm) at Keilira Station for the years 1945 – 2008, showing a marked decline in rainfall in recent years. The five year moving average indicates a steep decline since 2002, falling from the long-term mean of 555 mm (1945 – 2008) to 458 mm (2004 – 2008).

Interestingly, the extension of the drainage networks in the USE coincides with a decline in rainfall since 1990. The 5-year moving average for this region prior to 1990 indicates that rainfall patterns move in peaks and troughs, generally 100 mm above and 50 mm below the long-term mean of 555 mm. Since 1990 however, the peaks in the rainfall pattern barely exceed 45 mm above the long-term mean, whereas the troughs fall to below 465 mm for the years 1994 – 1998 and 2004 – 2008.

2.3 METHODS

Three study sites, named South, Central and North, were selected for investigation, spanning a distance of 30 km (Fig. 2.1). Each of the sites had a different drainage history, including one site (North) that was not artificially drained and yet displayed patches of poor plant growth similar to those seen at the drained South and Central sites.

2.3.1 Historic Groundwater Trends

In order to relate changes in soil chemical characteristics to changes in soil hydrology, monitoring data were obtained for two Department of Water, Land & Biodiversity Conservation observation wells located near each of the three study sites (Table 2.1). Historical monitoring has recorded standing water level data across the region, measured as the distance in metres from the ground surface to the water surface in the well hole. Data for this region indicate that maximum standing water levels (SWL) in the unconfined aquifer occur in spring, whereas minimum SWL are generally observed in autumn (Department of Water Land and Biodiversity Conservation 2009). Observation wells in this region are now monitored four times annually, usually in the months of March, June, September and December. While it is acknowledged that maximum and minimum groundwater levels may exceed those recorded in these months, the data collected in September and March are presented here as the maximum and minimum SWL to indicate the seasonal trends in groundwater.

Table 2.1 Location of study trenches and observation wells analysed in the study.

Site	Site Location	Groundwater Observation Wells	Well Location	Ground Elevation mAHD
South	36.81°S 140.15°E	MNC030	36.80°S 140.19°E	19.60
		MNC032	36.80°S 140.16°E	18.64
Central	36.73°S 140.11°E	MNC001	36.71°S 140.14°E	19.61
		MNC045	36.73°S 140.11°E	18.73
North	36.62°S 140.07°E	PEC004	36.63°S 140.11°E	19.68
		LAN011	36.60°S 140.08°E	18.70

2.3.2 Trench Location and Sampling

In March 2005 the land owner of each site identified the location for a trench approximately 3 m long to be excavated on their property, crossing perceived areas of ‘good soil’ and ‘poor soil’ based on their impressions of plant growth. Owing to the seasonal conditions, plant growth was negligible, therefore residual stubble cover, surface topography and soil physical characteristics were also considered in the determination of ‘good’ and ‘poor’ soil. Two profiles were sampled at each site, one from the ‘good’ and one from the ‘poor’ areas, and are labelled accordingly. Photographs of the profiles can be seen in Appendix 2. Samples were collected at regular intervals down each soil profile to a depth of between 0.7 and 0.9 m.

2.3.3 Soil Chemical Analyses

Samples were air dried and a representative portion was ground and passed through a 2 mm diameter sieve. On the fine earth fraction $pH_{(H_2O)}$, EC (as $EC_{1:5}$) and spontaneous dispersion were determined using a 1:5 soil:water suspension (Kelly and Rengasamy 2006). The soil salinity criteria of Shaw (1999) were used to assign salinity ratings for $EC_{1:5}$ data collected from soils with varying clay content. The sodicity guidelines for Australian soils identified by Northcote and Skene (1972) were used to assign sodicity ratings, and soil pH was classified according to the guidelines presented by Slattery *et al.* (1999). Once agitated, the suspensions were allowed to settle for 4 hours to determine the degree of mechanical dispersion (potential dispersion).

Total carbon content of the soil was determined by combustion in a Leco furnace and the organic carbon content was determined by Heanes wet oxidation following the method for saline soils (>0.5 % Cl) outlined in Rayment and Higginson (1992). Total carbonate content (as $CaCO_3$) was determined following the modified pressure-calcimeter method (Sherrod *et al.* 2002) using 2 grams of soil, 8ml of 3M HCl containing 3% by weight of

$FeCl_2$, and a pressure transducer monitored by a digital voltmeter. The voltage was correlated to a set of standard samples with varying $CaCO_3$ contents.

Due to the highly calcareous, alkaline and saline nature of these soils, the CEC and exchangeable cation concentration of the samples were determined following the Rayment and Higginson (1992) method for soils with $EC_{1:5} > 0.3$ dSm^{-1} and $pH_{H_20} > 7.4$. Following the removal of soluble salts, exchangeable basic cations were extracted using 1 M ammonium chloride at pH 8.5 (Rayment and Higginson 1992). The Ca, Mg, Na and K concentrations of the samples were determined by GBC-906 flame atomic absorption spectrophotometry. The CEC of the soils were determined by measurement of NH_4^+ and Cl^- in an auto-analyser. Exchangeable sodium percentage was calculated by the relationship ESP = (Na/CEC) x 100.

Particle size distribution was determined using a method adapted from Gee and Bauder (1986). The carbonate component of the soil was first removed using 1 M sodium acetate adjusted to pH 5 with acetic acid at a ratio of 1:2 soil:solution. Suspensions were mixed in a 250ml centrifuge bottle, allowed to stand in a 60°C water bath overnight, cooled, centrifuged and the supernatant decanted. The process was repeated until effervescence ceased. Organic matter was removed by adding sodium hypochlorite 12.5 w/v (adjusted to pH 8 with HCl) to the soil in the ratio of 1:4 soil:solution and allowed to stand in a fume cupboard for 16 hours (Mikhail and Briner 1978). Samples were centrifuged and repeatedly washed with distilled water until the EC of the suspension was <1 dSm^{-1}. Soils were dispersed using sodium hexametaphosphate (Calgon) and the proportions of sand, silt and clay determined by the sedimentation method of Gee and Bauder (1986).

Removal of the clay fraction was assisted by the addition of 1 M $CaCl_2$, following which all samples were centrifuged and washed with RO H_20 before being washed twice with ethanol and air dried.

For mineralogical analysis, a 0.04 g sample of the isolated calcium-saturated clay fraction (<2 µm) was dispersed in deionised water using an ultrasonic probe. The clay was oriented onto a porous ceramic membrane using a vacuum pump, solvated with 3 drops of glycerol and allowed to drain. X-ray diffraction (XRD) patterns were collected with a PANalytical X'Pert Pro Multi Purpose Diffractometer. A cobalt XRD tube operating at 40kV and 45mA with a flat graphite monochromator and programmable divergence slit was used to determine the mineralogical composition, aided by the Xplot program (Mark Raven, CSIRO, pers. comm. 2009).

2.4 RESULTS

2.4.1 South Study Site

The South site, on the property Shepherds Hill, is located within 3 km of the Blackford Drain, which was dug in 1956. The Jacky Whites Drain and a series of private shallow feeder drains (<2 m deep) intersect the Shepherds Hill property; these drains were gradually expanded in the years 1962, 1975, 1979, 1983, 1993 and 1997. Data from two observation wells, MNC030 and MNC032, were studied to determine the effects of artificial drainage on SWL at this site.

The study trench here was excavated across an area of thick stubble cover at the 'good' end and an area in a slight topographical low with only fair stubble cover at the 'poor' end. Samples were collected at different depths down each profile (Table 2.2) in relationship to their variable morphological properties.

2.4.1.1 Groundwater Trends

Observation well MNC030 (Fig. 2.3*a*) is located on the eastern side of the Avenue Plain, within 50 m of the East Avenue Range. Since 1992, autumn minima and spring maxima show seasonal and annual variability and do not appear to be affected by the artificial drainage schemes. The elevated spring SWL in 1992 can be attributed to a higher than average annual rainfall in this year of 693 mm (Fig. 2.2). The rise in 1998 is unexplained.

Observation well MNC032 (Fig. 2.3*b*), on the other hand, is located closer to the soil exploratory trench at the South site than MNC030 (Fig. 2.1). The mean SWL at this site, 0.95 m, is considerably closer to the surface of the soil than that of the MNC030 (mean 1.79 m). Some of this difference can be attributed to the difference in ground elevation of 0.96 metres Australian Height Datum (mAHD) (Table 2.1).

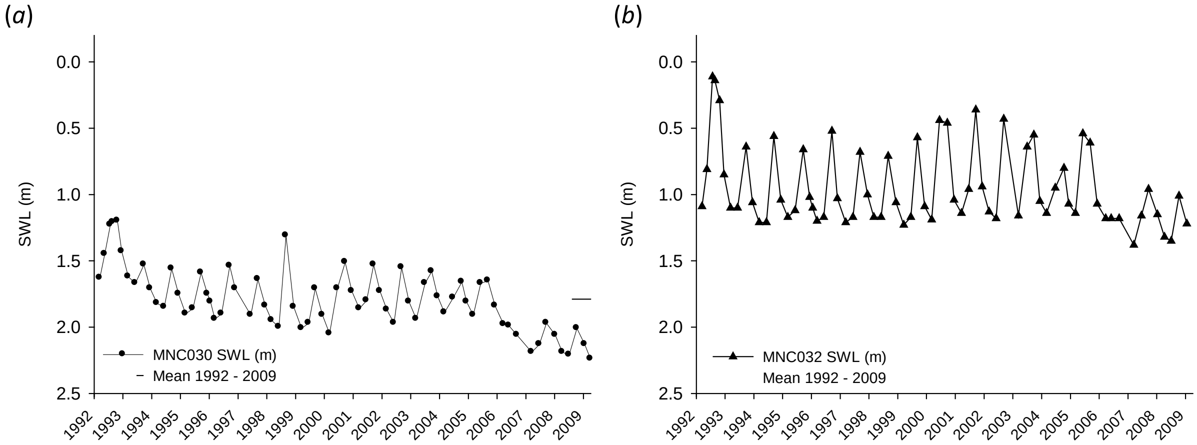

Fig. 2.3 Groundwater monitoring data for the years 1992 - 2009 for (*a*) Observation well MNC030 showing seasonal and annual flux and (*b*) Observation well MNC032, with variable trends in spring SWL and consistent minima recorded in autumn, indicating that the area close to the South study soil site is affected by the drawdown of artificial drains.

The relatively uniform minimum SWL observed at MNC032 over the period 1992 – 2005 is evidence that the local Jacky Whites Drain and deeper Blackford Drain have consistently lowered water tables in this area. September (spring) SWL range between 0.14 and 0.8 m, with a mean SWL of 0.55 m, exhibiting annual variation, whereas March (autumn) levels have a mean SWL of 1.16 m and much less variability (range 1.09 - 1.23 m).

During 2006 – 2008 the decline in both spring and autumn SWL at MNC030 and MNC032 can be attributed to the decline in annual rainfall from the long-term average of 555 mm to 450 mm for this time period, (Fig. 2.1) but the reduction at MNC030 is more pronounced.

2.4.1.2 Soil Chemistry

As seen in Table 2.2, pH, EC and ESP throughout the 'good' end of this trench steadily increase down the soil profile, becoming very strongly alkaline, very highly saline and strongly sodic at depth. The surface 0 – 0.1 m, however, exhibits chemical conditions conducive to better plant growth as it is non-sodic, with mild alkalinity and moderate salinity. In comparison, the 'poor' soil at this site exhibits better chemical conditions for plant growth, except for a higher concentration of salt in the surface 0 – 0.1 m ($EC_{1:5}$ of 0.52 dSm^{-1}), high enough to affect salt tolerant crop species (Shaw 1999). Below 0.1 m, the soil becomes moderately to very strongly alkaline, moderately saline and marginally sodic to a depth of 0.5 m.

A major difference between the two soils at this site is the depth to the carbonate rich horizon. At the 'good' end, carbonate content increases from <10 % to >70 % at 0.30 –

0.65 m (coinciding with high pH), where a fragmented and strongly cemented carbonate occurs. In contrast, at the ‘poor’ end, the soil contains <10 % carbonate to a depth of 0.4 m, only exceeding 50 % carbonate beyond 0.5 m.

Table 2.2 Chemistry of soils at the South site

Depth (m)	$pH_{1:5}$ (H_2O)	$EC_{1:5}$ (dSm^{-1})	Organic C (%)	Carbonate ($CaCO_3$ %)	Sand (%) (CO_3 free)	Clay (%)	CEC cmol (+) /kg	ESP (%)	Spontaneous Dispersion
				South - Good					
0 – 0.1	7.5	0.25	2.1	0.3	47.2	30.3	18	4.5	Low
0.1 – 0.2	9.0	0.31	1.0	0.6	24.7	65.3	32	11.8	Medium
0.2 – 0.3	9.5	0.43	0.9	7.4	14.0	80.6	36	24.4	Medium
0.3 – 0.65	10.1	0.44	0.1	74.4	37.6	48.6	9	36.5	High
0.65 – 0.9	9.4	0.82	0.2	14.1	63.9	10.2	21	25.7	Low
				South - Poor					
0 – 0.1	7.3	0.52	3.9	0.6	26.6	36.1	27	2.1	Low
0.1 – 0.2	8.1	0.14	1.6	0.4	62.5	8.0	26	3.1	None
0.2 – 0.3	9.1	0.11	0.8	1.0	83.2	3.9	33	5.9	None
0.3 – 0.4	9.2	0.31	0.6	8.6	63.8	15.2	41	8.8	Medium
0.4 – 0.5	9.4	0.32	0.2	27.8	10.2	82.7	37	11.1	Medium
0.5 – 0.8	9.6	0.39	0.4	57.5	14.6	66.9	18	16.8	Medium

The high proportion of sand sized particles (>60 %) and low clay content (<10 %) in the 0.1 - 0.3 m zone in the ‘poor’ profile are at odds with the high CEC observed here. The removal of cementing carbonates was difficult in these samples, which could possibly have led to the incomplete release of the clay fraction. The $CaCO_3$ content at this depth, however, was <1 %, so the high CEC coupled with a low clay content is therefore attributed to either the clay mineralogy or to insufficient dispersion of the clay fraction.

2.4.2 Central Study Site

The Central study site is situated on the property Lyndal Park, and lies approximately 3.8 km to the north east of the Blackford Drain. A series of shallow feeder drains were excavated across this farm in 1975 and 1987, before the 3m deep Fairview Drain intersected this property in 1997/98. Drainage on this farm was further aided when a private deep drain was dug in 2000 that also fed into the Fairview Drain.

2.4.2.1 Groundwater Trends

(a) Prior to construction of major drain

Standing water levels recorded from two observation wells in this area (MNCOO1 and MNC045, Fig. 2.4*a* and *b*) have varied substantially since the early 1970s, when March levels fell to below 1 m and September SWL were generally <0.15 m from the soil surface, indicating that the soils were saturated (Fig. 2.4*a*). The 1992 - 1997 March minima at MNC001 were similar to levels recorded from 1971-1975; however the spring maxima had fallen considerably, with saturation only occurring twice in this period (Fig. 2.4*a)*. This reduction was possibly caused by a significant increase in the number of both public and private artificial drains constructed extensively throughout South East SA since the 1950s, combined with a reduction in annual rainfall during this period (1993 – 1997) to a mean 465 mm from the long term average of 555 mm (Fig. 2.2).

(b) Following construction of major drain

A sharp drop in groundwater levels is also evident at MNC001 since the construction of the Fairview Drain in 1997 (Fig. 2.4*a*). The mean SWL for 1993 – 1997 is 0.82 m, with a dramatic reduction to a mean of 1.33 m below the soil surface in the recent time period (1998 – 2009). Since the construction of the Fairview Drain, spring maxima have rarely reached within 1 m of the soil surface, while autumn lows exceed 1.3 m. The extreme lows recorded in the years 2003, 2006 and 2007 were caused by pumping from the well for agricultural purposes (McKenzie G, Department of Water, Land and Biodiversity Conservation, pers. comm. 2008).

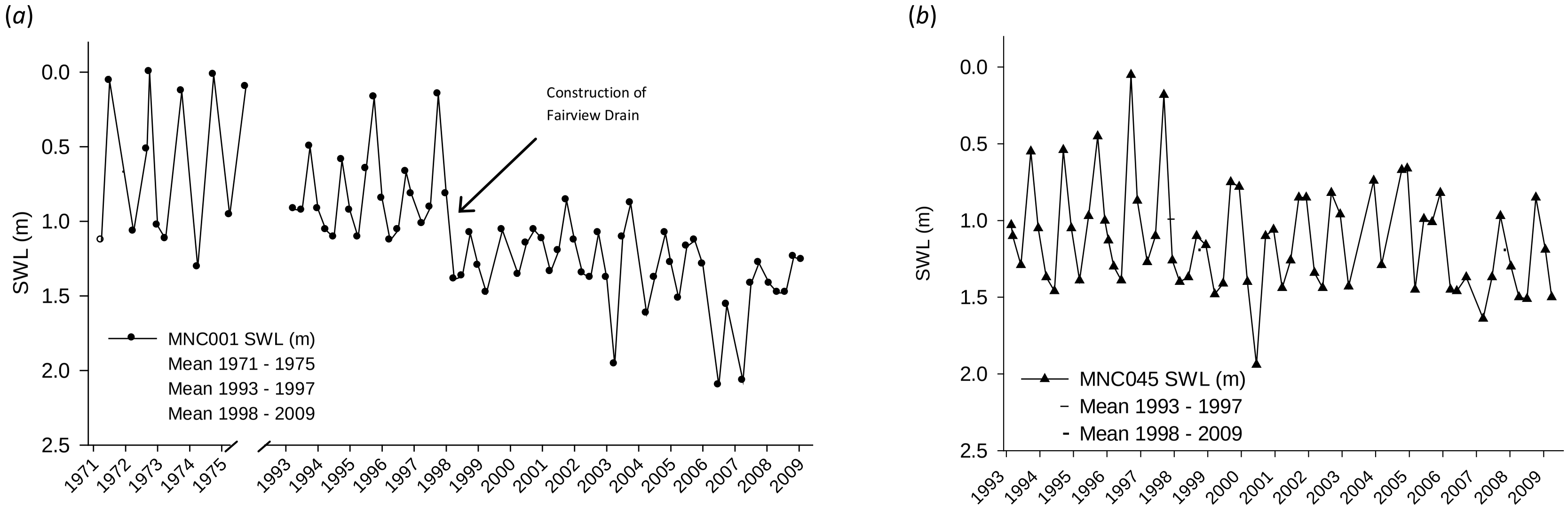

Fig. 2.4 (a) Groundwater monitoring data for the years 1971 – 1975, 1993 – 1997 & 1998 - 2009 for Observation well MNC001 showing the marked influence that the construction of the Fairview Drain had on SWL in 1997 and (b) 1993 – 2009 groundwater trends for Observation well MNC045, the consistent autumn minima indicating that SWL at this site are drawn down by both the Blackford and Fairview Drains.

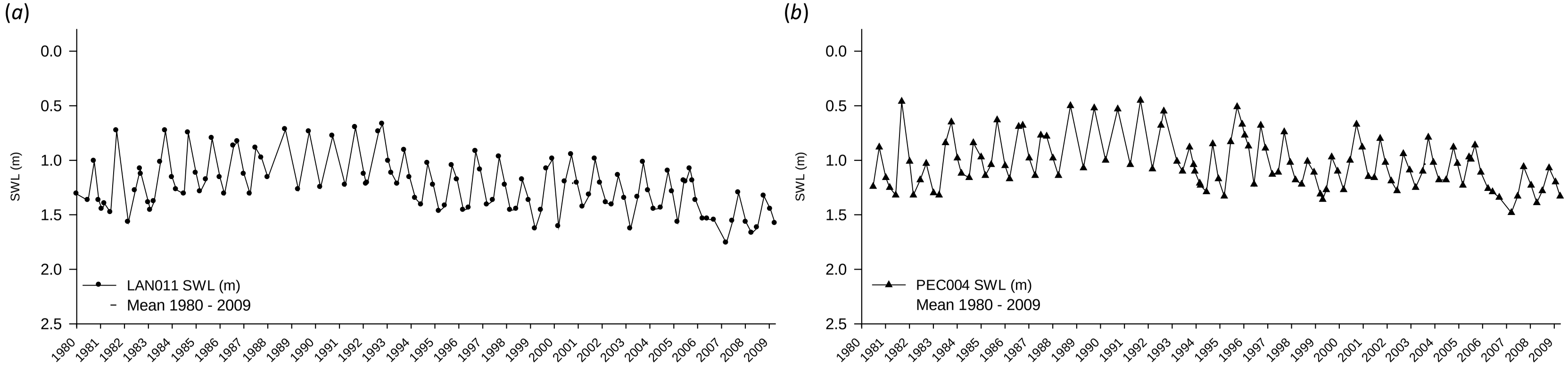

Fig. 2.5 Groundwater change over time near the North study soil trench, for the years 1980 - 2009 for (a) Observation well LAN011 and (b) Observation well PEC004, exhibiting seasonal and annual variation

In comparison, observation well MNC045 (Fig. 2.4*b*) is situated 200 m from the soil trench at the Central site and lies adjacent to the Fairview Drain. Autumn minima throughout the monitoring record are consistent for MNC045 prior to 1998 (in contrast to MNC001) and this is attributed to the drawdown of groundwater at this site by the nearby Blackford Drain. The effect of the construction of the Fairview Drain is also evident at this site after 1997, with spring maxima SWL falling from a mean 0.35 m pre-construction to a mean 0.93 m post-construction.

2.4.2.2 Soil Chemistry

The profile corresponding to good pasture growth at the Central site (Central 'good') had shallow soil (<0.3 m) overlying clay marl that was moderately to very strongly alkaline with depth, highly saline below 0.1 m (with a salt bulge in the profile at 0.3 m) and strongly sodic throughout (Table 2.3).

Table 2.3 Chemistry of soils at the Central site.

Depth (m)	pH$_{1:5}$ (H$_2$O)	EC$_{1:5}$ (dSm^{-1})	Organic C (%)	Carbonate (CaCO$_3$ %)	Sand (%) (CO$_3$ free)	Clay (%)	CEC cmol (+) /kg	ESP (%)	Spontaneous Dispersion
Central – Good									
0 – 0.1	7.8	0.33	1.9	0.4	61.1	23.5	14	16.1	Medium
0.1 – 0.2	9.5	0.62	0.8	0.6	40.4	51.8	25	44.0	High
0.2 – 0.3	10.1	0.92	0.8	8.5	23.7	70.8	28	52.3	High
0.3 – 0.55	10.1	0.53	0.5	49.4	28.2	33.5	17	52.7	Low
0.55 – 0.65	9.9	0.42	0.3	4.7	71.8	4.4	30	40.2	Medium
Central – Poor									
0 – 0.1	7.2	0.18	2.2	0.3	59.2	22.8	16	5.5	Low
0.1 – 0.2	8.3	0.10	0.9	0.3	51.7	31.9	15	12.8	High
0.2 – 0.3	8.9	0.17	0.8	0.8	33.1	58.6	27	22.8	High
0.3 – 0.6	9.9	0.40	0.8	35.6	40.4	28.4	23	39.6	Medium
0.6 – 0.9	9.9	0.51	0.0	41.4	36.1	28.1	23	40.0	High

The structure of the surface soil was less massive and exhibited less surface pugging than the adjacent 'poor' soil; the EC was sufficiently high enough to affect salt sensitive plant species (Shaw 1999).

The ‘poor’ soil exhibited better chemical conditions for plant growth in the surface 0.3 m than the ‘good’ profile, with low salinity, moderate sodicity and a mild to moderate alkalinity throughout the profile. The carbonate horizon in this profile was composed of a fractured limestone pan with pockets of rubble and friable clay. The particle size distribution of the 0.55 – 0.65 m horizon in the Central ‘good’ soil is at variance with the CEC and clay content, possibly the result of insufficient dispersion of the clay fraction.

2.4.3 North Study Site

The North study site lies 12 km north of the Central site, on the property Cherita. It currently (2009) has no artificial drainage but has been surveyed for the construction of the Baldhills Drain. The soil trench at the North site was excavated to a depth of 0.7 m, where a hard calcrete pan was intercepted.

2.4.3.1 Groundwater Trends

Observation wells LAN011 and PEC004, located on the eastern edge of the Avenue Plain, are approximately 2.8 km north-east and 3.1 km south-east respectively from the trench at the North site. Given the distance of these wells from the trench and their location on the eastern side of the Avenue Plain (where elevations are higher than the western side), it is expected that SWL at the study site would be closer to the soil surface. However, there are no observation wells with a long term monitoring record located on the central/western side of the plain; hence these two wells were selected for investigation.

LAN011 (Fig. 2.5*a*) and PEC004 (Fig. 2.5*b*) both exhibit seasonal and annual variability, indicating that this area is not affected by other regional drainage systems. Both wells also show a decline in mean SWL since 1992. For the period 1980 – 1992, the mean spring SWL for LAN011 was 0.81 m (range 0.67 – 1.13 m), falling to a mean 1.1 m (with a range of 0.91 – 1.55 m) for the years 1993 – 2008, while autumn SWL fell from a mean 1.29 m to 1.5 m during the same period. While the variability is not as great as for LAN011, SWL at PEC004 fell from a spring mean of 0.64 m to 0.88 m and an autumn mean of 1.15m to 1.22 m for the time periods 1980 – 1992 and 1993 – 2008 respectively, confirming that SWL are highly responsive to rainfall patterns.

At both wells, the most significant reduction in SWL occurred during 2006 – 2008, when the spring maxima SWL failed to exceed the long term annual mean. At LAN011, mean annual SWL fell to 1.54 m, a reduction of 0.23 m from the longer term average (1980-2005) of 1.19 m. At PEC004, mean annual SWL fell from 1.02 m to 1.27 m during the same period. This reduction in both spring maxima and the annual mean SWL in the period 2006-2008 again coincides with the reduction in annual rainfall for this period.

2.4.3.2 Soil Chemistry

In contrast to the Central and South sites, both ends of this trench were very strongly alkaline, extremely saline ($EC_{1:5}$ >1 dSm^{-1} in most cases) and strongly sodic (ESP >40 %); these characteristics were coupled with spontaneously dispersive clay throughout the profile (Table 2.4). Organic carbon is also notably higher in these soils than in those from the Central and South sites.

Despite the soils being strongly sodic, they were very well aggregated in the field, a characteristic that is probably at least partly due to the elevated EC and the high OC content at this site. In dispersion tests, the soil was easily dispersed, but once the soils were agitated (in order to determine mechanical dispersion) salts were dissolved and clays quickly flocculated.

Table 2.4 Chemistry of soils at the North site.

Depth (m)	$pH_{1:5}$ (H_2O)	$EC_{1:5}$ (dSm^{-1})	Organic C (%)	Carbonate ($CaCO_3$ %)	Sand (%)	Clay (%)	CEC cmol (+) /kg	ESP (%)	Spontaneous Dispersion
					(CO_3 free)				
North - Good									
0 – 0.1	9.9	0.73	2.7	11.5	47.9	13.4	29	45.6	Medium
0.1 – 0.2	9.9	1.07	2.4	22.7	45.6	19.2	28	48.2	Medium
0.2 – 0.3	10.0	1.39	1.0	45.8	20.5	48.0	24	57.4	High
0.3 – 0.45	9.8	1.48	0.8	37.7	19.5	63.5	23	50.7	Medium
0.45 – 0.7	9.6	1.35	0.2	54.3	44.7	19.8	19	40.1	Medium
North - Poor									
0 – 0.1	9.0	5.65	2.6	13.7	71.0	6.1	32	67.3	Medium
0.1 – 0.2	9.5	1.61	1.9	16.6	66.9	12.9	33	47.4	High
0.2 – 0.3	9.4	1.91	1.0	19.9	33.0	31.4	31	43.9	High
0.3 – 0.6	9.4	1.73	0.4	59.9	48.5	20.3	16	50.0	High

2.4.4 Clay Mineralogy of the Soils

Investigations of clay mineralogy indicate that there are two distinctive soil types present at the three sites: one rich in smectite and one rich in illite and kaolinite (Fig. 2.6). The smectite-rich soils are the South 'poor', North 'good' and North 'poor' profiles (Figs. 2.6*b*, 2.6*e* and 2.6*f*), and the soils rich in illite and kaolinite are South 'good', Central 'good' and Central 'poor' (Figs. 2.6*a*, 2.6*c* and 2.6*d*). The asymmetry of at least some of the XRD peaks for illite and smectite in the illite/kaolinite-rich soils indicate the occurrence of smectite/illite interstratification. Sepiolite, a clay mineral rarely found in soil (Singer 2002), was present in the South 'good' and Central 'poor' profiles, and in both profiles at the North site. Quartz was present in the patterns of the upper horizons, particularly those found at the South and Central sites.

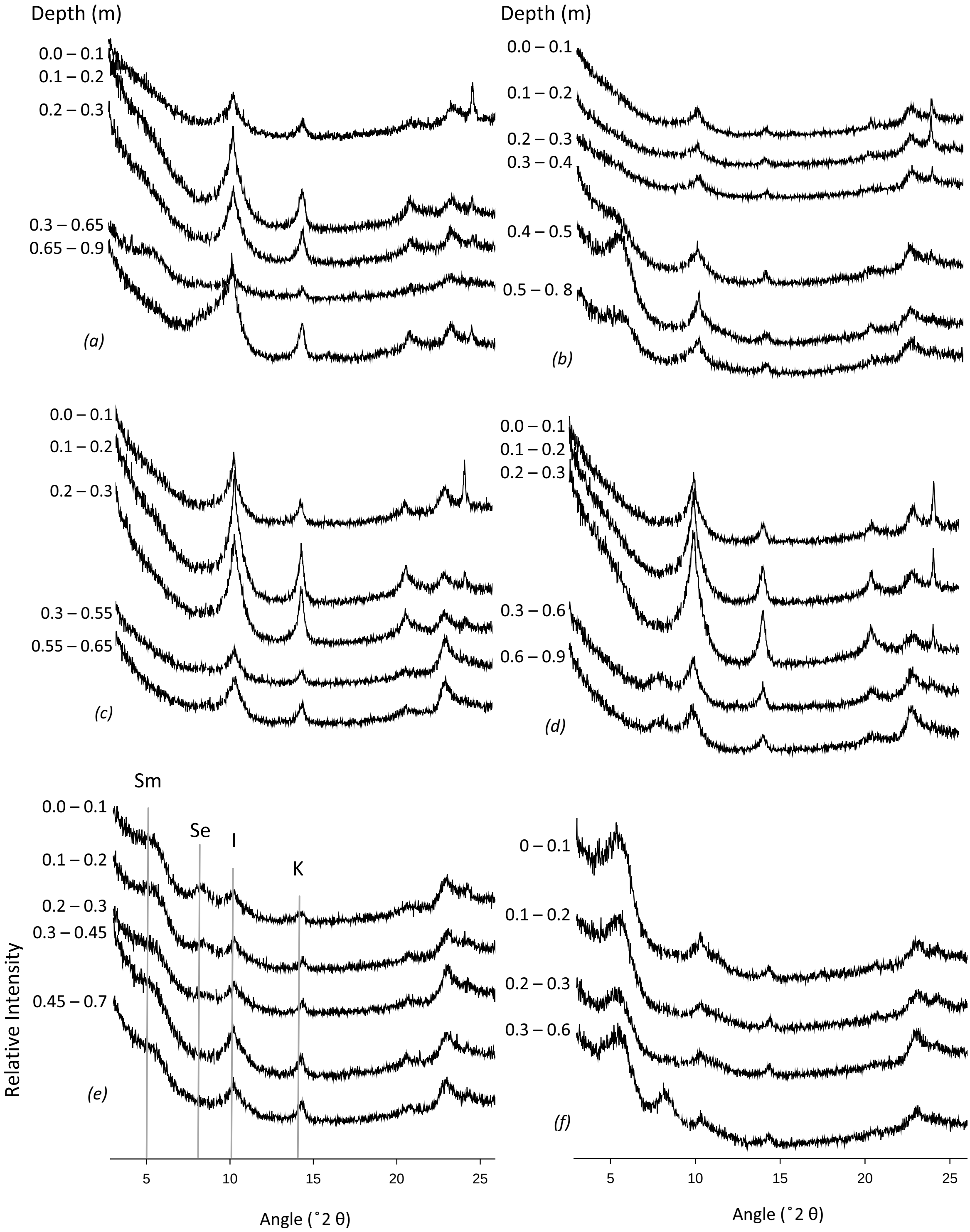

Fig. 2.6 XRD peaks of the clay fraction of the soil from the South good (*a*) South poor (*b*) Central good (*c*) Central poor (*d*) North good (*e*) and North poor (*f*) study sites. Peaks for the clay minerals smectite (Sm), sepiolite (Se), illite (I) and kaolinite (K) are also highlighted.

CEC data collected for the samples also support the observation of two distinct soil types. The surface 0 – 0.1 m of the illite/kaolinite-rich soils have a CEC <20 $\text{cmol}_{(+)}$/kg, increasing with depth. These soils are also shallow, with moderately to strongly indurated carbonate horizons occurring from 0.3m in the South ‘good’ and Central ‘poor’ soils. In contrast, the surface 0 – 0.1 m of the smectite-rich soils have a CEC > 27 $\text{cmol}_{(+)}$/kg, and indurated carbonate horizons that are only intercepted below 0.6 m. A related trend is also seen with organic carbon, with the higher CEC soils recording OC contents of 3.9, 2.7 and 2.6 % in comparison to the lower CEC soils with OC of 2.1, 1.9 and 2.2%.

The higher OC content recorded in the high CEC soils can be attributed to the texture and clay mineralogy of the surface soils. The combination of high OC content, the presence of smectites and possible inter-stratification may have led to the development of high CEC soils despite some horizons having relatively low clay contents, as seen in the South ‘poor’ and Central ‘good’ profiles.

2.5 DISCUSSION

The primary aim of this Chapter is to determine the likely effects that artificial drainage has had on soil physicochemical properties in the Keilira District in the Upper South East of South Australia, and to determine whether the observed plant decline in this region is caused directly by the drainage schemes. Annual rainfall and the implementation of artificial drainage have been considered when analysing the flux in SWL across the region, and the current condition of soils with differing drainage histories has been assessed.

2.5.1 Rainfall, artificial drainage and groundwater trends

Significant changes in rainfall intensity are evident in this region since the 1940s. In the years 1990 - 2008, annual rainfall only exceeds the long term mean (555 mm) four times, and in 2006 the moving 5 year average fell to the lowest levels on record (Fig. 2.1). This reduction in rainfall is reflected in standing water levels recorded from wells intercepting the unconfined aquifer in this region. In the northern part of the Keilira District no artificial drainage has yet been employed, however, observation well monitoring data for PEC004 and LAN011 (Fig. 2.5*a* and *b*) indicate that a decline in SWL has occurred since 1993. At both wells, the most significant reduction in SWL occurred during 2006 – 2008, with a reduction in both spring maxima and autumn minima. This reduction coincides with the decline in annual rainfall for these years (Fig. 2.2) and is a trend observed also for MNC001, MNC030 and MNC032 (Fig. 2.3*a*, 2.3*b*, 2.4*a*). At MNC045 (Fig. 2.4*b*) the same trend is not observed, a result that was possibly caused by the local land manager operating the weir in the Fairview Drain and thus manipulating SWL.

Whereas the wells show seasonal variation and a strong correlation to rainfall, the data also show that SWL have been altered by the implementation of artificial drainage. The consistent minimum SWL observed at MNC032 and MNC045 for the years 1993 – 2005 indicate that the Jacky Whites and Blackford Drains have effectively lowered groundwater in the vicinity of the South and Central study sites. In addition, the significant decline in SWL in 1998 seen at MNC001 coincides with the construction of the 3 m deep Fairview Drain in 1997/98. This observation well lies approximately 400 m north of the Fairview Drain on the Avenue Plain, and reductions in both autumn minima and spring maxima occur after 1997. These data suggest that the area of land between the Blackford Drain and observation wells MNC030 and MNC045 has been subject to a lowering of groundwater levels, and potentially of leaching, for over 50 years. Both the South and Central study sites are located within this zone. In addition, the land between the

Fairview Drain and MNC001 has been subject to improved drainage and leaching since the drain's construction in 1997. From these data it can be concluded that SWL are highly responsive to the implementation of artificial drainage and also to annual rainfall. It is therefore likely that the lowering of SWL in this region, both through a reduction in rainfall and through artificial drainage, facilitates the leaching of salts from these soils.

2.5.2 Interpretation of soil properties

All soils investigated in the current study are very strongly alkaline, highly saline and strongly sodic at some point in their profile. The combination of these factors creates hostile conditions for plant growth. Nonetheless, the soils from the South, Central and North sites together exhibit wide variability in their chemical and mineralogical properties.

Mineralogical investigations of the soils confirm that there are two distinct soil types present, which supports Blackburn's observations of 1952. Given these mineralogical similarities, the soils have been grouped into two classes, smectite-rich soils and illite/kaolinite-rich soils, and compared to Blackburn's historical data. The following sections discuss the data for each soil class, considering their historic and current chemical properties, drainage histories and observations of plant growth.

2.5.2.1 Smectite-rich Soils

When the chemical properties of the smectite-rich soils (South 'poor', North 'good' and North 'poor') are compared across sites, it is evident that the soil at the South site has the lowest pH, EC and ESP (Fig. 2.7*a*, 2.7*c* and 2.7*d)*. As previously discussed, the analysis of groundwater levels at the South site (Fig. 2.3*b*) indicate that the Blackford and Jacky Whites Drains have effectively lowered SWL to a consistent depth of approximately 1.2 m in autumn. The data presented in Figure 2.7 suggest that this lowering of SWL facilitates the leaching of salts. Hence soil pH and EC at the South site have been lowered in comparison to those of the undrained soils at the North site. The landowner at the South site has also applied gypsum (England R, pers. comm. June 2006) which, when combined with leaching, this may have contributed to the significantly lower ESP observed here (Fig. 7*d*).

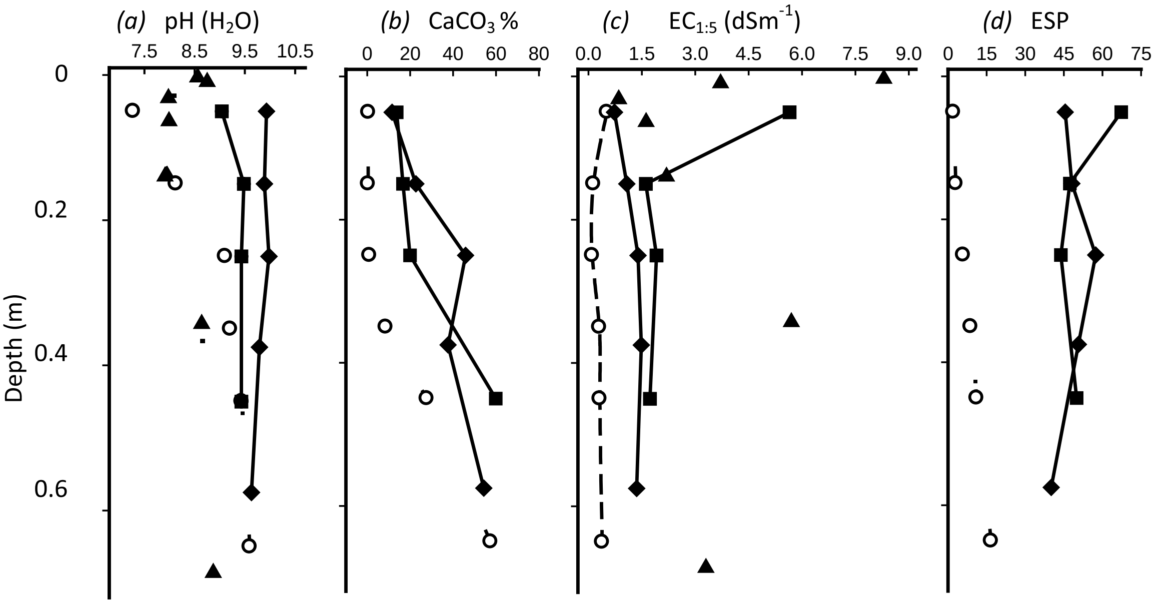

Fig. 2.7 Properties of smectite rich soils at the drained site, South 'poor' (○) and the undrained North 'good' (◆) and North 'poor' (■) sites, compared to the pH and EC measured for soil association J (▲) by Blackburn in 1950 prior to artificial drainage throughout this area. Open symbols are used here to represent drained sites, closed symbols for non-drained sites.

In comparison, soils at the North site clearly have the highest pH, EC and ESP (Fig. 2.7*a*, 2.7*c* and 2.7*d)* of the smectitic soils. These characteristics can be attributed to poor internal drainage, brought about by the high clay content of the soil, the dominance of smectite minerals, the presence of a highly indurated carbonate cap at 0.6 - 0.7 m and the absence of artificial drainage throughout this area.

However, the pH and EC data collected here are not the highest reported in an historical context. The observed chemical and physical properties of the smectite-rich soils closely align to the characteristics outlined for Blackburn's Soil Association J. The samples collected in Blackburn's study were retrieved from the CSIRO archives in Canberra and analysed following current methods using a 1:5 soil:water suspension, ensuring the valid comparison of recent and historic data. A representative profile for Soil Association J is profile number 18 (Clarke 1955), which exhibited extreme salinity throughout much of the profile (Fig. 2.7*c*). The variability in EC in this profile from 8.3 dSm^{-1} at the surface to 0.85 dSm^{-1} at 0.03 m increasing to 5.7 dSm^{-1} at 0.35 m, is attributed to a remarkable variability of thin soil horizons in the profile with differing texture. At the surface a light grey/brown fine sandy loam (5 % clay) was present, with an acid-effervescent surface crust, underlain by light grey fine sand (0.25 % clay). The clay content then increases steadily down the profile, reaching a maximum of 46 % at 0.35 m, with lower EC at 0.7 m as $CaCO_3$ content increases to >40 %. The presence of thin soil horizons with distinct textural contrasts were not found in the current study, the upper horizons appear to be more homogenous, possibly brought about by mechanical cultivation and livestock traffic.

At the North site it is possible that salt loads have been reduced since the 1950s because of the reduction in rainfall and the natural lowering of groundwater levels. The analysis of the wells PEC004 and LAN011 (Fig. 2.5*a* and 2.5*b*) showed that mean annual SWL have fallen since 1992 in the vicinity of the North study site, coinciding with the reduction in annual rainfall. It must be noted, however, that Blackburn did not sample soils in close vicinity to the North study site, so this particular inference is not supported by data.

Another possible explanation for the lowering of soil salinity throughout the northern area since the 1950s is the construction in 1956 of the Blackford Drain, which, for the first time, allowed discharge of drain water to the ocean and the export of salt from this region. Prior to the construction of this drain, drainage policies from 1900 – 1950 were to channel surface waters to the northwest, significantly increasing water flows, and potentially also salt loads in the USE (South East Catchment Water Management Board 2003).

At the time of Blackburn's study it was observed that plant species varied substantially between the soil associations. He noted that a combination of halophytic species often colonised the clay-rich saline areas; scattered samphire in a growth of thatching grass and broombush generally indicated higher soil salinity. As much of the landscape has been cleared of native vegetation, cultivated for agricultural purposes and sown down to pasture, current land managers in this region have few natural/native indicators to show the vastly different soil types present on their farms. This has been brought about as the native vegetation and undulation once associated with the saline clay-rich soils (soil association J) no longer segregates the two distinct soil types. Since the implementation of drainage and the subsequent lowering of soil salinity at the South site, the land manager has moved away from growing salt tolerant pasture species, cultivating a mixed lucerne, medic and chicory pasture (Robert England, pers. comm. June 2006). In contrast, salt-tolerant pasture species still predominate at the North site, leading to the observed thick stubble cover and prolific root growth seen here, despite the extreme salt loads in the soils. The areas of poor plant growth at the South 'poor' site and also at the North 'poor' site can therefore be attributed to the high concentration of salt at the surface (Table 2.2 and 2.4), potentially brought about by the evaporation of subsoil moisture during the summer months from the clay rich soil found here.

2.5.2.2 Illite-Kaolinite- rich soils

The observed properties of the soil profiles South 'good', Central 'good' and Central 'poor' correlate to Blackburn's Soil Association R and are rich in the clay minerals illite and kaolinite. When we compare the current soil properties of this soil type to Blackburn's historic data (profile 14), we also see that the pH and EC of these soils are generally lower than those observed in 1952 (Fig. 2.8*a*, 2.8*c*). This phenomenon is attributed to the implementation of artificial drainage in this region, falling SWL and the subsequent leaching of salts from the soils at the South and Central study sites.

The Central 'poor' and South 'good' profiles exhibit similar trends in pH, EC and ESP throughout (Fig. 2.8*a*, 2.8*c* and 2.8*d*), and the levels are lower than the pH, EC and ESP reported for the Central 'good' profile. Since the construction of the Jacky Whites, Blackford and Fairview Drains, maximum SWL at the South and Central sites rarely reach within 0.5 m of the soil surface (Figure 2.3b, 2.4*a* and 2.4*b*), well below the indurated carbonate cap that separates the upper and lower soil horizons in the South 'good' and Central 'poor' profiles. This calcrete is not conducive to capillary rise due to its extremely low porosity, and it is likely that salts are no longer mobilised into the root zone of pastures through upward movement of saline groundwater. In contrast, the 0.3 – 0.55 m horizon in the Central 'good' profile contains marl, with a higher clay % and CEC (Table 2.3), and is therefore more conducive to water movement up and down the profile. This may explain the higher pH, EC and ESP that are observed here. Therefore, the soils with shallow indurated carbonate-rich horizons and low SWL are more prone to leaching and hence exhibit better chemical conditions for plant growth, as seen here in the South 'good' and Central 'poor' profiles.

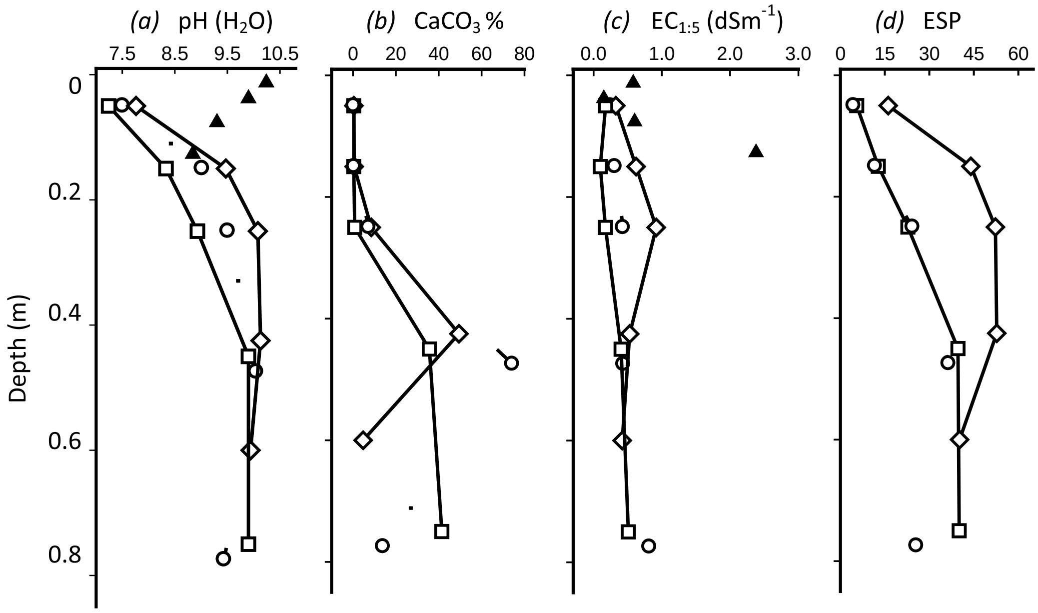

Fig. 2.8 Properties of illite/kaolinite-rich soils at the drained sites of South 'good' (○), Central 'good' (◇) and Central 'poor' (□) sites, compared to the pH and EC measured of soil association R (▲) by Blackburn in 1950 prior to artificial drainage throughout this area.

However, the nature of the clay minerals present in these soils, predominately illite and kaolinite, combined with a low to moderate salinity and high ESP in the 0.1 - 0.3 m zone results in these soils being unstable when wet (Churchman *et al.* 1993), causing them to degrade physically. Field observations during trench excavation showed that livestock movement and machinery operations caused significant structural decline when these soils were saturated. Once dispersed, soil density and strength increase as the soil dries to an extent that it is not easily penetrated by plant roots. Subsequent water infiltration is compromised in these dispersive soils, compounding the hostile conditions for plant growth. Unlike the smectite-dominant soils, these soils lack the ability to shrink and swell and hence to regenerate structure once dispersion has occurred. The combination of these factors has led to a compacted surface underlain by a massive columnar structure in the Central 'poor' profile and is responsible for the observed poor plant growth at this site, despite it having lower EC and ESP than the 'good' end. However, as the upward movement of saline groundwater is no longer a common occurrence, these soils should be easily ameliorated with gypsum application.

2.5.3 Observations of pH for all Soils

Soil pH values in all drained sites are lower than those observed by Blackburn, coinciding with a low $CaCO_3$ content of the upper 0.3 m of soil, whereas the soil pH values of the undrained North sites are higher (Fig. 2.7*a*). Drained sites have <10 % carbonate in comparison to the North site values of 11 – 45 %, implying that the leaching of sodium, chloride, and carbonate and bicarbonate ions is occurring, resulting in lower soil pH.

2.6 CONCLUSION

Groundwater levels in the Upper South East of South Australia are highly responsive to rainfall and also to the implementation of artificial drainage, and show a falling trend since the early 1990s, especially since the construction of the Fairview Drain in 1997. This reduction in groundwater has facilitated the leaching of salts, and the physicochemical condition of the soils has changed since Blackburn's investigations in 1952. Problem soils observed by landowners of the three study sites have been caused by the combination of high soil pH, high to extreme EC and extremely high ESP and have been affected by a reduction in groundwater levels; these soils commonly are smectitic in mineralogy. The combination of these factors has led to the development of soils that are both chemically hostile and structurally unstable. Nevertheless, the mineralogy of the soil governs the level of structural degradation when the soils are sodic, such that the illite/kaolinite-dominant soils are particularly degraded, resulting in the highly compacted form observed.

From this study it is further concluded that the observed decline in plant growth has multiple causes; it is not related solely to the extension of the artificial drainage network, as the local farmers had feared.

The most outstanding feature of these soils is the high variability of soil chemical, physical and mineralogical characteristics that were found to occur across very small spatial scales. An understanding of the factors that govern the development of such characteristics will contribute to the effective management of this region, especially when the further extension of artificial drainage networks is being considered.

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CHAPTER 3

COMBINING GEOPHYSICAL TOOLS, SOIL SURVEY AND SOIL CHEMISTRY TO INVESTIGATE THE CAUSE OF SPATIAL VARIABILITY OF SOILS IN THE UPPER SOUTH EAST OF SA

3.1 INTRODUCTION

The South East Region of South Australia (SA) is characterised geologically by a sequence of relic stranded beach dunes and inter-dunal plains that have formed over the past 800 Ka (Huntley *et al.* 1993). The inter-dunal plains are often affected by surface-water inundation and have historically been saline (Blackburn 1952). Engineering (artificial drains) and agronomic mitigation strategies have been employed by local land holders and regional Natural Resource Management Boards to ameliorate dryland salinity, and to interrupt the surface waters with the aim of lowering groundwater levels (South East Catchment Water Management Board 2003). Previous studies conducted by Blackburn (1952) on the soils in the Kingston-Avenue district showed that they were extremely saline and moderately to strongly alkaline. Despite the implementation of 50 years of artificial drainage throughout this region, a recent study found that some soils were still salt-affected (Chapter 2 of this thesis). Such soils often exhibit strongly sodic properties in addition to being strongly alkaline and extremely saline, and patches of declining pasture growth were also often observed. In both of the previous studies, however, the chemical and mineralogical characteristics of the soils were found to be highly variable, even across small distances, the cause of which had not been identified. Given the decline in plant growth observed and the current and proposed further extension of the drainage network in this region, a more thorough understanding of the scale and extent of such variability and the factors responsible for its development is required.

In order to gain such information, a strategic investigation of the soil and underlying geomorphology of the landscape is required; however, traditional soil surveying methods are often time consuming and costly, particularly in environments where indurated horizons are present. To reduce the resources needed and to aid such investigations, geophysical tools, such as Electromagnetic Induction (EMI) scanning and Ground Penetrating Radar (GPR), can be used as rapid, non-invasive methods for indirectly collecting soil information. EMI sensors respond to bulk soil conductivity, known as apparent conductivity (EC_a, typically recorded in dSm^{-1}) and can be used for mapping soil features that affect the electrical conductivity (EC) of subsurface layers, such as clay content, salt concentration and moisture content (James *et al.* 2003). GPR in contrast, transmits pulses of radio-frequency electromagnetic energy which propagate through the soil and are reflected at layers or objects with contrasting dielectric properties (Doolittle *et al.* 2006). The identification of soil physicochemical properties and subsurface structures, such as the boundaries between different materials, can therefore be inferred from GPR surveys. When EMI and GPR surveys are conducted and analysed in unison, they can provide an indicator of important soil properties and their spatial distribution within the landscape (Sudduth *et al.* 2001).

The aims of this study therefore were to: (i) conduct an EMI and GPR survey across a 4 hectare area in the Keilira District, (ii) analyse the constructed EC_a and GPR images in conjunction with preliminary soil results in order to identify the zone of greatest soil and geological variability, (iii) chemically characterise this variability, and (iv) determine the cause of the spatial variability of soil properties in this region.

3.2 METHODS

Various methods were used in this study to strategically investigate the soils. Initially, a geophysical survey was conducted across the selected study site and preliminary soil samples were collected. The concurrent interpretation of these data led to the location of a study trench where profiles were strategically sampled and analysed.

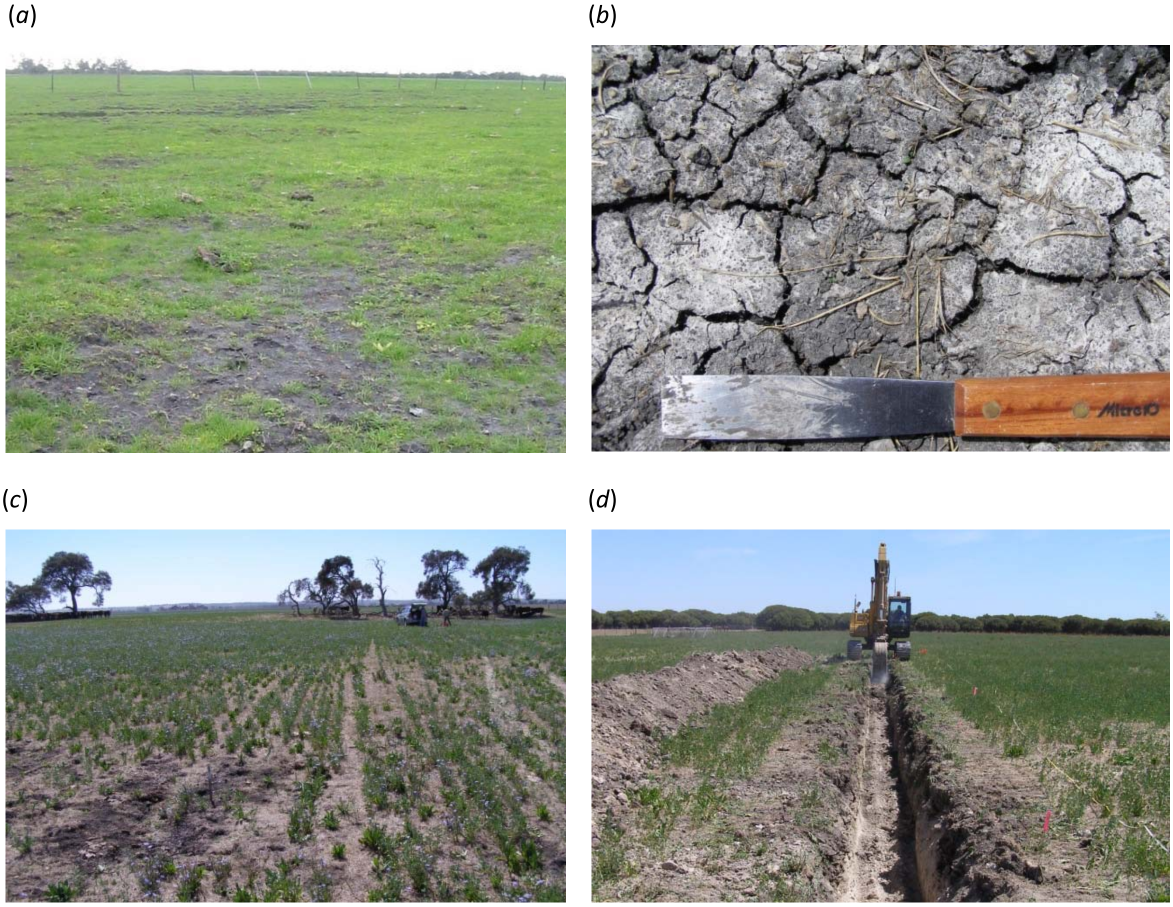


Fig. 3.1 (*a*) Patchy seedling emergence (winter 2006) with area of poor plant growth and slumping in the background. (*b*) Surface crusting and efflorescence in a bare patch. (*c*) Site of the study trench, before excavation, looking east (summer 2007). Area of poor plant growth (lower left hand corner) corresponds to that of photo *a* above and soil profiles 1 and T3. (*d*) Excavating the trench, looking west.

3.2.1 Study Site

The property 'Shepherds Hill' is located in the area locally referred to as the Keilira District, in the Upper South East of South Australia, approximately 30km inland from the coastal township of Kingston. The land owners had previously identified areas across the property with declining pasture growth (Fig. 3.1*a*) and a survey site, approximately 200m x 200m in size, was selected for investigation. Varying plant species and proliferation, bare patches of soil and variable microtopography were observed.

3.2.2 Geophysical Surveys

Geophysical surveys (EMI and GPR) were conducted in July 2006 by Ecophyte Technologies Pty Ltd. A report was prepared by them, detailing the methods used for data collection, analysis and image preparation; the report has been drawn upon to provide a summary of these methods herein.

A Geophex Ltd GEM-2 broadband electromagnetic sensor was used to conduct the EMI survey, with data collected at frequencies of 46,275, 40,275, 34,525 and 30,875 Hz. EM penetration investigation depths were calculated at 3.4, 3.5, 3.7 and 3.8 m respectively (non-weighted average), based on the assumption of homogenous substrates. The calculations do not account for changes in magnetic susceptibility or the variability in subsurface composition; therefore, the exact penetration depth is not known. These calculated depths can be considered as likely maxima.

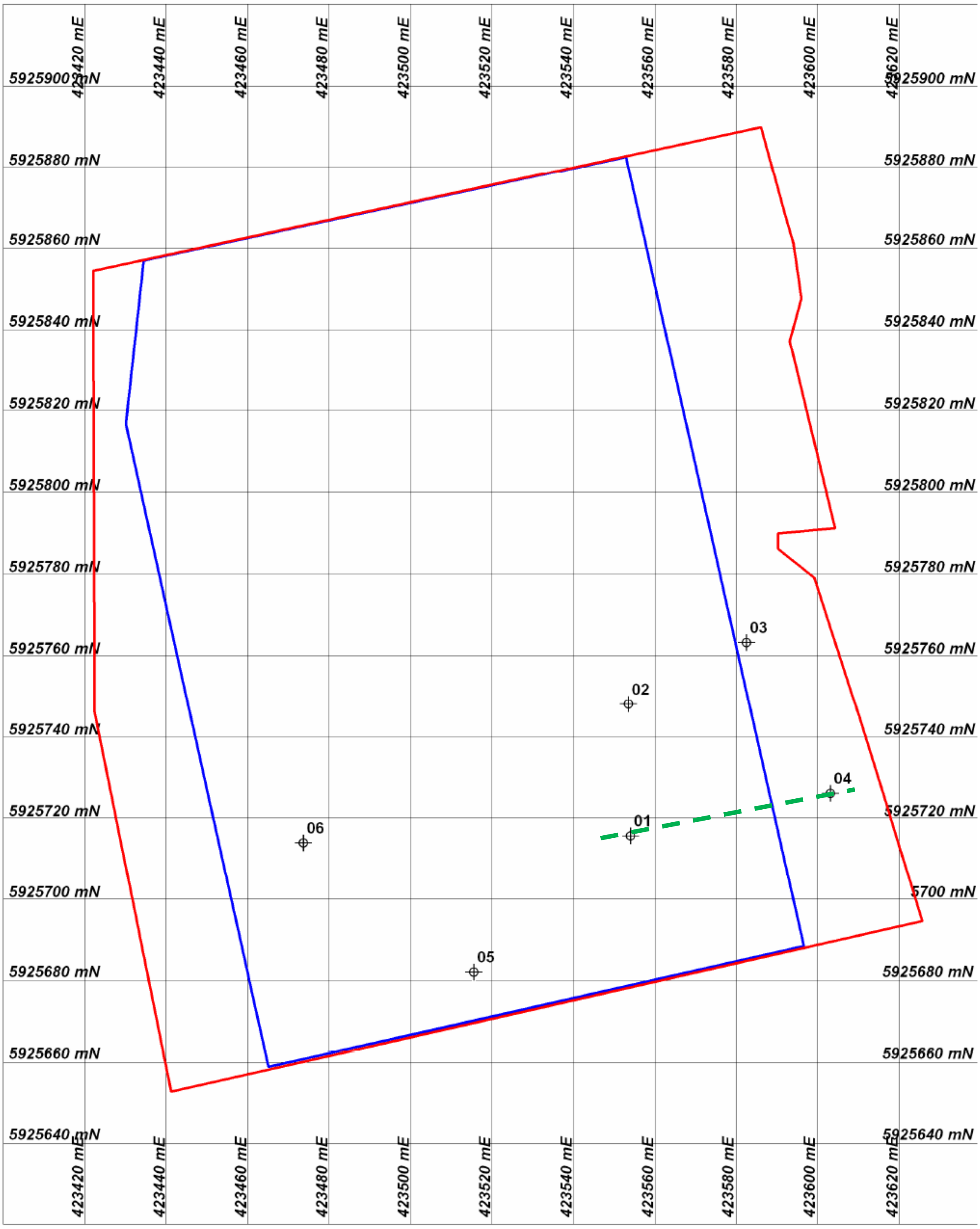


Fig. 3.2 Clipped survey areas for EMI (red) and GPR (blue), location of preliminary soil profiles 1-6 (q) and location of the study trench (▬ ▬ ▬) that was excavated along a transect between profiles 1 – 4 (see Fig. 3.8)

GPR data were collected using a Mala Ramac X3M control unit and 250 MHz antenna. Both surveys were conducted using a quad bike, with the EMI sensor mounted on the bike and the GPR antenna towed behind the bike on a plastic skid. The survey was conducted at a slow travelling speed to ensure steady contact with the ground surface. Outputs from EMI and GPR were coupled to a differential global positioning system. The surveys were conducted along 99 parallel survey lines, positioned approximately 2 m apart and were 160 m long, oriented northeast to southwest. Raw EMI and GPR data were filtered and edited prior to processing to remove unreliable data and a core survey area was clipped from the survey coverage (Fig. 3.2). Electroconductivity images were constructed for each of the collection frequencies and GPR data were presented as both vertical profiles (radargrams) as collected, and as time-depth slices cut from a 3-D block.

3.2.3 Preliminary Soil Sampling

Six soil profiles were sampled in conjunction with the geophysical survey to allow preliminary analysis of the constructed images; the location of the sample sites is illustrated in Fig. 3.2. Profiles were sampled at 0.1m intervals using a hand auger, with the overall profile depth governed by the presence of indurated carbonate horizons.

3.2.4 Soil Chemical Analysis

Samples were air dried and a representative portion was ground and passed through a 2 mm diameter sieve. On the fine earth fraction pH_{H_20}, EC and spontaneous dispersion were determined using a 1:5 soil:water suspension (Kelly and Rengasamy 2006). Samples from each horizon were hand-textured (McDonald and Isbell 1990) and the soil salinity criteria of Shaw (1999) were used to assign salinity ratings. The sodicity guidelines for Australian soils identified by Northcote and Skene (1972) were used to assign sodicity ratings, and soil pH was classified according to the guidelines presented by Slattery *et al.* (1999). Because of the highly calcareous, alkaline and saline nature of the soils, CEC and exchangeable cation concentration were determined following the method of Rayment and Higginson (1992) for soils with $EC_{1:5} > 0.3$ dSm^{-1} and $pH_{H_2O} > 7.4$. Following the removal of soluble salts, exchangeable basic cations were extracted using 1 M ammonium chloride at pH 8.5 (Rayment and Higginson 1992) and the Ca, Mg, Na and K concentrations were determined by GBC-906 flame atomic absorption spectrophotometry. CEC was determined by measurement of NH_4^+ and Cl in an auto-analyser. Exchangeable sodium percentage was calculated by the relationship ESP = (Na/CEC) x 100.

3.2.5 Trench Location

EMI, GPR and preliminary soil sampling data were analysed collectively and a zone was identified in the lower southeast quadrant of the geophysical survey area that exhibited both a high level of radargram variation and profile patterning, and a transition across EM zones. Within this zone a transect was selected for the excavation of a trench to facilitate detailed investigations on the soils and underlying geology. The transect selected lay between the preliminary soil sampling points 1 and 4 (Fig. 3.2) corresponding to GPR survey line 19. A 60 m long, 1 m wide trench was excavated to a depth varying between 0.9 and 1.7 m (Fig. 3.1*c* and *d*). During excavation it became evident that a strongly indurated horizon was present in the profile, generally located between 0.7 and 0.9 m. This horizon was hard to penetrate solely with the excavator bucket; a rock breaker was required to allow excavation below this impediment. Owing to the cost and time involved in excavating a trench of this size, only some profiles were excavated below the indurated horizon.

3.2.6 Trench Soil Sampling and Chemical Analysis

A total of 13 profiles were sampled in the trench (at 5 m intervals) according to horizon characteristics and were classified following the Australian Soil Classification (Isbell 2002). Visual comparisons were made between the profiles and seven were selected as being representative of the major morphological variations present. These profiles were analysed for pH and EC following the method of Rayment and Higginson (1992) and an aliquot of the extract was reserved for chloride determination. The extract was diluted 3-fold using 0.015M $Ba(NO_3)_2$, vortexed and allowed to settle before chloride was determined by an auto analyser. Exchangeable cations were measured following the method outlined previously and the data were analysed to identify similarities in profile characteristics. The full suite of data has been included in Appendix 3. From this analysis, three profiles representative of the primary soil types within the trench were selected for further examination. Data from these profiles are presented here and are referred to as T1 (profile 103; samples designated 103.1 - 103.8), T2 (profile 110; 110.1 – 110.6) and T3 (profile 112; 112.1 – 112.6), collected from 5 m, 39.5 m and 50 m respectively along the length of the trench. From these three profiles, organic carbon content was determined by Heanes wet oxidation method following that for saline soils (>0.5 % Cl) outlined in Rayment and Higginson (1992). Total carbonate content (expressed as $CaCO_3$) was determined following the modified pressure-calcimeter method (Sherrod *et al.* 2002) using 2 g of soil, 8 ml of 3M HCl containing 3 % by weight of $FeCl_2$, and aided by a pressure transducer monitored by a digital voltmeter. The voltage was correlated to a set of standard samples with varying $CaCO_3$ content. The particle size distribution of the soil was determined by a method adapted from McKenzie *et al*. (2002). All samples (including indurated carbonates) were ground to <100 µm and partially dispersed by ultrasonic probe. Organic matter was removed by pre-treatment with hydrogen peroxide, carbonate with acetic acid and soluble salts by washing. Samples were dispersed by shaking with sodium hexametaphosphate, following which samples were wet sieved (<65 µm) into a sedimentation cylinder before mixing. Pipette sub-samples were taken at calculated times and depths to determine the proportions of sand (> 20 µm), silt (20 – 2 µm) and clay (<2 µm).

3.3 RESULTS

3.3.1 EMI Survey

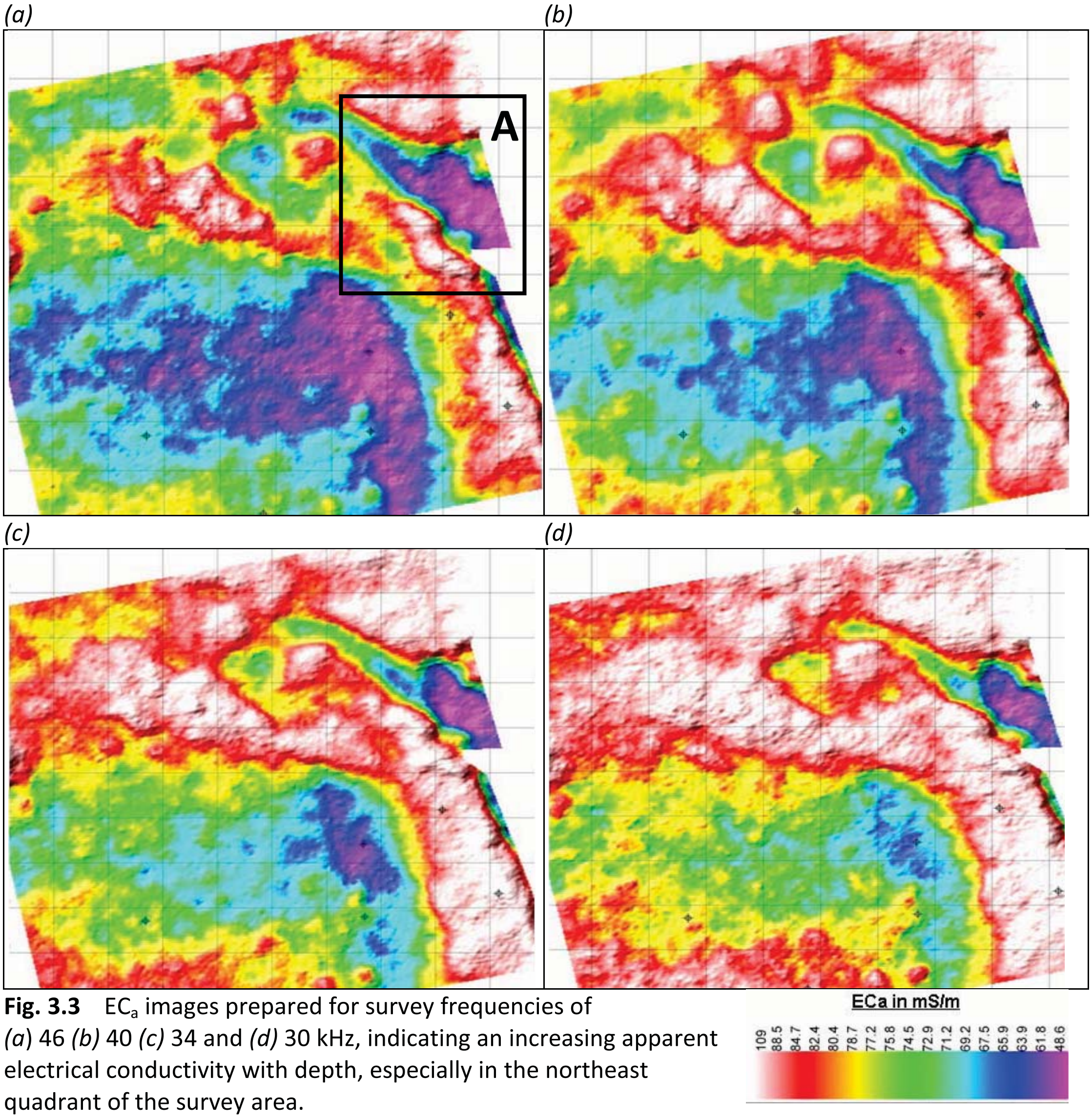


Fig. 3.3 EC$_a$ images prepared for survey frequencies of *(a)* 46 *(b)* 40 *(c)* 34 and *(d)* 30 kHz, indicating an increasing apparent electrical conductivity with depth, especially in the northeast quadrant of the survey area.

Discrete zones of high apparent electrical conductivity (EC_a) were identified in the EMI survey and strong correlations in EC_a were evident between the images for the four collection frequencies. EC_a generally increased with depth in most zones (Fig. 3.3). The highest EC_a is observed in the arc that extends from the southeast corner of the survey to the northwest corner. One discrete zone (A, Fig. 3.3a) in the northeast quadrant exhibits the lowest EC_a for the survey area and remains relatively unchanged for each collection frequency. This area corresponds to the outcropping of a limestone ridge that has a higher elevation than the surrounding areas and was vegetated with eucalyptus trees rather than pasture species.

3.3.2 GPR Survey

A total of 99 GPR survey lines, 135m long and 2m deep, were processed using a consistent set of image processing parameters that facilitated the best overall distinction of soil profile features. The Ecophyte Technologies Report (2007) identifies a number of distinct features evident on the radargrams (Fig. 3.4) viz.:

(a) Grey, smooth, relatively featureless zones.

(b) Zones extending from a few to tens of metres, dominated by distinct vertical ‘streaks’ that have sharp, distinct edges extending through the radargrams.

(c) Zones dominated by closely packed lines that are sometimes ‘wavy’, near parallel to the ground surface.

(d) Parabolic features that indicate strongly reflective subsoil features, generally less than 1 m deep in the profile.

(e) Layers of near parallel lines that appear to be less closely packed below 1 m.

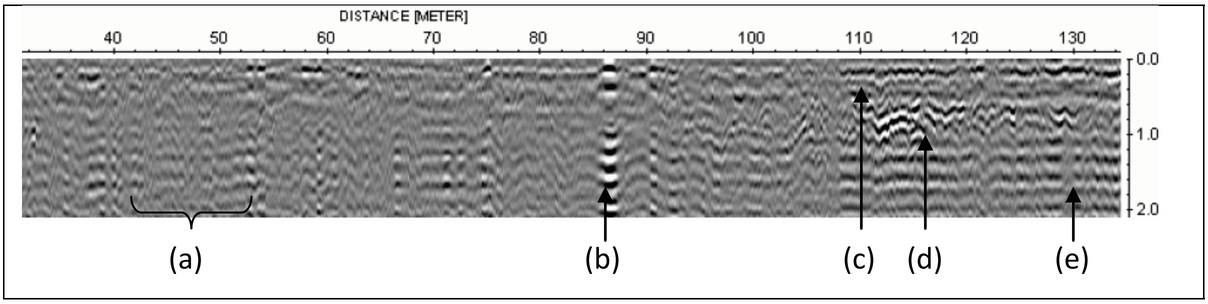


Fig. 3.4 GPR radargram depicting the five distinct features (a – e) observed in the survey.

Whereas the constructed radargrams depict the vertical arrangement of subsoil features, the spatial distribution of subsoil layers (according to relative electrical conductivity / reflectance) is evident in the GPR time – depth coverages (Fig. 3.5*a*-*e*).

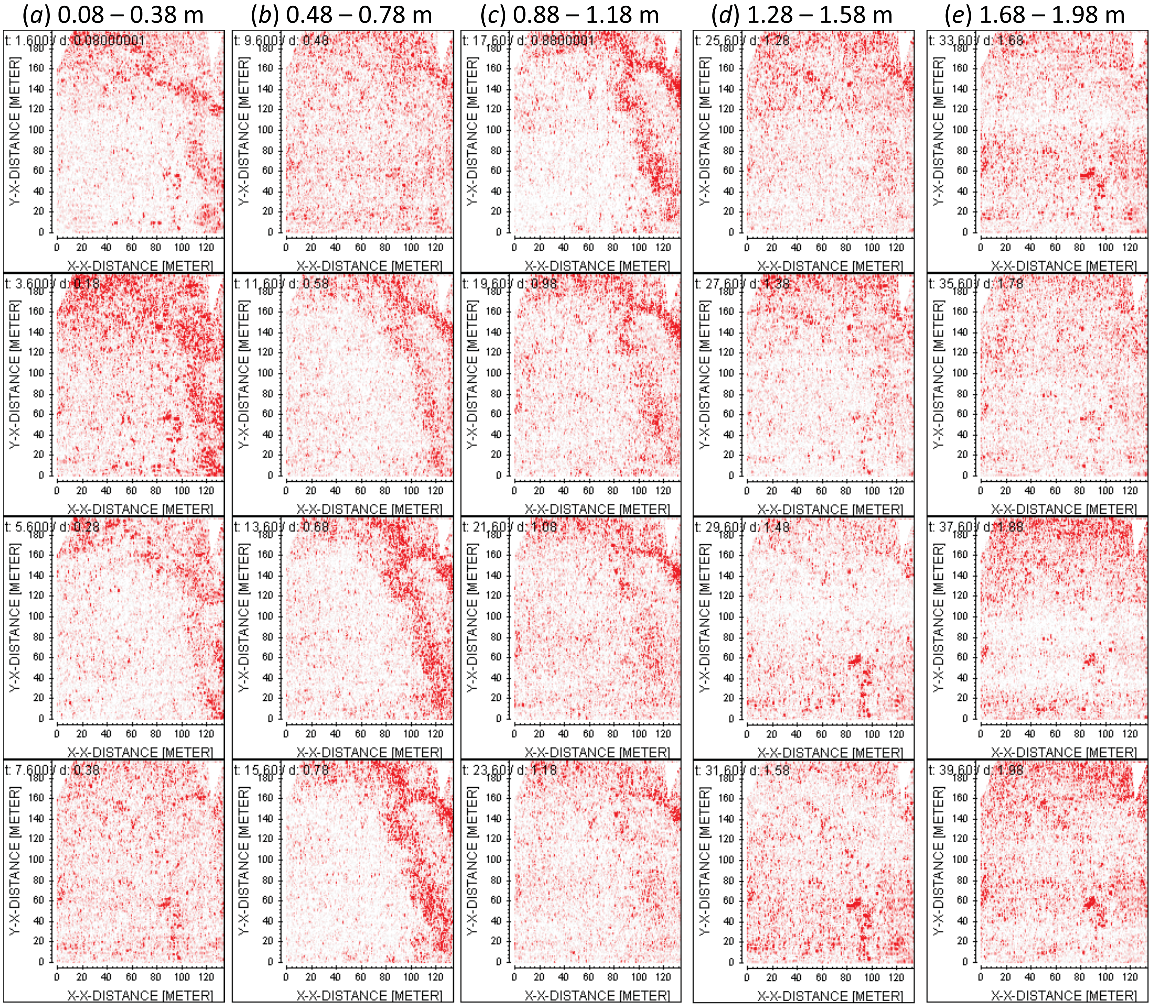

(*a*) 0.08 – 0.38 m (*b*) 0.48 – 0.78 m (*c*) 0.88 – 1.18 m (*d*) 1.28 – 1.58 m (*e*) 1.68 – 1.98 m

Fig. 3.5 GPR time-depth coverages prepared at 0.1m intervals from 0.08 – 0.38 m (column *a*), 0.48 – 0.78 m (column *b*), 0.88 – 1.18 m (column *c*), 1.28 – 1.58 m (column *d*) and 1.68 – 1.98 m (column *e*).

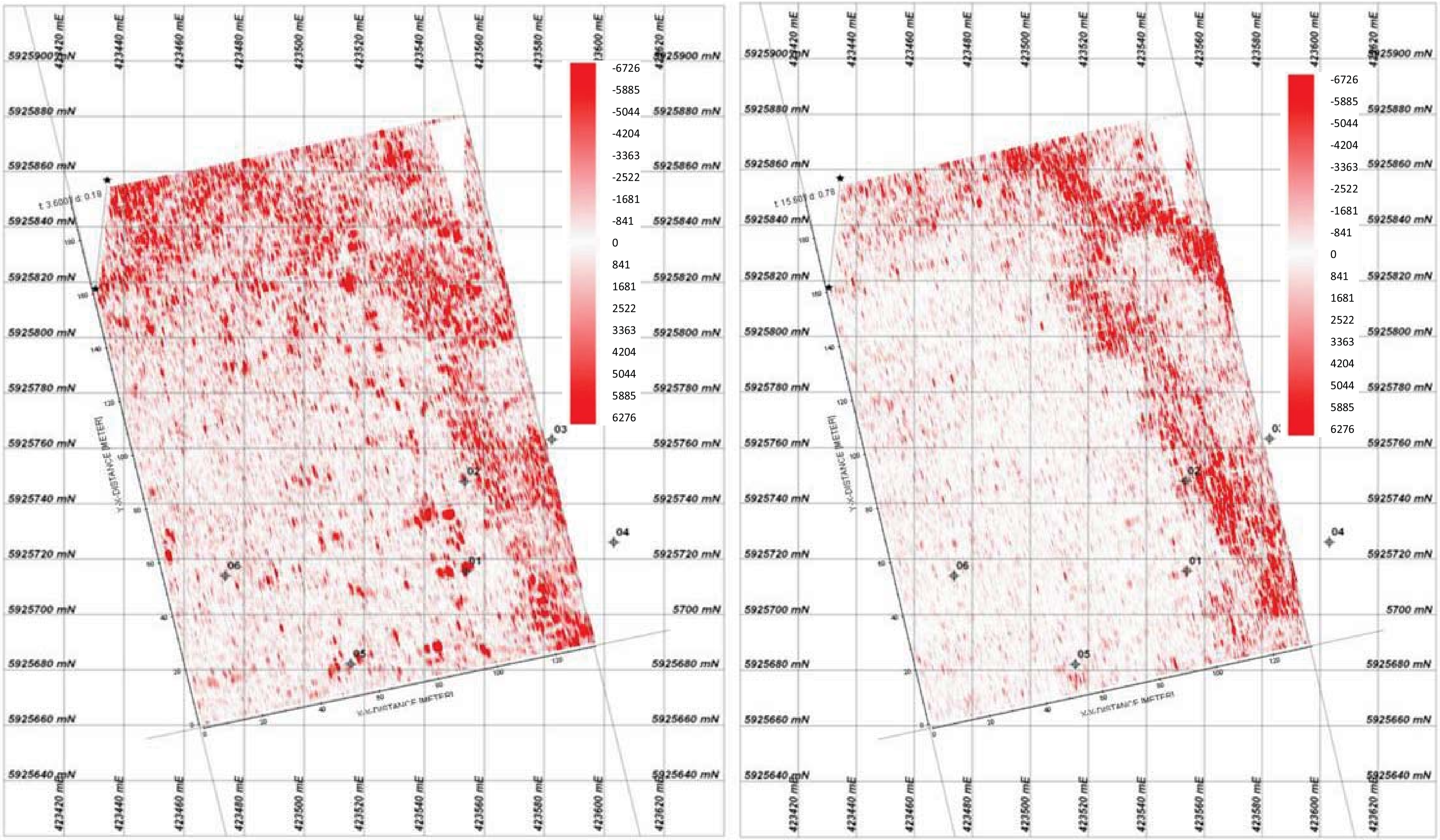


Fig. 3.6 GPR time - depth coverages for 0.18 and 0.78 m.

The images were constructed at 0.1 m depth intervals, starting at 0.08 m and extending to 1.98 m in the profile. Two coherent GPR patterns were evident, primarily between 0.18 and 0.28 m and between 0.58 and 0.98 m. The discrete patterning in the 0.18 m and 0.78 m images indicates the presence of strongly reflective (i.e. not conductive) subsoil features (Fig. 3.6). Below 1.58 m the patterning becomes much more consistent across the survey area, especially in the northern sector.

3.3.3 Preliminary Soil Survey

Six soil profiles were sampled in conjunction with the geophysical survey, herein referred to as profiles 1, 2, 3, 4, 5 and 6 (Fig. 3.2 and Table 3.1). Profiles 2, 3 and 4 were all very shallow, with an indurated carbonate horizon intercepted within 0.2m of the surface. Profiles 1, 5 and 6 were much deeper, with indurated horizons present beyond 0.6 m. Physicochemical similarities were apparent within the two distinct soil profile groups, hereafter called shallow and deep.

The shallow profiles (2, 3 and 4) were mildly to moderately alkaline and non sodic throughout. Salinity was moderate, except for surface accumulations of salt in profiles 2 and 4, leading to high soil salinity. Despite the lighter texture and low ESP, profiles 2 and 4 spontaneously dispersed, albeit to different degrees.

The deep profiles (1, 5, and 6) also had similar physicochemical properties to each other, and were significantly different from the shallow profiles. Profiles 1 and 5 were moderately to strongly alkaline, highly to extremely saline and strongly sodic below 0.2 m. They also had the highest CECs of all of the profiles and showed variable degrees of spontaneous dispersion, with lower levels of dispersion recorded as EC increased in the profiles. Profile 6 was moderately to very strongly alkaline and marginally to strongly sodic throughout. The EC in this profile was generally lower than in profiles 1 and 5, despite still being very highly saline. The high spontaneous dispersion in this profile, in comparison to that in profiles 1 and 5, can be attributed to the lower EC and extremely high ESP.

Table 3.1 Chemistry and texture of soils sampled in conjunction with geophysical survey

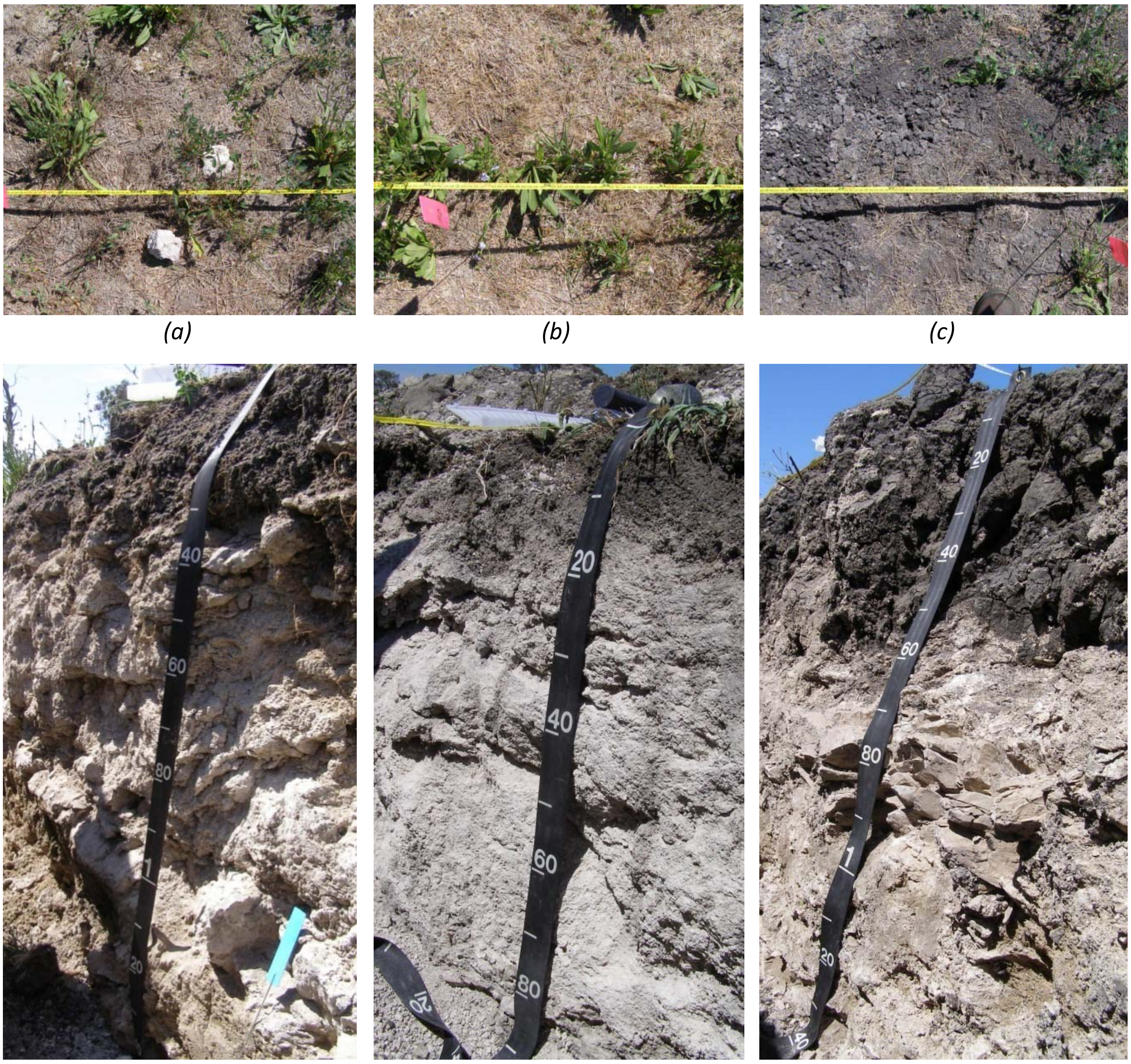
Soil Depth (m)	$pH_{1:5}$ (H_2O)	$EC_{1:5}$ (dSm^{-1})	Texture	CEC cmol (+)/kg	ESP (%)	Spontaneous Dispersion
			Profile 1			
0 – 0.1	8.3	0.64	Sandy Clay Loam	36	6.4	High
0.1 – 0.2	8.6	0.89	Clay loam	37	14.4	Medium
0.2 – 0.3	8.2	3.38	Light Clay	38	30.5	None
0.3 – 0.4	8.4	2.73	Heavy Clay	41	41.8	None
0.4 – 0.5	8.7	2.46	Heavy Clay	38	49.5	None
0.5 – 0.6	8.8	2.35	Heavy Clay	36	52.0	None
			Profile 2			
0 – 0.1	7.5	0.61	Sandy Clay Loam	37	0.6	Medium
0.1 – 0.2	8.3	0.34	Clay Loam	35	0.9	Low
			Profile 3			
0 – 0.1	7.5	0.41	Sandy Loam	17	0.3	None
0.1 – 0.2	8.3	0.33	Sandy loam	24	1.0	Low
0.2 – 0.3	8.7	0.32	Sandy Clay loam	28	1.4	Low
			Profile 4			
0 – 0.1	7.4	0.76	Sandy Clay Loam	28	0.9	Medium
0.1 – 0.2	7.8	0.43	Sandy Clay Loam	24	0.9	High
			Profile 5			
0 – 0.1	8.0	0.72	Sandy Loam	31	6.6	High
0.1 – 0.2	8.6	1.15	Sandy Clay Loam	35	24.4	High
0.2 – 0.3	8.7	2.33	Medium Clay	39	46.9	Medium
0.3 – 0.4	8.8	2.86	Heavy Clay	39	59.9	Low
0.4 – 0.5	8.7	3.26	Heavy Clay	40	62.1	Low
0.5 – 0.6	8.8	2.56	Heavy Clay	41	62.1	Low
			Profile 6			
0 – 0.1	8.0	1.33	Clay Loam	31	3.1	High
0.1 – 0.2	8.4	0.54	Light Clay	37	6.4	Medium
0.2 – 0.3	9.0	0.76	Medium Clay	33	19.0	High
0.3 – 0.4	9.3	0.91	Heavy Clay	29	33.9	High
0.4 – 0.5	9.4	0.88	Heavy Clay	30	45.8	High
0.5 – 0.6	9.4	1.09	Heavy Clay	36	53.4	High
0.6 – 0.7	9.5	1.01	Heavy Clay	27	57.7	High

Despite having a lower EC than the deep profiles, the shallow profiles were generally located within zones of high conductivity on the EMI survey, and with subsurface features that were strongly reflective to GPR. Conversely, the highly saline deep profiles were located within zones of lower conductivity that were relatively non-reflective to GPR (Figs. 3.3 and 3.6).

3.3.4 Trench Results

The three key profiles selected for detailed analysis (T1, T2 and T3) had markedly different physicochemistry despite their close proximity to each other (Table 3.2). Profile T1 was similar to the shallow profiles (2, 3 and 4) from the preliminary soil survey, whereas profile T3 was similar to the deep profiles (1, 5 and 6). Profile T2 was selected because it has physicochemical properties distinct from those of both T1 and T3. Visual inspections confirmed that the bulk of the trench contained soils similar to those of Profile T1, whereas T2 and T3 occurred in discrete zones. Surface soil characteristics and pasture species also varied significantly at the three sites (Fig. 3.7).

Profile T1 had a thin surface A horizon (0 - 0.1 m) that was mildly alkaline, highly saline and non sodic, overlying a moderately alkaline, moderately saline, non sodic heavy clay B horizon that extended to 0.27 m, below which was semi-indurated carbonate. The CEC of the surface horizons was high (>25 cmol (+) / kg), but decreased with depth. Lucerne, medic and chicory pasture species were all present at T1 (Fig. 3.7*a*) and root growth was prolific in the surface horizons. Beneath the indurated 2Bk horizon, a very strongly alkaline, moderately saline, marginally to strongly sodic marl of clay texture was present. From 0.95 – 1.1 m a highly indurated carbonate lens overlay a very strongly alkaline, very highly saline, strongly sodic clay-rich horizon (1.1 – 1.3 m) that became less saline and sodic with depth. Plant roots were found both above and below the indurated carbonate, which will herein be referred to as ‘calcrete’. This profile is classified as a Petrocalcic, Grey, Chromosol due to the increasing clay content in the B horizon and presence of a shallow indurated carbonate lens. Owing to the complex interplay of sedimentary, pedologic and hydrologic processes that formed these soils, the lower horizons in the profile cannot reliably be assigned horizon notations.



(a) *(b)* *(c)*

Fig. 3.7 Plant growth, surface soil and profile characteristics of the three key profiles selected from the study trench for detailed physicochemical investigation (*a*) T1, (*b*) T2 and (*c*) T3, collected from 5, 39.5 and 50 m respectively along the length of the trench.

Profile T2 was highly calcareous throughout, and although the pH steadily increased with depth (becoming very strongly alkaline), it did not exhibit the shallow indurated features of T1; it is classified as an Epihypersodic, Petrocalcic, Hypercalcic, Calcarosol. Plant growth at this site was not as prolific as in T1, and medic was absent (Fig. 3.7*b*). The carbonate in this profile was soft and friable, and although the clay content was relatively low, the soil was highly saline and strongly sodic in the section 0.2 – 0.8 m. In the zone 0.8 – 0.87 m a calcrete horizon was present, beneath which lay a very strongly alkaline, highly saline, strongly sodic clay-rich lens that was 0.03 m thick. The full extent of this calcrete horizon is not known as the profile was not excavated below 0.9 m where the indurated calcrete was again present.

Table 3.2 Chemistry of three distinct profiles representative of soil types in the study trench

Soil Depth (m)	Horizon	$pH_{1:5}$ (H_2O)	$EC_{1:5}$ (dSm^{-1})	Cl^- (mg/kg)	Organic C (%)	Carbonate ($CaCO_3$ %)	Sand (%) (CO$_3$ free)	Clay (%)	CEC (NH_4) cmol (+) / kg	ESP (%)
Profile T1										
0.0 – 0.1	A	7.7	0.57	20.0	2.6	2.6	40.8	32.1	27.3	1.2
0.1 – 0.27	B	8.4	0.39	26.0	0.8	8.0	3.5	93.2	37.1	1.7
0.27 – 0.4	2Bk	- - Indurated Carbonate - -			0.8	74.0	40.4	55.9	11.3	4.7
0.4 – 0.65	-	9.2	0.27	19.2	0.4	65.1	12.6	83.4	17.0	7.9
0.65 – 0.95	-	9.4	0.36	27.9	0.3	70.6	7.2	87.7	14.9	19.1
0.95 – 1.1	-	- - - - - - - - Calcrete - - - - - -			0.3	66.1	9.7	83.0	15.9	34.7
1.1 – 1.3	-	9.5	1.23	1086.6	0.2	22.1	10.3	87.3	30.5	38.2
1.3 – 1.5	-	9.4	0.8	734.3	0.2	86.8	22.1	70.6	16.6	28.2
Profile T2										
0.0 – 0.1	A	8.38	0.34	18.6	1.8	21.5	20.8	68.6	36	2.4
0.1 – 0.2	Bk	8.9	0.41	27.6	0.5	73.2	10.3	81.1	13	7.6
0.2 – 0.5	Bk	9.5	0.42	42.5	0.3	82.7	11.1	86.1	11	20.5
0.5 – 0.8	Bk	9.5	0.45	46.7	0.2	74.9	12.4	83.9	10	31.1
0.8 – 0.87	-	- - - - - - - - Calcrete - - - - - -			0.2	84.7	33.8	55.5	8	38.5
0.87 – 0.9	-	9.4	0.70	72.6	0.3	17.0	24.6	61.2	27	33.1
Profile T3										
0.0 – 0.1	A	8.9	1.01	349.5	1.7	21.3	16.5	45.0	36	18.8
0.1 – 0.3	B	9.5	2.22	650.7	0.7	31.5	4.3	74.9	38	41.3
0.3 – 0.5	B	9.8	2.18	843.0	0.8	34.4	3.7	77.0	30	55.9
0.5 – 0.7	Bk	9.6	1.36	609.2	0.4	61.8	9.8	76.6	14	52.0
0.7 – 1.0	-	- - - - - - - - Calcrete - - - - - -			0.3	81.0	39.4	51.3	4	44.5
1.0 – 1.4	-	9.7	0.48	154.5	0.2	79.9	47.8	45.1	8	39.3

In contrast to profiles T1 and T2, profile T3 was deep (0.7 m) and mostly black (dry colour 5Y 2.5/1) clay-rich, very strongly alkaline, extremely saline and strongly sodic, below which was calcrete and is classified as an Episodic, Epipedal, Black, Vertosol. Whereas the chloride content was high throughout T3 (>300 - >800 mg/kg), corresponding to the extremely high salinity, in the 1.1 -1.3 m horizon of T1, the chloride content was >1000 mg/kg. This chloride value is much greater than those of profile T3, despite the EC being lower in T1. Some of the EC response in T3 may therefore be attributed to the presence of pedogenic sodium carbonate and bicarbonate, given the high pH also observed here. The CEC was also high in these upper horizons, exceeding 30 cmol (+) / kg to 0.5 m depth. Pedological characteristics of this profile were also significantly different to those observed in T1 and T2. The upper 0.5 m of soil was dominated by massive peds of columnar shape (Fig. 3.7*c*). Distinct vertical cracks were present and slickensides were evident, with smooth faces ranging in size from a few to tens of centimetres. These features are consistent with those associated with Vertosols (Isbell 2002) or Vertisols (Soil Survey Staff 1975). Beneath the calcrete the EC decreased from 1.36 to 0.48 dSm^{-1} (highly saline), and appears to be a unique feature in this landscape. The CEC was also lower in the deeper horizons than that of the horizons above the calcrete, yet they remained strongly sodic. Pasture growth at T3 was sparse and only chicory was present (Fig. 3.7*c*). The surface soil was well aggregated and salt efflorescence was evident, characteristics not observe in profiles T1 and T2.

3.4 DISCUSSION

The primary aim of this study was to investigate the spatial variability of soil physicochemical properties in the study area and potentially to identify its cause and extent. The combination of EMI and GPR surveys was useful in identifying variability in subsurface characteristics. When the surveys were interpreted with preliminary soil information, the location for a trench was identified. The trench aligned with two of the preliminary soil sampling points (deep profile 1 and shallow profile 4), zones of low and high EC_a on the EMI image and high levels of radargram variation on the GPR trace for this transect (survey line 19). At the time of excavation it became evident that significant variability in plant growth, surface soil and profile characteristics occurred along the selected transect. Sampling and inspection within the trench allowed the detailed investigation of soils and sedimentary layers to be conducted.

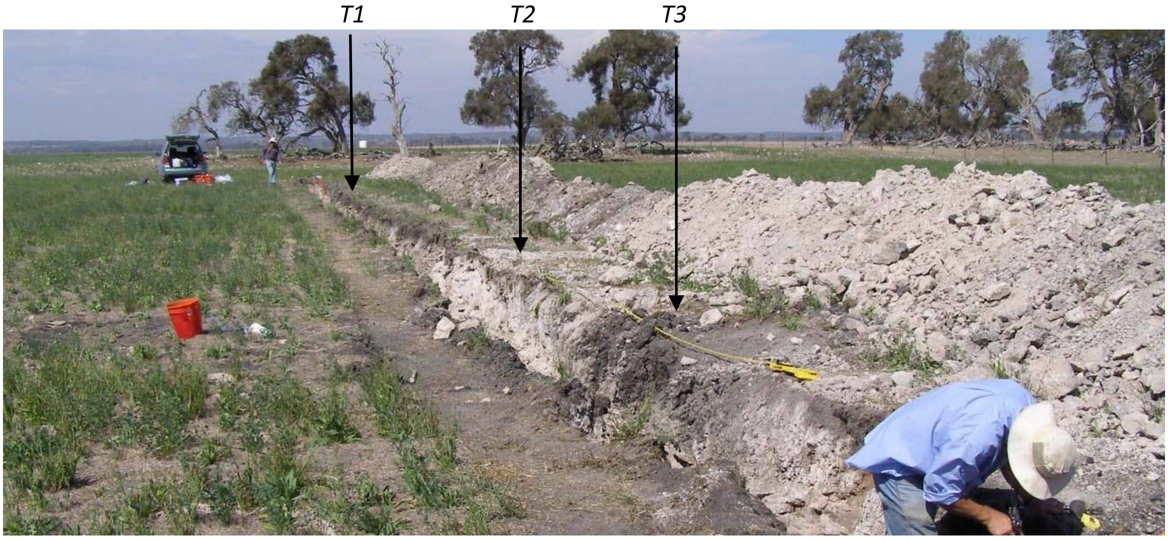


Fig. 3.8 Trench showing the location of the three profiles (T1, T2 and T3) selected for detailed physicochemical investigation. The red bucket in the centre of the patch of bare soil and poor plant growth corresponds to the vertical ‘streaking’ seen in the GPR trace and the location of profile T3.

3.4.1 Key Profiles

A comparison of the three key profiles confirms that significant physicochemical and geological variability occurs in this region. The patchy decline in plant growth observed here can be attributed to such variability. Thick pasture growth observed near profile T1 (see the background of the photograph of the trench in Fig. 3.8 and surrounding area), thinned progressively toward T2, whereas pasture was mostly absent at T3 (marked by the red bucket in the image, Fig. 3.8). The thick plant growth between T1 and T2 was a function of the lower pH, EC and ESP observed in the surface 0.3 m of these soils in comparison to the much higher values in T2 and T3 (Fig. 3.9*a, b, c*). The strongly alkaline pH of T2 (Fig. 3.9*a*) may have led to the absence of medic, and the combination of strongly alkaline, extremely saline and strongly sodic properties at T3 (Fig. 3.9*a, b, c*) resulted in the loss of both medic and lucerne; only chicory persisted.

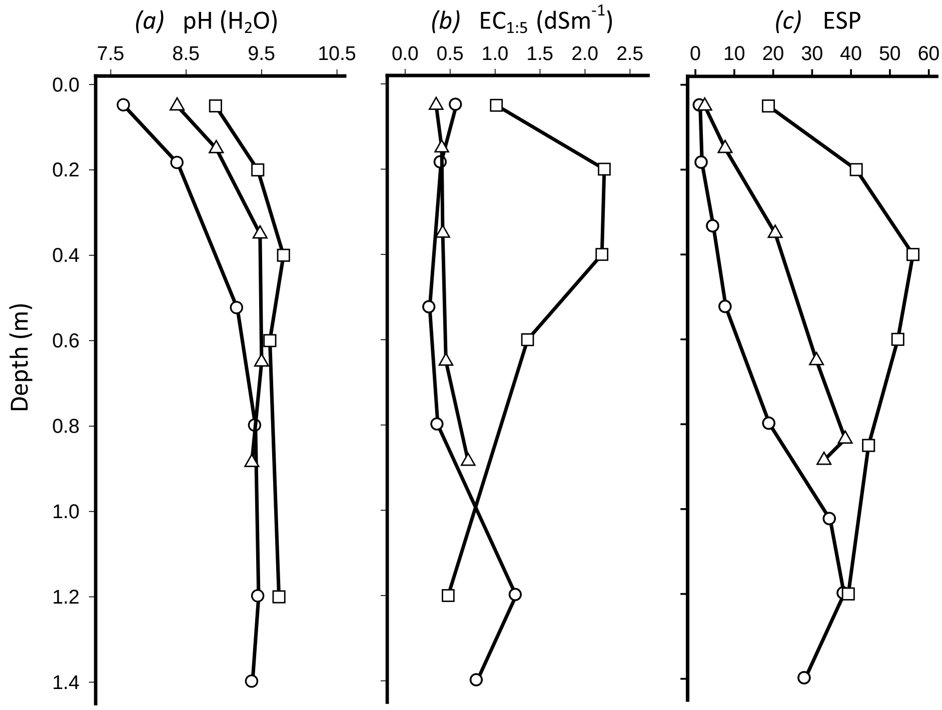


Fig. 3.9 Chemical properties of T1 (○), T2 (△) and T3 (□). Note the strongly alkaline, extremely saline and strongly sodic nature of profile T3.

The presence of, and depth to, indurated carbonate also varied between the three soils. Shallow indurated carbonate was present in T1 (the dominant soil in the trench), but was absent in both T2 and T3, and is of particular interest because it coincides with more robust plant growth. Along the whole trench a moderately to strongly indurated calcrete horizon of varying depth and thickness was intercepted. The soil underlying calcrete was often saturated. The capillary rise of shallow groundwater may be responsible for calcrete formation, but the validity of this inference requires further investigation.

The CEC of the soils varied both within and across profiles, indicating the presence of different clay minerals. In T1 and T2, the CEC was notably higher (>30 cmol(+) / kg) in the surface horizons than the horizons below, and the clay content was also high (>50 %) in the surface soil. The same features were also observed in the horizon directly underlying calcrete in T1 and in the clay lens running through the calcrete in T2. Profile T3 had a higher CEC throughout the profile than T1 and T2 and the clay content was also relatively high (>40 % to a depth of 0.5 m). In contrast to the clay rich horizons underlying the calcrete in profiles T1 and T2, those of T3 (1.0 – 1.4 m) were carbonate rich (>75 %), moderately indurated and had a low CEC (8 cmol(+) / kg). The high CEC, structural form and presence of slickensides in some of the soil horizons indicate the presence of smectite clay minerals (Churchman *et al.* 1993) that are prone to shrink/swell behaviour. Mineralogical investigations of the soil will be undertaken to help understand the causes of the physicochemical variability observed (Chapter 4).

3.4.2 Relationships between soil profile properties and geophysical features

Comparison of the surveys to the soil geomorphological and physicochemical data allowed inferences to be made about the possible cause of the features depicted in the constructed images. After the trench was excavated, the radargram for GPR survey line 19 was extended from 130 m (cropped survey area) to 160 m to coincide with the full length of the trench, located between 90 and 150 m on the radargram (Fig. 3.10). The position of profiles T1, T2 and T3 are shown in Figure 3.8, and distinctly different radargram patterns associated with the soil profiles can be seen in Figure 3.10.

From 120 – 160 m on the GPR trace (Fig. 3.10), the majority of the radargram is dominated by two shallow horizontal lines in the top 0.4 m, parabolic/wavy features at 0.8 m, and a set of less closely packed horizontal lines below 1 m. From 110 – 120 m, the shallow horizontal features were not present, giving way to wavy patterns close to the surface; this area corresponds to the location of profile T2. Further along the trench at 100 – 105 m, a distinct vertical streak occurs corresponding to the position of profile T3.

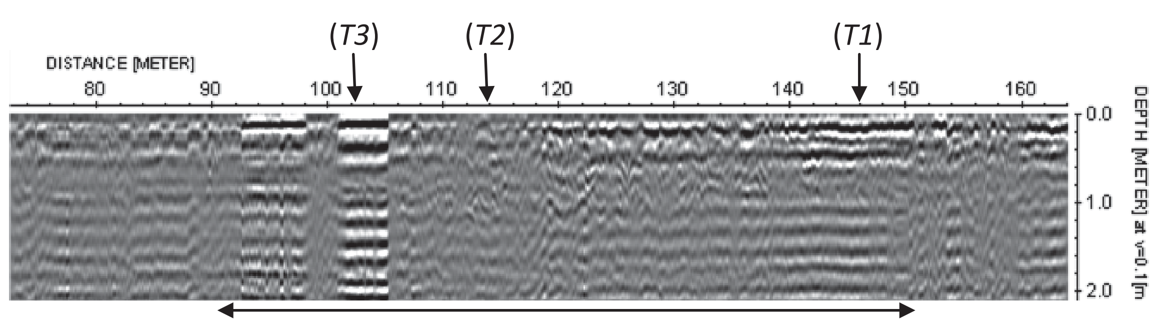


Fig. 3.10 Radargram for GPR run 19 from 70 – 165 m, the arrows indicating the location and length of the excavated study trench and the location of profiles T1, T2 and T3.

From 120 – 150 m on the GPR trace, soil profile characteristics in the trench were largely consistent with those observed in profile T1, viz. a shallow indurated carbonate horizon occurs between 0.2 and 0.3 m. From 105 – 120 m, the shallow horizontal lines disappear, consistent with the profile characteristics of T2, where, despite the carbonate content being high throughout (>70 % at 0.1 m), no shallow indurated carbonate horizon was present. Therefore the horizontal lines on the GPR trace within 0.4 m of the surface in the 120 – 150 m zone are indicative of the boundary between shallow indurated carbonate and the clay rich B horizon that it commonly underlies. The spatial distribution of this carbonate is most clearly illustrated in the 0.18 m time – depth slice presented in Fig. 3.6*a*.

The parabolic/wavy features located between 0.6 - 0.8 m depth across the length of the radargram corresponds to the position of the highly indurated calcrete horizon that was found in every sampled profile. The spatial distribution of calcrete can therefore best be seen in the 0.78 m GPR time-depth slice (Fig. 3.6*b*).

Beneath the indurated calcrete, a clay-rich saline horizon was commonly intercepted and the depth to groundwater in a local observation well (MNC032) at the time of sampling was recorded at 1.18 m (Department of Water Land and Biodiversity Conservation 2009). The less closely packed horizontal lines observed below 1 m across the full extent of the radargram have therefore been related to the presence of a groundwater capillary fringe. Doolittle *et al*. (2006) explain that as the width of the capillary fringe increases, GPR reflections from groundwater have increasingly lower amplitudes, more dispersed characteristics, and are therefore less distinguishable on GPR radargrams. This is reflected in the presence of the less closely packed features on the GPR trace below 1m. The patterning associated with the capillary fringe and depth to groundwater can be seen in Fig. 3.5 between 1.18 and 1.98 m.

The distinct vertical streaking that occurs in survey line 19 at 105 m corresponds to the presence of deep, clay-rich, highly saline and strongly sodic Vertosols, such as those found in profile T3. The combination of these properties results in the soil being highly electromagnetically conductive, and hence non reflective to GPR, and a ‘conductivity shadow’ (Fig. 3.10 *T3*) results through the vertical extent of the radargram. A profile was also sampled between 90 and 100 m that exhibited the same physicochemical characteristics as T3 (Appendix 3, profile number 113; 113.1 – 113.4), corresponding to the second vertical streak present on the radargram.

3.4.3 Relationship between EMI and GPR patterns

In addition to the relationships between the soil physicochemical properties and the GPR images, there are also relationships between the GPR and EMI surveys. EMI images for the four collection frequencies indicate that EC_a increased with depth in most zones. When these images were compared with GPR time-depth slices, there was a correlation in the patterns between EC_a at all frequencies, and GPR features at 0.68 – 0.98 m. In Fig. 3.11, the 46 kHz EMI image was converted to grey scale and overlaid with a transparent image of the GPR time-depth slice from 0.78 m.

Visual observations of these patterns suggest that there are areas of low EC_a that are highly reflective to GPR (Fig. 3.11 A) and areas of high EC_a with low GPR reflectance (Fig. 3.11 B). The GPR patterning observed in the time-depth slice for 0.78 m was related to the presence of a highly indurated calcrete lens; however field observations showed that its thickness and uniformity varied. In profile T1, calcrete occurs at 0.95 m and was only 0.15 m in thickness (Fig. 3.7*a*). A clay-rich horizon was found below the calcrete that was saturated and highly saline and many roots were present both above and below the calcrete. Similar observations were made 19.5 m along the trench, where a calcrete horizon in the zone 1.0 – 1.25 m was again underlain by a saturated clay horizon. Such observations lead to the conclusion that the calcrete found in this zone does not form an impenetrable barrier to water movement and root exploration.

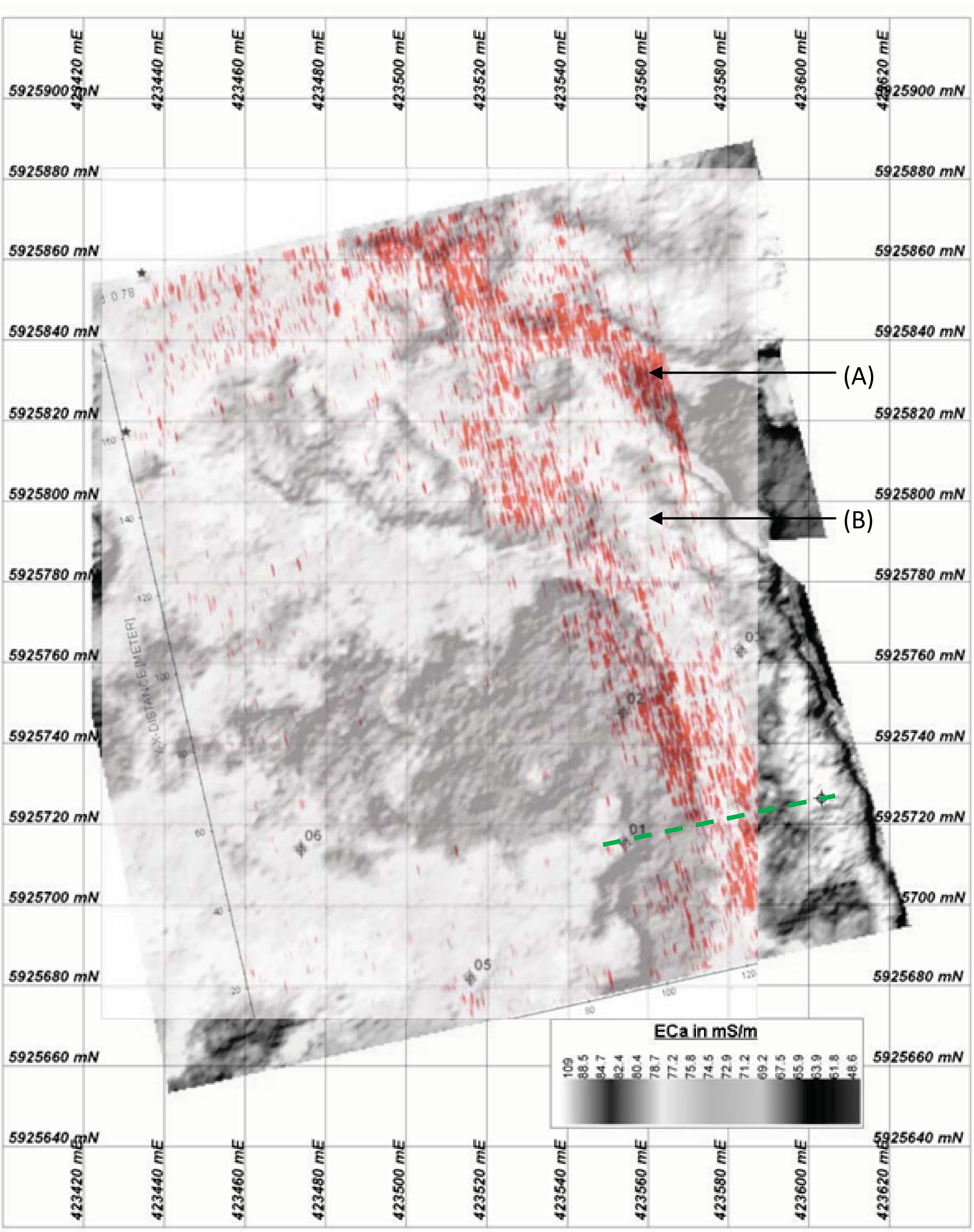


Fig. 3.11 EMI image converted to grey scale, overlaid with a transparent GPR time-depth slice from 0.78 m. Two main zones become apparent (A) areas of low conductivity that are highly reflective to GPR and (B) areas of high conductivity that are non-reflective to GPR.

Along the trench, however, calcrete thickness increased to > 0.7 m between T2 and T3 at 45 m (Fig. 3.12*b*). The calcrete in T3 was 0.3 m thick and exhibited limited vertical cracking and no plant roots.

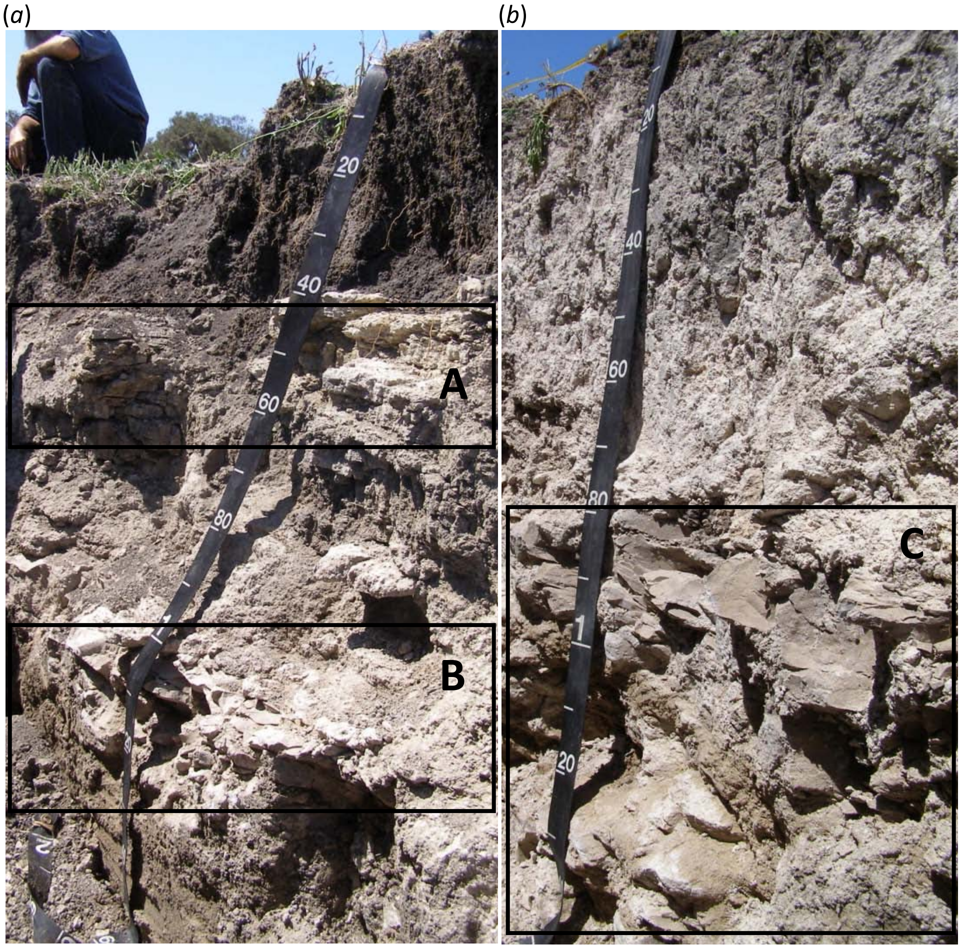


Fig. 3.12 Photographs of sampled profiles from (*a*) 19.5 and (*b*) 45 m in the study trench. The profile in image *a* is similar to that seen in T1, exhibiting shallow indurated carbonate (A) and a deeper thin calcrete lens (B), underlain by a saturated clay rich horizon. In image *b*, no shallow indurated horizon is present but a 0.7 m thick calcrete is found (C).

From these visual associations, we further conclude that the GPR patterning in the 0.78 m time - depth slice is related to thick accumulations of calcrete not conducive to capillary rise and water accumulation, leading to the low EC_a and high GPR reflectance observed (Fig. 3.11 B). The highly conductive zones that fringe this area of high reflectance are therefore attributed to either subsoil moisture (the groundwater capillary fringe) and/or saline clay-rich horizons that were found below the fractured, thin accumulations of calcrete (Fig. 3.12*a*).

3.5 CONCLUSION

The primary aim of this paper was to investigate the variability of soil physicochemical properties in the study area and to potentially identify its cause and extent.

The EMI survey revealed discrete conductivity zones that are most likely linked to the depth of the groundwater capillary fringe and the presence of clay-rich horizons positioned below calcrete. Isolated patches of deep, clay rich, extremely saline and strongly sodic Vertosols occurred sporadically, and were identifiable by distinct vertical streaks that extended through the GPR radargrams. The GPR survey identified the presence of an indurated carbonate horizon typically located between 0.18 and 0.38 m in the profile. Thick accumulations of calcrete were also detected by GPR. Good pasture growth was consistently observed in the Chromosols that have clay-rich, high CEC surface horizons overlying shallow indurated carbonate from 0.2 m. Extreme pH, EC and ESP values were recorded in the Vertosols and have a profound effect on plant growth. Transitions between these two soil types were also observed (Calcarosols). Further investigations of the chemistry and form of the indurated carbonate horizons and the mineralogy of the soils in these key profiles is required to adequately determine the cause of such variability in the landscape.

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CHAPTER 4

GENESIS AND DISTRIBUTION OF CLAY MINERALS AND CARBONATES IN LACUSTRINE AND PALUSTRINE SEDIMENTS OF UPPER SOUTH EAST SA

4.1 INTRODUCTION

Recent investigations in South Australia’s Upper South East region found that there was a range of soil physicochemical constraints across different soil types. A study was instigated as a result of localised patches of declining plant growth being observed by farmers on the Avenue Plain; results confirmed that some soil types were highly saline, sodic and alkaline, creating hostile conditions for plant growth (Chapter 2 of this thesis). Multiple carbonate-rich horizons, both unconsolidated and indurated, were present within the top 2 m of the soil profile. Soils that supported good pasture growth typically had shallow grey surface soils that were not strongly saline or sodic, overlying an indurated carbonate horizon within 0.3 m of the surface. In contrast, the soils that expressed poor pasture growth were deep (> 0.6 m), black, clay rich and strongly alkaline, saline and sodic; the shallow indurated carbonate horizon was absent in these soil types (Chapter 3 of this thesis). In addition, another study found that a diverse range of clay minerals were present in these soils, including kaolinite, sepiolite, illite and smectite; the clay mineralogy also appeared to affect plant growth and proliferation when the soils were sodic (Chapter 2). These results and observations have raised the question of how these soils, and their contrasting chemical, mineralogical and morphological properties, formed in this landscape, given that these properties clearly affect plant growth.

4.1.1 Study setting

The study is located on the Avenue Plain in the Upper South East (USE) of South Australia (SA), in an area locally referred to as the Keilira district, which is situated between the East and West Avenue ranges (36.71°S 140.16°E). These ranges are two of thirteen prominent coastal barriers that feature on the Coorong to Mount Gambier Coastal Plain in SA's South East. Part of the Bridgewater Formation (Firman 1973), these Pleistocene barriers (dune ranges), are the product of shoreline sedimentation during successive interglacial maxima and various interstadials. Preservation of the original morphology of these landforms is the result of the interplay of the gradual uplift of the coastal plain, successive sea-level transgressions and regressions, and rapid calcrete genesis. The spatial separation of the ranges has been brought about by steady, epeirogenic uplift in response to Quaternary volcanism (Murray-Wallace *et al.* 1999).

Whereas much is known about the age, origin and morphology of these barriers (Schwebel 1983; Murray-Wallace *et al.* 1999; Huntley and Prescott 2001), little work has been conducted on the inter-dunal plains that separate the relic dunes. As part of the Coonambidgal Formation (Firman 1973), the Avenue Plain is one such area. Composed of both indurated and unconsolidated calcareous materials (continental carbonates) of predominantly lacustrine origin (Schwebel 1983), these sediments appear to have been deposited initially as part of a regressive sequence at the stabilised interglacial sea level, and then continued to accumulate in areas of outcropping watertable as the sea level retreated (Schwebel 1983). Any consideration of the origins of the soils in this region would therefore need to include investigations of the carbonates found here to determine the effect that the lacustrine sediments have had on mineral genesis and soil profile development.

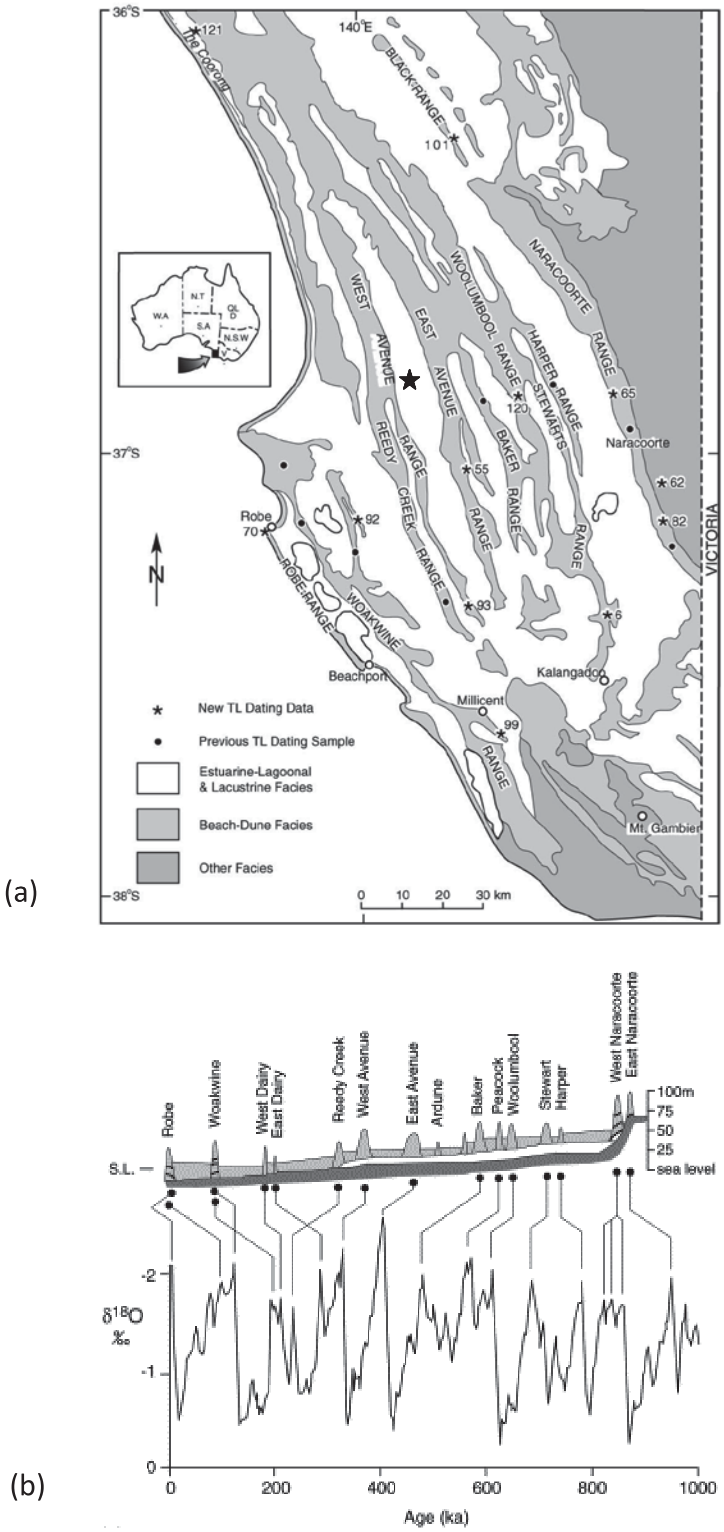

Fig. 4.1 Map showing the position (a) and predicted ages (b) of the relic coastal barriers in South East South Australia, from Huntley and Prescott (2001). The ★ denotes the location of the Keilira District on the Avenue Plain.

4.1.2 Types of continental carbonates and their identification

The types of minerals that accumulate in lacustrine sediments are affected by the source area, the salinity of the waters and hydrology of the lake basin (including output and input of surface water, rainfall and groundwater) and include primary precipitates, detrital and clastic materials and minerals formed through early – later diagenetic processes (Gierlowski-Kordesch 2010). Carbonates are a common precipitate found in lacustrine sediments, deposited mostly in the form of mud – sized material. They include carbonates and bicarbonates of Ca, Mg, Ba, Mn, Fe, Na and Sr (and varying combinations of these) to form minerals such as low Mg calcite, high Mg calcite, aragonite, magnesite, dolomite, siderite, trona and ankerite, to name but a few (Gierlowski-Kordesch 2010).

Recent research into the formation of continental carbonates, however, shows that their development in such sedimentary environments is affected by the interplay of many complex processes (Alonso-Zarza 2003). Of the vast range of continental carbonates, lacustrine and palustrine carbonates and calcretes are the common types formed in hydrologically restricted depositional environments, such as the Avenue Plain. Lacustrine carbonates are those deposited in saline and freshwater *perennial* lake systems of any depth (subaqueous), whereas palustrine carbonates include those formed in *ephemeral* lakes, including alluvial and fluvial systems, and on perennial lake margins. These environments typically have very low gradients and low water energy and are prone to the periodic exposure of the sediments (subaqueous to subaerial conditions) as the level of the lake water fluctuates (Gierlowski-Kordesch 2010). The term 'calcrete' is used to describe authigenic carbonate minerals that accumulate in the vadose and / or phreatic zones of the soil profile (Alonso-Zarza and Wright 2010b). A transition between these carbonates can also occur in any given landscape, as described in detail by Alonso-Zarza (2003) and shown in Figure 4.2.

Due to their depositional conditions and subsequent alteration, each of these types of continental carbonates exhibit characteristic facies (morphological characteristics). Petrographic examination of the facies and microfabrics therefore provide an indication of their origin and the environmental conditions under which they formed. Lacustrine carbonates commonly have a muddy texture and if lithified are referred to as mudstone, micrite or calcilutite; they generally contain > 80 % carbonate by weight (Gierlowski-Kordesch 2010). Marl and chalk are other carbonates that can form in lacustrine settings, containing between 20 – 80 % w/w and > 60 % w/w of carbonate respectively. Common petrographic features of lacustrine carbonates include the presence of charophytes (green algae), ostracods (bivalved micro-crustaceans) and molluscs (bivalves and gastropods) (Fig. 4.2). Palustrine carbonates, which form from lacustrine mud, exhibit signs of diagenesis and a loss of their primary muddy texture. Their diagenetic modification is driven by desiccation processes, root and soil organism activity and the remobilisation of carbonate and iron (Alonso-Zarza 2003). The common petrographic features observed in palustrine carbonates include desiccation cracks, mottling, and grains such as intraclasts, peloids and nodules (Fig. 4.2).

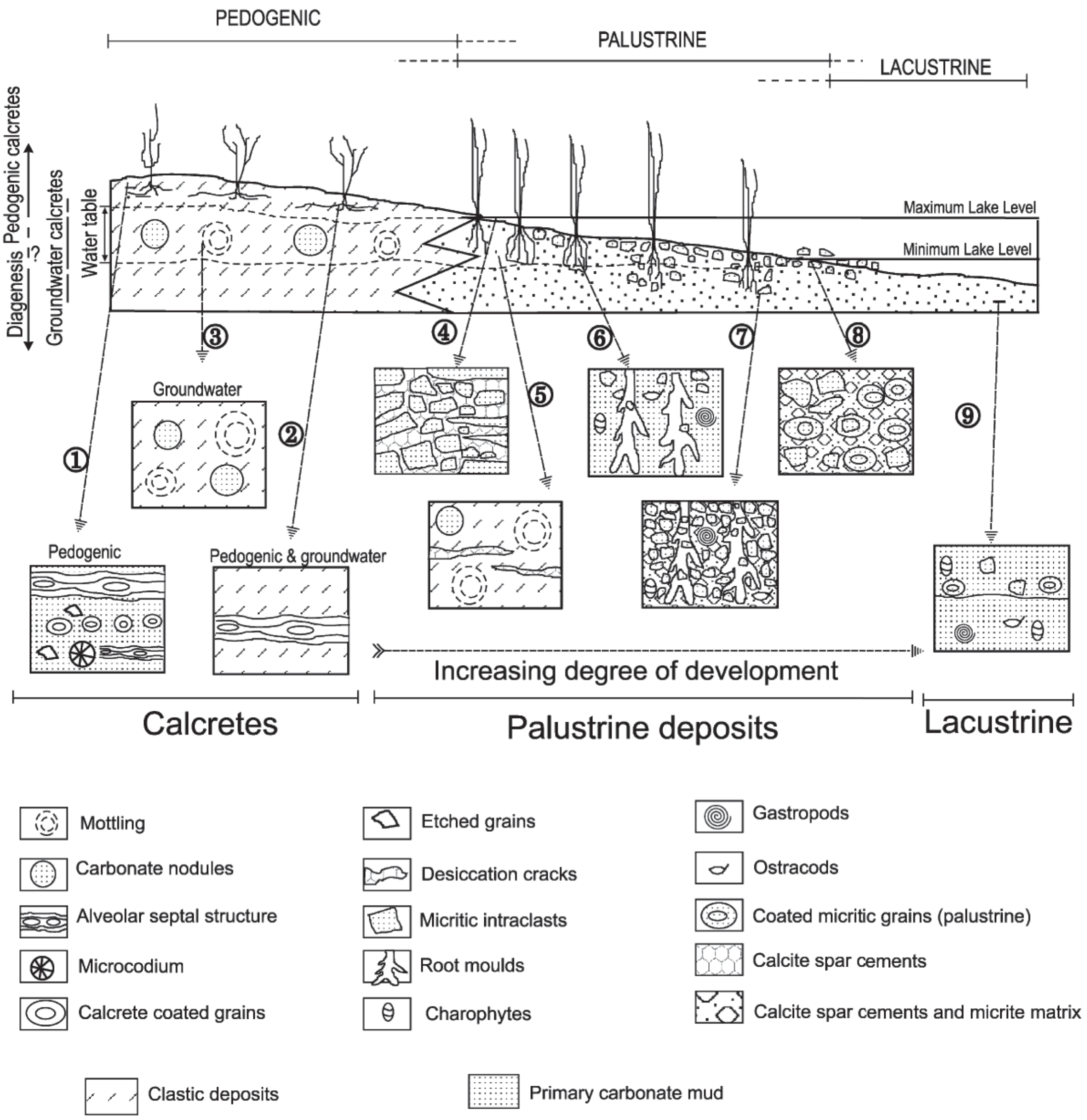

Fig. 4.2 Sketch of the depositional environments and common petrographic features of various lacustrine and palustrine carbonates and calcretes (pedogenic and groundwater) from Alonso-Zarza (2003).

In contrast, calcretes are formed by the precipitation of carbonates from meteoric soil and ground waters. They can form through pedogenic processes in the vadose zone of soils (above the groundwater table) or precipitate directly from groundwaters in the lower phreatic zone (Fig. 4.2) and are considered to be composed dominantly, but not exclusively, of $CaCO_3$. Their morphology can range from nodular and powdery to highly indurated (Alonso-Zarza and Wright 2010b). Under petrographic examination, carbonate nodules, mottling, calcrete coated grains and alveolar-septal structures (by-products of fungal activity), among others, may be observed (Fig. 4.2).

In addition to petrographic examination, oxygen and carbon stable isotope analyses are useful tools that can be used to help determine the types and origin of continental carbonates. As lacustrine, palustrine and calcrete carbonates precipitate from continental (non marine) solutions, either through inorganic precipitation or through biologically mediated processes (Deocampo 2010), they incorporate the isotopes of C, O and Sr within them. Stable isotopes are discussed in terms of their ratios, and most commonly the ratio of abundance of the second most common isotope, compared to the most common isotope, e.g. $^{13}C/^{12}C$ or $^{18}O/^{16}O$ (Halverson 2008). Isotopic ratios are typically expressed in *Delta* notation (δ), in which they are normalised against the ratio of a geologically meaningful and internationally recognised standard and expressed in per mil variations (‰). For terrestrial carbon and oxygen isotope analysis, the reference material used is Vienna Pee Dee Belemnite (VPDB) from the USA. The concentration of ^{13}C in a sample therefore is commonly expressed as $\delta^{13}C$, whereby: $\delta^{13}C = (R/Rs – 1) *100)$, where R = $^{13}C/^{12}C$ ratio in the sample, and Rs = $^{13}C/^{12}C$ ratio in the VPDB standard. Similarly, $\delta^{18}O$ is the ratio of $^{18}O/^{16}O$ in the sample, compared to the $^{18}O/^{16}O$ ratio of the VPDB standard (Halverson 2008).

Investigations of the composition and partitioning of stable isotopes can, in some instances, provide valuable information about the environmental and climatic conditions in which they were precipitated. Alonso-Zarza (2003) reports that oxygen isotope ($\delta^{18}O$) values of lacustrine carbonates reflect the isotopic composition of the lake water in which they formed, which in turn is affected by the isotopic composition of rainwater, potential evaporation, the influence of groundwater flows and any changes in water sources. In addition, Tanner (2010) reports that the oxygen isotope composition of pedogenic soil carbonates (vadose calcretes) is controlled by the $\delta^{18}O$ of the water from which the carbonate precipitates; which in turn reflects the mean annual temperature at the time of formation, with the carbonates becoming increasingly enriched with ^{18}O with higher mean annual temperatures and evaporation rates.

Additionally, carbon isotope ($\delta^{13}C$) levels in lacustrine carbonates are affected by the carbon isotope composition of the lake waters from which they precipitated. $\delta^{13}C$ values in lake carbonates are largely controlled by biogenic factors, whereby high rates of organic productivity cause a decrease in dissolved ^{12}C in the lake water, leading to an enrichment of ^{12}C in the precipitated lacustrine carbonates. However, $\delta^{13}C$ values can also be affected by the type of vegetation cover surrounding the body of water and this factor is more important in palustrine carbonates and calcretes than in any other lacustrine setting. If C_3 plants (trees, most shrubs, cool season grasses) are dominant in the area, the waters of the drainage basin will be enriched in ^{12}C and this too will be reflected in the precipitated carbonates (Alonso-Zarza 2003). Similarly, numerous factors control the carbon isotope composition of calcretes, including the C_3/C_4 vegetation ratio, the depth of carbonate accumulation, the temperature of carbonate precipitation, the isotopic composition of atmospheric carbon, and soil C productivity, which is largely dependent on the climatic regime (Tanner 2010). The isotope values of palustrine carbonates however can be very complex to interpret as soil processes and early meteoric diagenesis (vadose or phreatic) contribute to the modification of the primary isotope values (Alonso-Zarza 2003).

4.1.3 Previous studies of soils in the region

The bulk of the studies conducted on soils of south-east SA was performed between 1940 and 1970; a review of these findings can be found in Blackburn (1983). In an earlier publication, Blackburn *et al.* (1965) reported that the most widespread soils of this region were derived either mainly from calcareous beach sands, or from estuarine and lacustrine deposits; the former including podzol and terra rossa soils and the latter including ground-water rendzina and solodized solonetz soils. All of these soil types exhibit textural contrasts between the A (sand and clay textures) and B (calcareous) horizons, and it was observed that a hard, dense capping of calcium carbonate occurred at the interface; this was considered to be a secondary accumulation (Blackburn *et al.* 1965). A study of terra rossa and rendzina soils from the south-east of SA by Norrish and Rogers (1956) concluded that both soil types were residual from the underlying calcareous parent material, based on the assessment of their mineralogy, amount of iron present and particle size distributions. This theory was contradicted in a study by Giles (1960) who concluded that the trace element content of the acid insoluble part of the calcareous material was high enough to ensure that it could not have been the parent material of the A horizon. In addition, a recent study by Krull *et al.* (2006) concluded that the organic and inorganic history of texture contrast Red brown earths from the south-east region indicate that two distinct depositional and soil forming episodes were probably responsible for their stark texture contrast. Previous mineralogical studies of the A horizon of a rendzina found illite and kaolinite to be the dominant clay minerals with the iron oxides, goethite and haematite, also present. Reference was also made to an unidentified clay mineral, presumed to be a randomly interstratified mica, which the authors termed ‘hydrated mica’, although they acknowledge that this term was not strictly correct (Norrish and Rogers 1956); ‘very little’ was detected in contrast to ‘much’ illite and ‘moderate’ amounts of kaolinite. In the underlying limestone (calcareous B horizon), much calcite was detected, along with moderate amounts of illite and very little smectite and hydrated mica. These mineralogical findings somewhat concur with those reported in Chapter 2 of this thesis viz. some soils were dominated with illite and kaolinite, however, in other analyses in this thesis, smectite was the dominant clay mineral detected, in addition to sepiolite in some soils.

From the foregoing discussion it is evident that further investigation is required due to contradictory conclusions about the origin of soils and range of clay minerals reported here, together with recent advancement in our understanding of the different types of continental carbonates. The aim of this study therefore was to characterise the morphological, mineralogical and geochemical properties of contrasting soil profiles that are representative of some common types found in the Keilira District. The carbonates present were investigated through the study of their petrography and stable isotope geochemistry. Mineralogical and elemental investigations of the bulk soil and isolated clay sized (<2 µm) fraction was achieved using X-ray diffraction, X-ray florescence and transmission electron microscopy. These investigations aimed to determine the genesis and mode of alteration of clay and carbonate minerals in this landscape and their subsequent effect on plant growth.

4.2 METHODS

The physicochemical properties of three key profiles (T1, T2 and T3) from the study site were determined and reported previously (Chapter 3 of this thesis), however, some data are also presented here for context (Table 4.1). The methods used for their determination are reported in Chapter 3.

Mineralogy was estimated by X-ray diffraction (XRD) on both powder bulk samples and the oriented clay fraction (carbonate free). Air dried samples of soil and indurated horizons were initially ground to <100 µm in a Seib mill. A portion of the bulk powder sample was ground to a very fine powder in an agate mortar and pestle and back-pressed into welled-ingot sample holders. The mineralogy of the <2 µm fraction was determined following dispersion by ultrasonic probe and separation from the coarse fractions by sedimentation (Gee and Bauder 1986). The removal of carbonates from this fraction was achieved by the addition of acetic acid until all frothing ceased. 10 ml of 1 M calcium chloride was subsequently added to the clay fraction and, following centrifugation, the supernatant was decanted and the process repeated before washing with deionised H_2O and subsequently with ethanol. A 0.04g sample of the isolated calcium-saturated clay fraction was subsequently dispersed in deionised H_2O using an ultrasonic probe and oriented onto a porous filter membrane using a vacuum pump, solvated with 3 drops of glycerol and allowed to drain. XRD patterns from the whole powdered and oriented clay fractions were collected with a PANalytical X'Pert Pro Multi Purpose Diffractometer with a cobalt XRD tube operating at 40kV and 45mA with a flat graphite monochromator and programmable divergence slit. The mineralogical composition of the samples was derived from the patterns, aided by the Xplot program (Mark Raven, CSIRO, pers. comm. 2009).

Total chemical analyses (expressed as percentage of oxides) were obtained of a <2 mm fraction (carbonate free – removed with HCl) by X-ray fluorescence (XRF) spectroscopy using a PANalytical Axios advanced, wavelength-dispersive X-ray spectrometer. Major and trace elements were evaluated with beads produced by fusion with lithium borate following the method of Norrish and Hutton (1969) for all samples. XRD analysis was also obtained of the samples prepared for XRF, following the method for bulk powdered samples outlined previously. Micromorphological investigations of the <2 µm fraction of seven of the samples were conducted using a CM200 Phillips transmission electron microscope (TEM). Samples were dispersed in distilled H_2O and 1 drop of the suspension was allowed to dry on carbon support film on a copper-mesh TEM grid. An EDAX DX4 energy dispersive X-ray (EDS) detector was used to determine the elemental composition of some samples (Peter Self, CSIRO, pers. comm. 2010).

Petrographic and geochemical investigations were also performed, but only on the carbonate component of the profile. Whole rock samples were collected for each of the indurated horizons and thin sections were prepared from four of the samples. These samples were collected from the 0.27 – 0.4 m, 0.95 – 1.1 m and 1.3 – 1.5 m zones of profile T1 and from the highly indurated 0.7 – 1.3 m horizon of T3. Photomicrographs were obtained and their petrography briefly described by Pontifex (2010). The geochemistry of the carbonates in the soils was also determined, with $\delta^{13}C$ and $\delta^{18}O$ stable isotope data acquired simultaneously on a Fisons Optima dual inlet mass spectrometer attached to an Isocarb preparation device at the University of Adelaide, South Australia. Approximately 3 mg of powder was reacted in a common, purified H_3PO_4 bath at 90°C for 420 seconds. Evolved CO_2 was cryogenically distilled then measured against an in-house reference gas. $\delta^{18}O$ was corrected for equilibrium with H_2O during reaction using the Craig equation (Craig 1957) and both $\delta^{13}C$ and $\delta^{18}O$ samples were calibrated to VPDB using an in-house calcite standard. External error (1sd) based on house standards was better than ± 0.05‰ for $\delta^{13}C$ and about ± 0.1‰ for $\delta^{18}O$. All $\delta^{13}C$ and $\delta^{18}O$ values are reported with respect to the VPDB as per mil deviations (‰) (Galen Halverson, University of Adelaide, pers. comm. 2009).

4.3 RESULTS

Previous analysis showed there to be significant physicochemical differences between the three key profiles T1, T2 and T3 (Table 4.1); T3 stands out as being distinctly different from the other two profiles and was classified as a Vertosol. The soil here was deep, black (dry colour 5Y 2.5/1), clay-rich, very strongly alkaline, had a high CEC and was strongly sodic throughout. The exchange complexes of profiles T1 and T2, in comparison, were dominated by magnesium, exhibiting a much greater exchangeable magnesium percentage (EMP) than T3 (Table 4.1). Exchangeable potassium was also higher in these profiles than in T3. Calcium carbonate was detected in all samples.

4.3.1 XRD patterns of the Powder Bulk Samples

The XRD plots of the powder bulk samples for profiles T1, T2 and T3 are shown in Figure 4.3. Patterns from these samples are presented at different intensities for the collection angles 5 – 20 °2 θ and 20 – 40 °2 θ to enable greater resolution in the basal peak area for layer silicates and also for primary minerals. The vertical bar (⌶) represents 1000 counts in each case (intensity).

Table 4.1. Physical and chemical characteristics of profiles T1, T2 and T3.

Soil Depth (m)	$pH_{1:5}$ (H_2O)	OC (%)	Carbonate ($CaCO_3$ %)	Clay (%) (CO_3 free)	CEC (NH_4) cmol (+) / kg	Ca	Mg	Na	K	ESP (%)	EMP (%)
						Exchangeable Cations cmol (+) / kg					
Profile T1											
0.0 – 0.1	7.7	2.6	2.6	32.1	27.3	12.3	9.3	0.3	2.6	1.2	37.9
0.1 – 0.27	8.4	0.8	8.0	93.2	37.1	12.8	18.8	1.6	4.5	1.7	51.2
0.27 – 0.4	-	0.8	74.0	55.9	11.3	3.4	5.9	1.5	1.5	4.7	52.0
0.4 – 0.65	9.2	0.4	65.1	83.4	17.0	4.1	10.1	1.4	1.8	7.9	58.1
0.65 – 0.95	9.4	0.3	70.6	87.7	14.9	3.3	8.2	3.0	1.1	19.1	53.0
0.95 – 1.1	-	0.3	66.1	83.0	15.9	2.9	7.0	5.8	1.0	34.7	41.8
1.1 – 1.3	9.5	0.2	22.1	87.3	30.5	4.5	14.0	12.5	1.8	38.2	42.7
1.3 – 1.5	9.4	0.2	86.8	70.6	16.6	3.4	8.3	5.0	1.1	28.2	46.7
Profile T2											
0.0 – 0.1	8.38	1.8	21.5	68.6	35.7	19.0	8.5	0.7	2.3	2.4	28.0
0.1 – 0.2	8.9	0.5	73.2	81.1	12.5	4.2	8.1	1.1	0.7	7.6	57.5
0.2 – 0.5	9.5	0.3	82.7	86.1	11.3	1.9	7.4	2.5	0.5	20.5	60.4
0.5 – 0.8	9.5	0.2	74.9	83.9	10.1	1.8	5.0	3.3	0.5	31.1	47.1
0.8 – 0.87	-	0.2	84.7	55.5	7.9	1.0	2.5	2.5	0.4	38.5	38.5
0.87 – 0.9	9.4	0.3	17.0	61.2	27.0	4.4	12.2	8.8	1.3	33.1	45.5
Profile T3											
0.0 – 0.1	8.9	1.7	21.3	45.0	35.8	15.4	17.0	7.8	1.3	18.8	40.9
0.1 – 0.3	9.5	0.7	31.5	74.9	37.8	7.4	15.0	16.8	1.5	41.3	36.9
0.3 – 0.5	9.8	0.8	34.4	77.0	29.9	3.6	10.3	19.0	1.1	55.9	30.3
0.5 – 0.7	9.6	0.4	61.8	76.6	13.8	2.5	5.4	9.3	0.7	52.0	30.2
0.7 – 1.0	-	0.3	81.0	51.3	4.1	0.9	1.1	1.9	0.4	44.5	25.8
1.0 – 1.4	9.7	0.2	79.9	45.1	7.5	1.3	2.9	3.0	0.5	39.3	36.9

The major primary minerals detected included quartz, Mg-rich calcite and ankerite (iron-bearing dolomite), albeit at different proportions both within and across profiles.

The proportion of Mg-rich calcite detected by XRD is largely consistent with the percent of $CaC0_3$ determined previously (Table 4.1), viz. Mg-rich calcite was detected in relatively high proportions in the zone 0.27 – 1.1 m in profile T1 (Fig. 4.3), corresponding to a $CaC0_3$ content >65 %. Mg-rich calcite was less prevalent both above and below this zone, consistent with a $CaC0_3$ content <25 %. The amount of Mg-rich calcite detected in T2 and T3 is also consistent with $CaC0_3$ content measured (Fig. 4.3 and Table 4.1). The proportion of quartz appears to be inversely related to that of Mg-rich calcite. Trace amounts of K-feldspar, plagioclase and the Ti mineral, anatase, were also detected in the surface horizons of all profiles. Ankerite is present in the 0.27 – 0.65 m zone of profile T1 and throughout the profile of T2, but was only detected below 1 m in T3.

In the basal peak range of the XRD patterns from the powder bulk samples, the layer silicate minerals sepiolite, palygorskite, illite, kaolinite and smectite were detected. Sepiolite and palygorskite are two closely related fibrous clay minerals known to occur in lacustrine environments, however, sepiolite was only rarely found in soils (Singer 2002). In this study, sepiolite and palygorskite occur concurrently in most cases and were the predominant layer silicates detected in the powder bulk samples from profile T2 (Fig. 4.3). They also occur in zones of both low and high Mg-rich calcite/$CaCO_3$ content, such as in the clay-rich 1.1 – 1.3 m zone of T1 and the carbonate-rich 0.87 – 0.9 m zone of T2. Illite and kaolinite were the predominant clay minerals detected in the surface A and B horizons (0 – 0.27 m) of T1 that overlie indurated carbonate. The asymmetry of the kaolinite peak in the 0 – 0.1 m horizon and the low angle rise in 0.1 – 0.27 m pattern suggest that interstratified kaolinite/smectite minerals may also be present. Beneath this, sepiolite and palygorskite were predominant, whereas T3, in comparison, exhibited strong smectite peaks down to 0.5 m depth, with sepiolite and palygorskite detected primarily below this zone (Fig. 4.3).

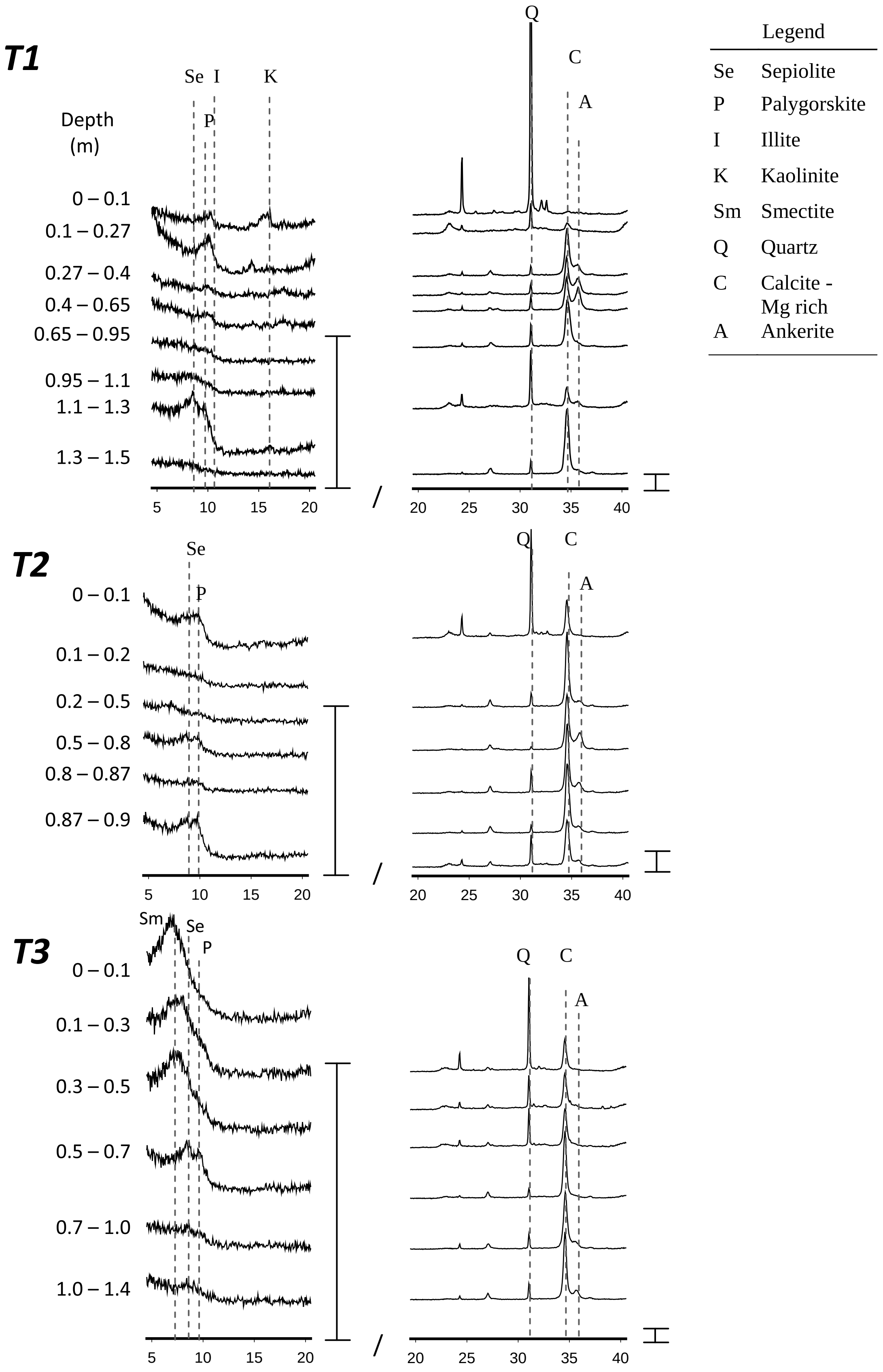

Fig. 4.3 XRD patterns of the bulk soil samples (pressed powder) for the three profiles investigated.

4.3.2 Elemental analysis

Quantitative analysis of the major elements (Si, Al, Fe, Mg, K, Ca and Na) was conducted by XRF on a carbonate free fraction of bulk soil (Table 4.2) and pressed powder samples of this fraction were also analysed by XRD.

Table 4.2. XRF Elemental and quartz XRD data for profile T1, T2 and T3

Soil Depth	LOI	SiO_2	Al_2O_3	Fe_20_3	MgO	K_20	CaO	Na_2O	Cl	Si:Al Ratio	Mg:Al Ratio	Quartz Intensity
(m)	(%)	Elemental composition expressed as oxides (%) (XRF fused beads)							%			XRD $CaCO_3$ free
Profile T1												
0.0 – 0.1	35.0	42.1	7.0	3.5	3.8	1.4	2.4	1.2	2.9	6.0	0.5	11,700
0.1 – 0.27	34.2	36.7	13.5	6.5	3.4	3.3	0.8	0.6	0.2	2.7	0.3	9,200
0.27 – 0.4	35.4	41.4	11.1	5.5	2.5	2.6	0.3	0.3	0.3	3.7	0.2	10,800
0.4 – 0.65	35.1	41.0	10.5	5.2	3.2	2.5	0.6	0.5	0.7	3.9	0.3	9,800
0.65 – 0.95	36.5	41.3	6.1	3.1	4.3	1.4	2.1	1.5	3.1	6.8	0.7	10,000
0.95 – 1.1	34.7	48.4	6.9	3.2	3.5	1.3	0.6	0.4	0.5	7.0	0.5	21,800
1.1 – 1.3	37.8	40.6	6.2	2.9	6.1	1.0	0.9	0.3	3.7	6.6	1.0	30,500
1.3 – 1.5	35.0	32.2	4.9	2.5	5.0	0.9	7.6	0.3	11.0	6.5	1.0	11,000
Mean	**-**	***40.5***	***8.3***	***4.1***	***4.0***	***1.8***	***1.9***	***0.6***	***2.8***	***5.4***	***0.6***	**-**
Profile T2												
0.0 – 0.1	35.5	45.4	7.7	3.4	4.2	1.6	0.9	0.5	0.2	5.9	0.6	18,500
0.1 – 0.2	33.6	54.7	5.1	1.8	1.0	1.5	0.4	0.9	0.2	10.6	0.2	70,600
0.2 – 0.5	35.2	45.5	6.8	3.2	3.2	1.6	1.5	0.8	1.7	6.7	0.5	7,300
0.5 – 0.8	37.9	35.6	4.7	2.3	5.4	0.9	5.1	2.2	5.5	7.5	1.1	5,900
0.8 – 0.87	39.3	45.5	6.3	2.8	3.6	1.3	0.2	0.3	0.2	7.2	0.6	19,300
0.87 – 0.9	37.3	47.4	5.2	2.3	4.1	1.1	0.7	0.7	0.9	9.2	0.8	17,400
Mean	**-**	***45.7***	***6.0***	***2.7***	***3.6***	***1.3***	***1.5***	***0.9***	***1.4***	***7.9***	***0.6***	**-**
Profile T3												
0.0 – 0.1	34.4	42.9	5.0	2.0	11.5	0.9	2.0	0.4	0.4	8.5	2.3	33,900
0.1 – 0.3	35.2	39.2	5.8	2.6	14.0	1.0	1.0	0.3	0.4	6.8	2.4	12,000
0.3 – 0.5	39.0	41.0	4.8	2.4	8.6	1.0	0.8	0.6	1.1	8.6	1.8	16,000
0.5 – 0.7	40.3	34.6	3.5	1.7	5.4	0.7	4.6	2.4	6.3	9.9	1.5	7,300
0.7 – 1.0	33.4	52.8	5.2	2.1	2.9	1.2	0.7	0.5	0.6	10.2	0.6	36,000
1.0 – 1.4	33.4	50.1	6.9	2.9	3.4	1.3	0.6	0.4	0.4	7.3	0.5	26,500
Mean	**-**	***43.4***	***5.2***	***2.3***	***7.6***	***1.0***	***1.6***	***0.8***	***1.6***	***8.6***	***1.5***	**-**

The major primary minerals detected by XRD on these samples included quartz, orthoclase and albite, which account for the presence of some of the Si, Al, Na and K detected in the samples. However, there were also peaks for layer silicate minerals in virtually all of the samples. These were identified as sepiolite, palygorskite and /or smectite along with occasional illite and kaolinite, all of which contribute to the Al, Mg and K also detected in the samples. The presence and combination of these primary and layer silicate minerals results in different elemental compositions. Si levels vary both within and across the profiles and in both T1 and T3, the highest Si content was recorded in the indurated 0.95 – 1.1 m and 0.7 – 1.0 m horizons, with values of 48.4 % and 52.8% respectively. In T2, however, relatively higher Si values were recorded throughout (mean 45.7 %). From these data it can be seen that profile T1 was enriched with Al, Fe and K in comparison to T2 and T3 (Table 4.2). This enrichment largely occured in the 0.1 – 0.65 m zone, resulting in the lowest Si:Al ratios observed (2.7 – 3.9; Table 4.2). There was also an enrichment of Mg in T3, largely in the surface 0 - 0.5 m zone that is much greater than in the other two profiles. Mg does, however, become more prevalent in T1 with depth, exceeding 5 % in the 1.1 – 1.5 m zone. This enrichment of Mg occurred in the zones where smectite was detected by XRD in some of the samples.

Ca and Na contents were relatively low in the majority of samples, although one significant trend is evident. In the zones 0.65 – 0.9 m and 1.3 – 1.5 m of T1, 0.5 – 0.8 m of T2 and 0.5 – 0.7 m of T3, the proportion of both Ca and Na is elevated (Table 4.2). However, Cl levels were also elevated in these zones (up to 11%). The removal of carbonates from these samples was facilitated via the addition of HCl; it is therefore concluded that insufficient washing of the samples prior to XRF analysis resulted in the elevated Ca, Na and Cl content detected, because of the formation of CaCl and NaCl following this treatment.

4.3.3 XRD patterns and TEM of the <2 µm fraction

The dominant layer silicate minerals detected by XRD in the <2 µm samples corresponded to those identified in the powder bulk samples (smectite, sepiolite, palygorskite, illite and kaolinite). Illite and kaolinite occur concurrently and were predominant in the shallow grey (dry colour 10YR 5/1) surface soils (0 - 0.27 m) of profile T1 (Fig. 4.5) where TEM investigations detected an abundance of primary minerals and unweathered material, such as diatoms (Fig. 4.4*a*) and quartz grains. EDS (not shown) also confirmed the presence of anatase (Fig. 4.4*b*) as identified in the powder bulk sample for this horizon (Fig. 4.3). Despite the absence of sepiolite and palygorskite XRD peaks in this zone (from both the powder bulk and <2 µm fraction), a few fibrous rods were evident in TEM images in both horizons (Fig. 4.4 *c* and *e*).

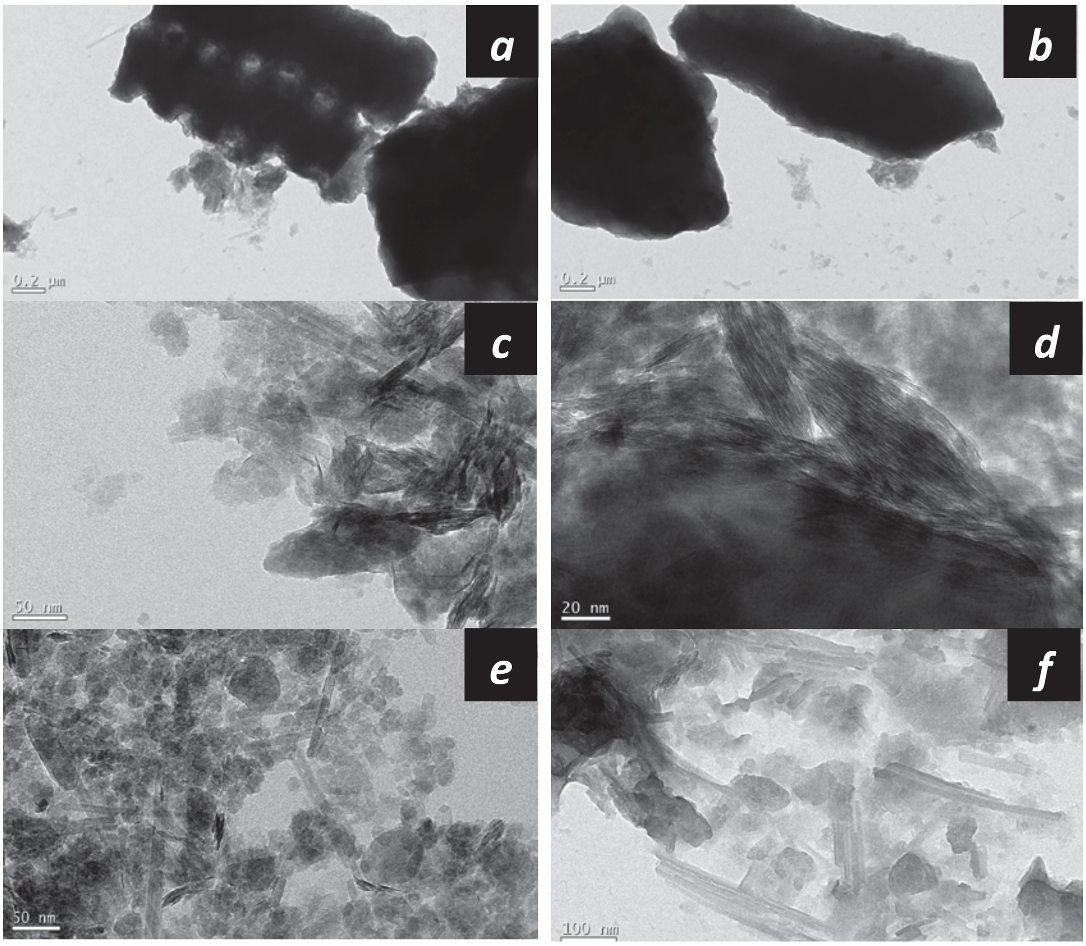

Fig. 4.4 TEM images *a*, *b* and *c* from the 0 – 0.1 m horizon of T1; *d* and *e* from 0.1 – 0.27 m of T1; *f* 1.1 – 1.3 m of T1.

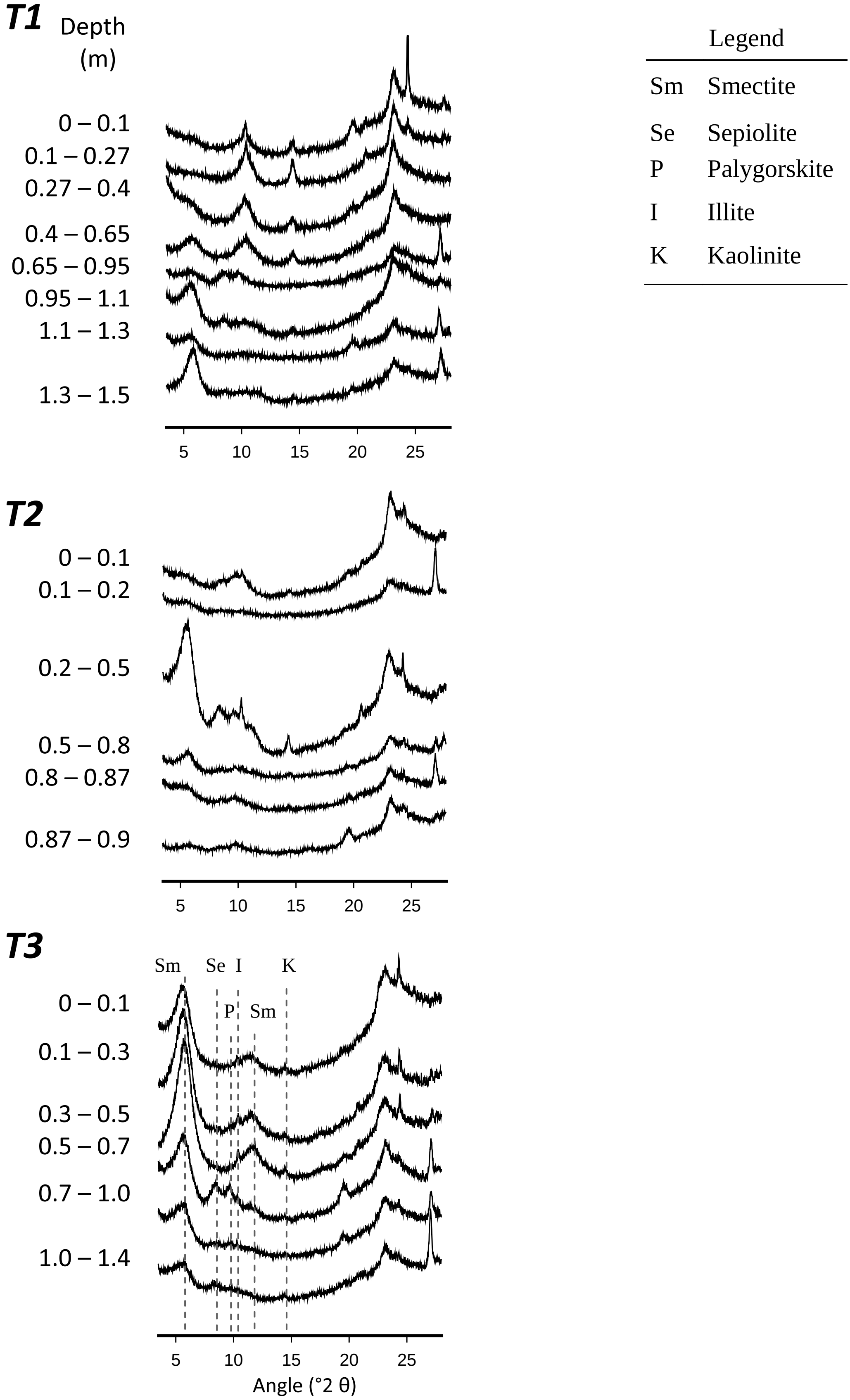

Fig. 4.5 XRD patterns from the <2um fraction of $CaCO_3$ free soil (oriented).

Below 0.27 m, illite and kaolinite were still detected, but smectite becomes more prevalent with depth. Sepiolite and palygorskite were detected in the 0.65 – 1.1 m carbonate rich zone (Fig. 4.5). Below this depth, however, in the clay-rich 1.1 – 1.3 m horizon, sepiolite and palygorskite were not detected by XRD in the <2 µm fraction, despite the presence of small peaks for these minerals in the powder bulk sample (Fig. 4.6*a*) and the detection of fibrous rods by TEM (Fig. 4.4*f*). Whereas palygorskite and sepiolite are generally unstable in acids, the presence of a palygorskite peak in the carbonate-free powder bulk samples (Fig. 4.6*c*) suggests that it was not destroyed in this case, despite being treated with HCl.

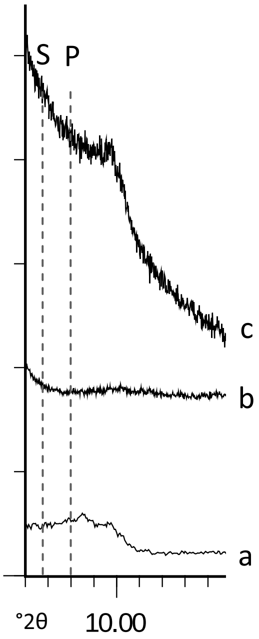

Fig. 4.6 XRD Peaks of T1 1.1 – 1.3 m zone indicating sepiolite (S) and palygorskite (P) in (a) bulk sample (b) the $CaC0_3$ free <2 µm sample and (c) $CaC0_3$ free bulk sample.

In view of earlier observations (Marshall 1964; Abdul - Latif and Weaver 1969) that sepiolite is considerably less stable than palygorskite, it appears that sepiolite was completely destroyed with HCl treatment, but palygorskite was not. This observation also holds true for the samples from T2 0.5 – 0.8 m and for T3 0.7 – 1.0 m. The absence of both minerals in the <2 µm sample (Fig. 4.6*b*) is therefore attributed to the insufficient removal of carbonates with acetic acid, leading to the incomplete dispersion of the clay fraction.

Similar mineralogical trends were observed in profile T2, with illite and kaolinite present in the shallow horizons and with increasing amounts of smectite, sepiolite and palygorskite detected with depth (Fig. 4.5). TEM investigations showed the predominant presence of micaceous minerals (Fig. 4.7) in the A horizon (0 – 0.1 m).

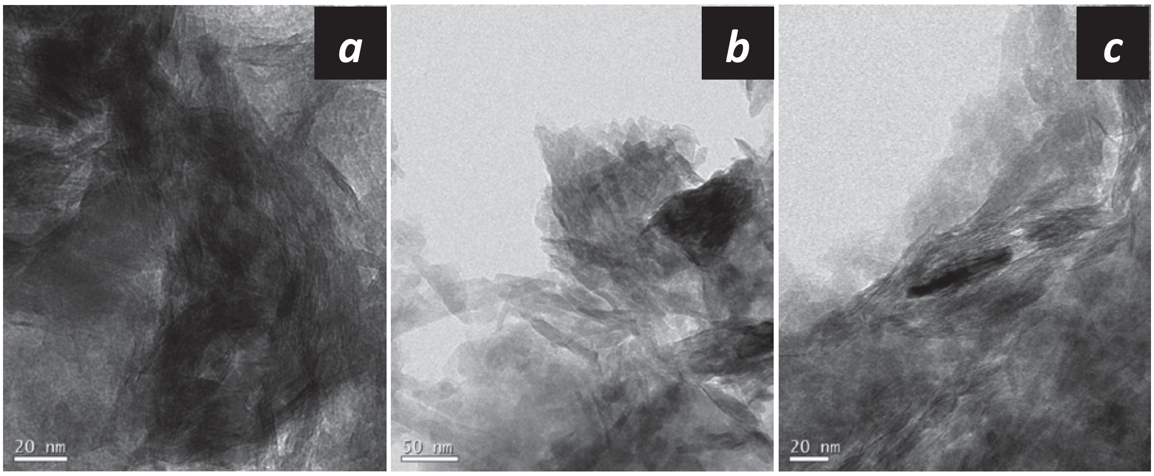

Fig. 4.7 TEM of the clay fraction of the 0 – 0.1 m horizon of T2.

Profile T3 in contrast, exhibits strong smectite peaks in the zone 0 – 0.5 m, with trace amounts of illite and kaolinite also detected (Fig. 4.5); this is consistent with the CEC measured (> 30 cmol (+)/kg). Below this depth, illite and kaolinite are not detected and the smectite peaks become less intense, coinciding with the presence of sepiolite and palygorskite below this depth.

Smectite minerals were predominant according to TEM in the surface 0 – 0.1 m horizon (Fig. 4.8*a* and *b*), with few palygorskite/sepiolite minerals also detected in the 0.1 – 0.5 m zone (Figs. 4.8*c* – *f*), however, smectite is the dominant mineral in the images. EDS analyses (not shown) of the smectite showing high Mg suggests that it is saponite, a Mg rich 2:1 layer silicate smectite mineral.

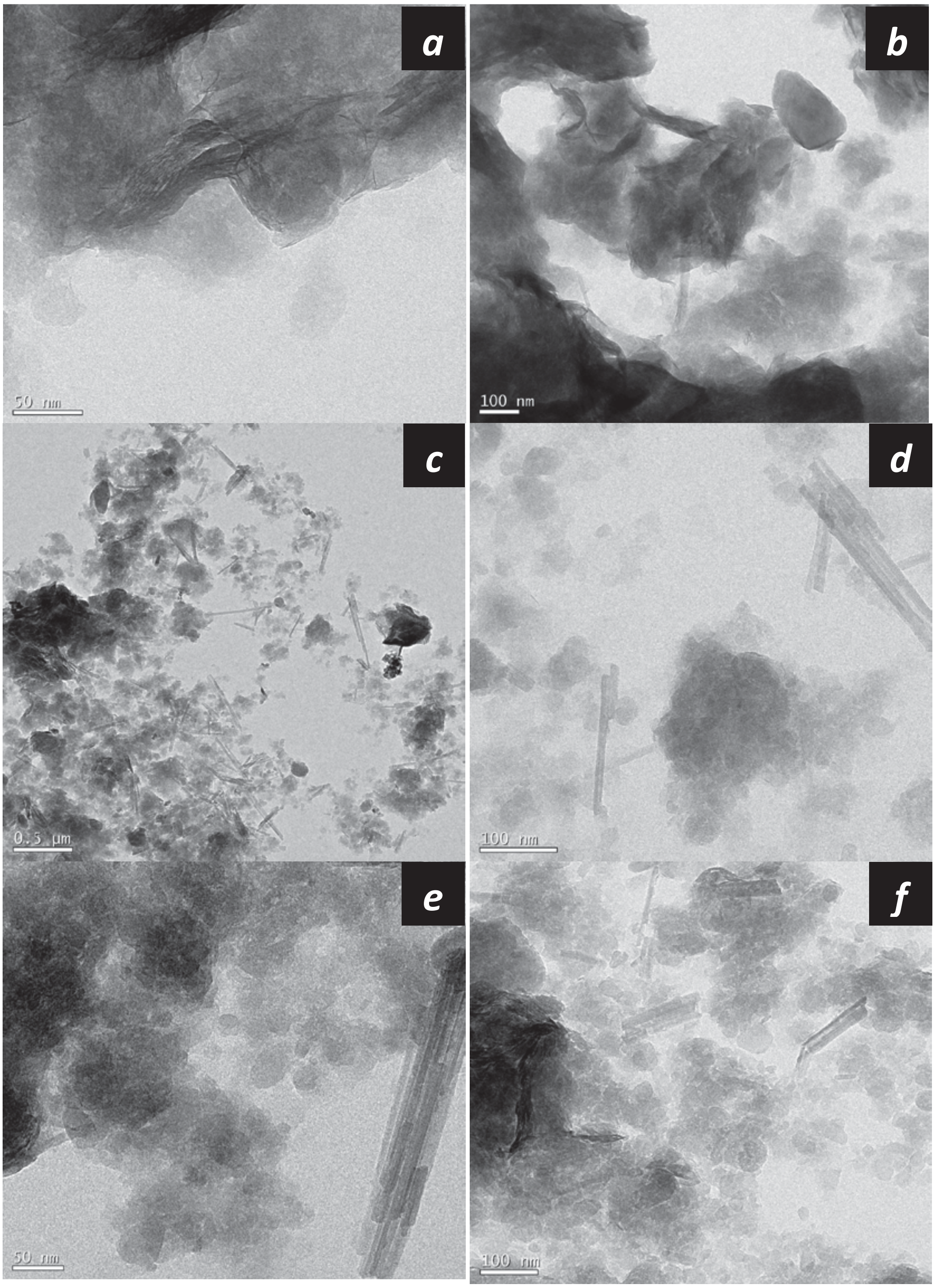

Fig. 4.8 TEM images: *a* and *b* 0.0 – 0.1 horizon of T3; *c* and *d* 0.1 – 0.3 m horizon of T3; and *e* and *f* from the 0.3 – 0.5 m horizon of T3.

4.3.4 Petrographic examination

Three distinctive types of carbonate were detected in the studied profiles. These included highly indurated zones (such as 0.27 – 0.4 m of T1), zones composed of powdery marl (0.1 – 0.8 m of T2) and powdery nodules within the soil matrix (0 – 0.5 m of T3). Petrographic examination was only conducted on four samples of the indurated carbonate collected in the study. Some were found to mainly contain peloids and intraclasts cemented in a micrite (finely-textured microcrystalline calcite) matrix of varying colour and heterogeneity, whereas others contained massive fabrics. Peloids are identified as more or less rounded grains, up to several mm in width, coated with irregular micritic laminae. Intraclasts are irregular fragments that can be rounded to angular in shape, ranging in size from less than a mm to several cm long. Both peloids and intraclasts largely consist of micrite; some clay may also be present. Desiccation cracks were also prominent in some samples, whereas fossils were observed in others.

Examination of the photomicrograph from the 0.27 – 0.4 m horizon (Fig. 4.9) of T1 show it to be largely heterogeneous. This sample is composed of loosely packed and weakly layered stained peloids and intraclasts ranging in size from 0.2 to 5.0 mm, cemented in a micritic matrix. Irregular and generally elongate desiccation cracks are prominent both within the intraclasts and the intragranular pores. Numerous smaller rounded pores are also present; much of the pore space is lined with an irregular clear carbonate and some with clay minerals. The sample also contains mottled areas that are generally concentrated around the desiccation cracks, indicating the oxidation of Fe; few small quartz grains are also visible in the section.

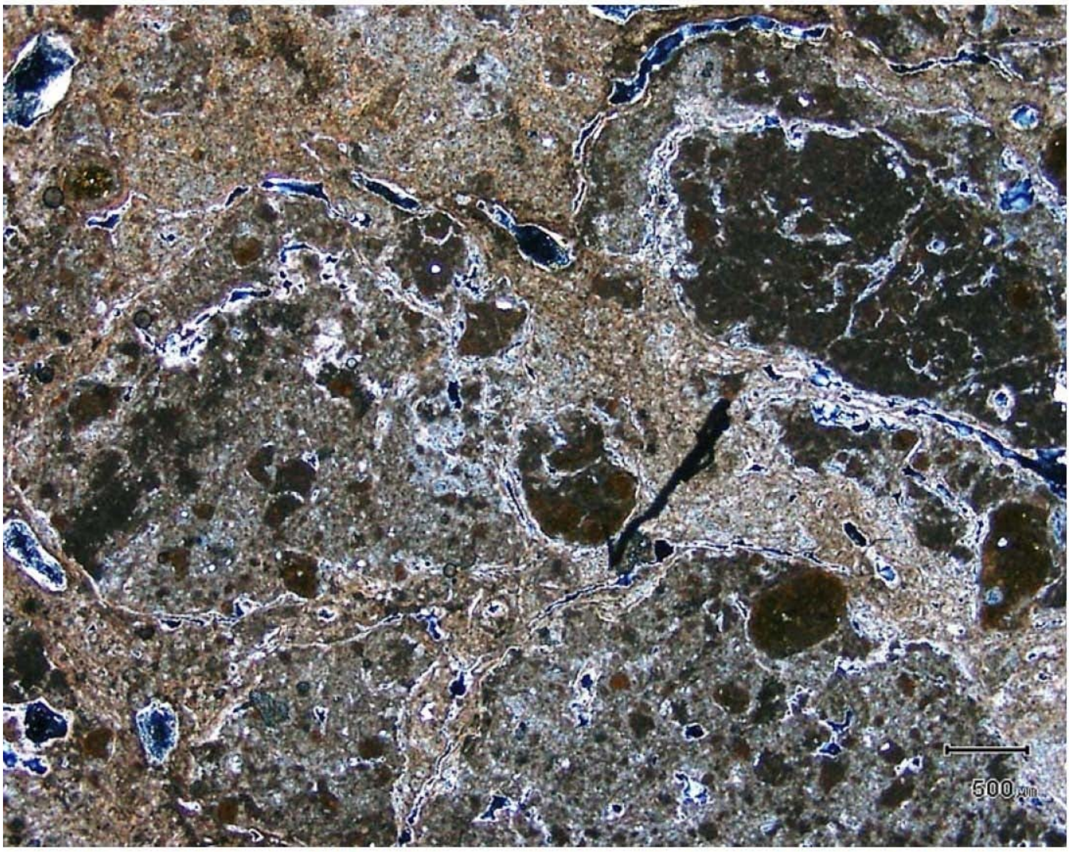

Fig. 4.9 Photomicrograph of T1, 0.27 – 0.4 m horizon. Crossed nicols (Xnic).

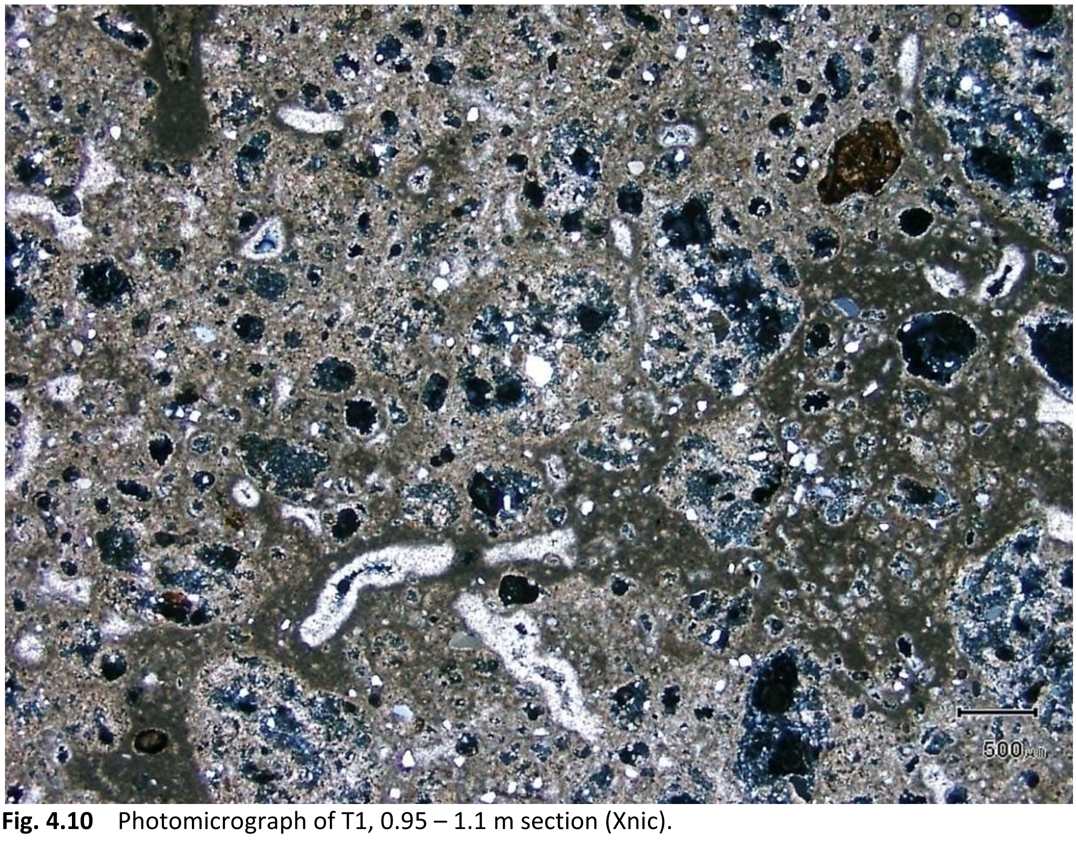

Fig. 4.10 Photomicrograph of T1, 0.95 – 1.1 m section (Xnic).

The 0.95 – 1.1 m horizon of this profile is composed of an irregular micritic matrix with up to 20% scattered porosity (Fig. 4.10). There are also many random irregular scalloped patches that are optically clouded (up to 20 mm long). Pores are mostly rounded, ranging in size from 0.5 to 3 mm; significantly larger than the elongate voids (generally 0.2 x 1.0 mm in size) observed in the shallower 0.27 – 0.4 m horizon (Fig. 4.10). Some elongate voids are also present in the deeper sample and are mostly lined with a clear microcrystalline secondary carbonate; however this lining is thicker than the lining seen in the pores of the shallower sample.

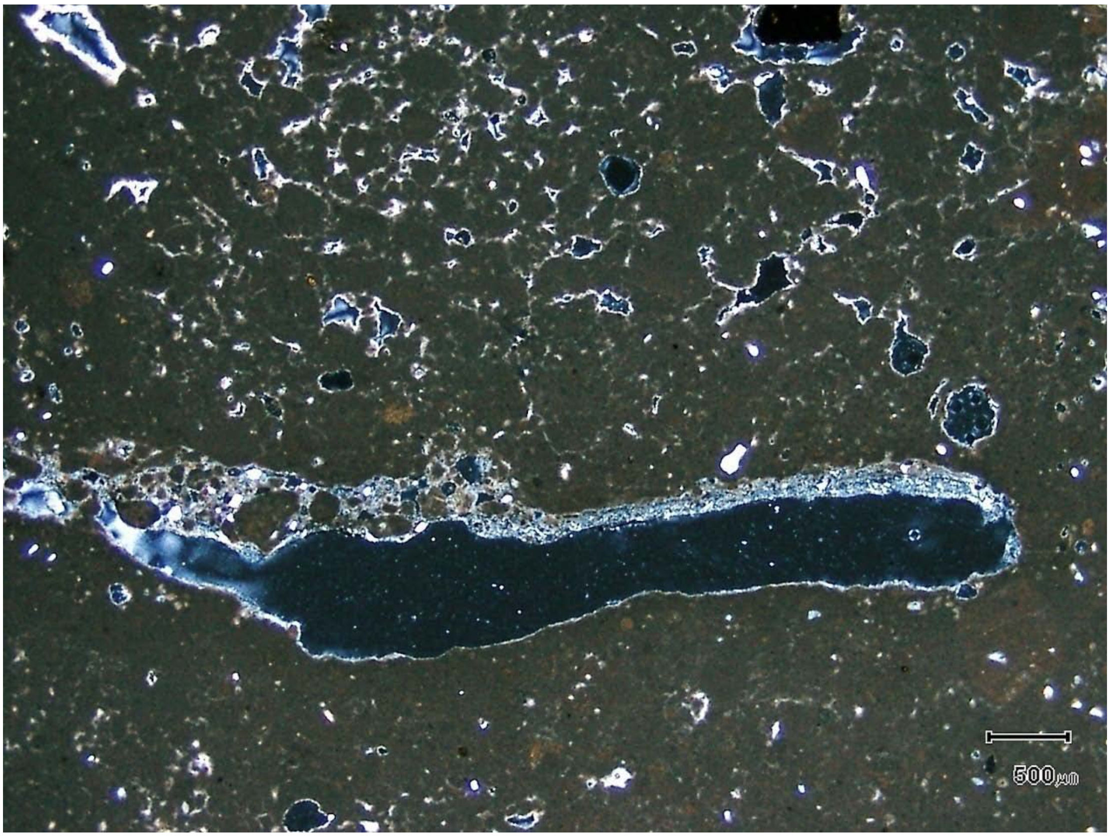

Fig. 4.11 Photomicrograph of T1, 1.3 – 1.5 m horizon (Xnic).

Below this horizon, in the 1.3 – 1.5 m zone (Fig. 4.11), the matrix is highly indurated, fairly homogenous and optically clouded, and can be described as a massive micrite (Gierlowski-Kordesch 2010). A weak layering of discontinuous, streaky fissures, occupying about 15% of the sample are also present; many of these are lined with clear secondary carbonate, apparently so finely divided that it can be characterised as cryptocrystalline. The top half of this thin section appears more nodular and exhibits greater porosity; below the large fissure (lined on the upper-side by nodules, intraclasts and calcite) the matrix is massive.

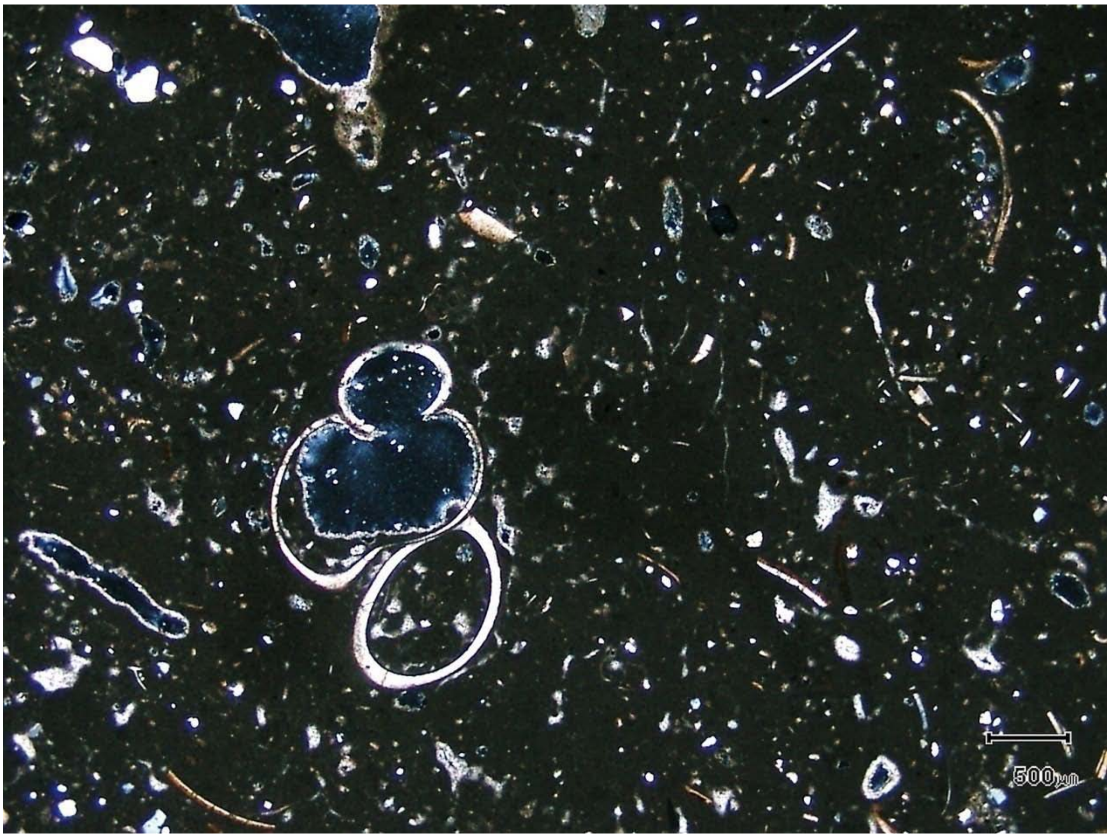

Fig. 4.12 Photomicrograph of T3, 0.7 – 1.0 m section (Xnic).

The carbonate intercepted in the 0.7 – 1.0 m zone of profile T3 was observed to be an optically clouded, massive micrite that is essentially the same as that found in the 1.3 – 1.5 m zone of T1 (Fig. 4.12). This section, however, also incorporates scattered and weakly layered microfossils and fossil fragments (molluscs). Few irregularly shaped pores are present and are largely occupied by a thin layer of clear cryptocrystalline carbonate. Many quartz sand grains are scattered throughout the sample and appear larger than those seen in T1.

4.3.5 Isotopic analysis

Isotopic analysis of the carbonates showed a wide variation of signatures between the profiles. In the upper 0.8m, T1 and T3 show the greatest difference in their δ^{13}C and δ^{18}O values with an average δ^{13}C of -7.42 and -5.24 ‰ and δ^{18}O of -0.67 and +0.56 ‰ respectively. T2 values lie between the two with average δ^{13}C and δ^{18}O values of -6.85 and +0.06 ‰ respectively. The carbonates present in the upper 0.4 m of profile T1 were isotopically lighter in both O and C than in profiles T2 and T3, with positive covariance of δ^{13}C and δ^{18}O values generally observed (Fig. 4.13).

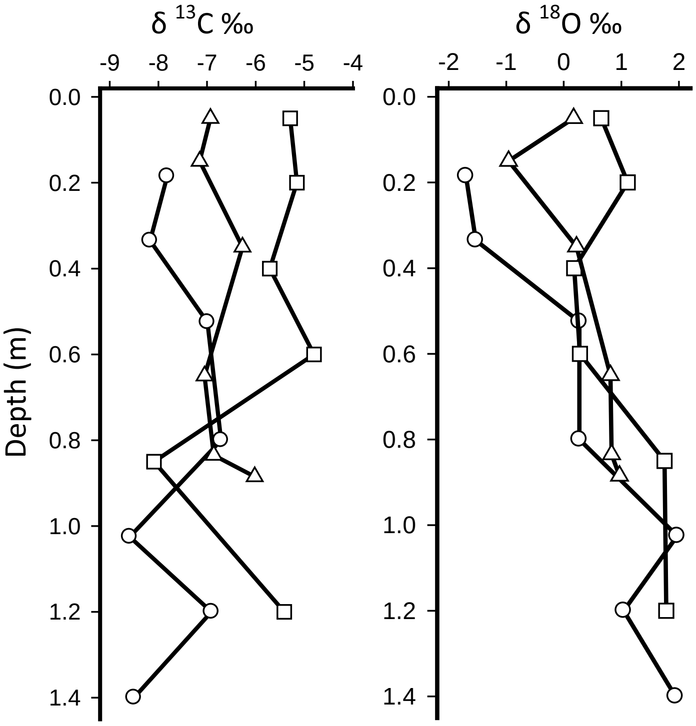

Fig. 4.13 Isotopic signatures of the three key profiles, T1 (○), T2 (△) and T3 (□).

In the mid section of all profiles (0.5 – 0.8 m) similar δ^{13}C and δ^{18}O values were recorded. Below 0.8 m, inverse covariance is observed in the indurated carbonate horizons of both T1 (0.95 – 1.1 and 1.3 – 1.5 m) and T3 (0.7 – 1.0 m), with similar O and C isotope values recorded for both profiles.

4.4 DISCUSSION

The aim of this study was to investigate the mineralogy, morphology and geochemistry of the clay and carbonate minerals that are present in the soils at Keilira and to attempt to determine their genesis in the landscape. In regard to clay minerals, the dominant types detected were smectite, sepiolite, palygorskite, illite and kaolinite. The carbonates were Mg-rich calcite and ankerite; different morphologies were present, with indurated, marl, and soft powdery forms occurring. Much quartz was also detected, both in the surface and at depth. The proportions of these minerals was highly variable both within and between profiles; it is likely that relationships between the clay and carbonate species occur. The types and genesis of these minerals will be discussed here in further detail.

4.4.1 Genesis and types of clay minerals

Analysis of the clay minerals reveals three distinct mineralogical relationships: horizons dominated by illite and kaolinite, horizons dominated by sepiolite and palygorskite in addition to smectite, and horizons dominated by smectite alone.

Illite and kaolinite were detected in every profile, however they were most dominant in the zone of shallow top soil in T1 (0 - 0.27 m). This zone contained only trace amounts of Mg-rich calcite and ankerite, consistent with the $CaC0_3$ content <10 %. TEM investigations of this zone revealed an abundance of primary minerals and unweathered materials, such as diatoms and quartz grains (Fig. 4.4*a* and *b*); anatase was detected by EDS and both K-feldspars and plagioclase were also detected by XRD. These observations are supported by elemental data that show there to be the greatest proportions of both elemental Al and K in this zone in comparison to profiles T2 and T3 (Tables 4.1 and 4.2). From these observations we propose that kaolinite, in addition to the other primary minerals detected here, is mostly detrital in origin, having been transported by the surface waters that once seasonally inundated this landscape (Holmes and Waterhouse 1983). Despite the indication of distinct illuviation in profile T1 (clay content increases to >90 % in the 0.1 – 0.27 m zone), these primary alluvial materials have mostly remained stratified due to the presence of the indurated carbonate over which they lie (0.27 – 0.4 m). One anomaly does occur, however, in respect to kaolinite. In the 0.1 – 0.27 m horizon of profile T1, a relatively large sharp kaolinite peak is detected in the <2 µm pattern (Fig. 4.5), despite this mineral being almost undetected in the bulk sample (Fig. 4.3). However, in the bulk sample, a significant rise is seen in the pattern at low angle, although no smectite was specifically detected. Chemical data for this horizon shows extremely high CEC for a soil dominated by illite and kaolinite alone, high exchangeable Mg and the highest FeO_2 content for any sample. The combination of these factors may indicate that kaolin-smectite interstratification occurs in this horizon, brought about by the alteration by weathering of smectite, which is known to produce kaolin and iron oxides as a result of improved drainage (Borchardt 1989; Churchman *et al.* 1994).

The origin of illite is also difficult to conclusively establish. Fe-rich authigenic illite has been identified in soils of lacustrine origin in Australia, and particularly in soils from Willallooka in the USE, which is located only 40 km from this study site (Norrish and Pickering 1983). These minerals were characterised by their very uniform shape and size (~0.07 µm), which is much smaller than the minerals found here (Fig. 4.4). Therefore, given the distinct lack of $CaC0_3$ in this zone and the non-uniform shape and size of the clay minerals, it is unlikely that this material is the diagenetic product of a lacustrine deposit. Also, as this mineral generally occurs concurrently with kaolinite, quartz and feldspars, it is likely to also be of detrital origin. Illite and kaolinite were both detected in profiles T2 and T3, albeit as minor components; their ubiquitous presence throughout these profiles is the result of periodic surface water inundation in this region and the absence of a shallow indurated horizon.

Mg-rich clays were also detected in this study. Non-carbonate minerals such as these are known to precipitate directly from solution in lacustrine and palustrine environments, (Akbulut and Kadir 2003; Bustillo and Alonso-Zarza 2007; Alonso-Zarza and Wright 2010a) and whereas illite and kaolinite appear to be principally detrital in origin, as discussed, we propose that smectite, palygorskite and sepiolite are authigenic lacustrine and palustrine precipitates. However, further analysis reveals some distinct relationships. In profile T3, EDS analysis of the clay minerals indicated that the smectite present was likely to be saponite, which is a Mg-rich layer silicate mineral. To confirm this, further analysis of the XRD patterns collected from the powder bulk samples (carbonate free) (Fig. 4.15) from the 0 – 0.1 m layer of T3, shows a distinct peak at 71.5 °2θ that corresponds to the 060 peak of saponite, which being a trioctahedral smectite gives a 060 spacing between 1.525 and 1.54 Å (Fanning and Keramidas 1977).

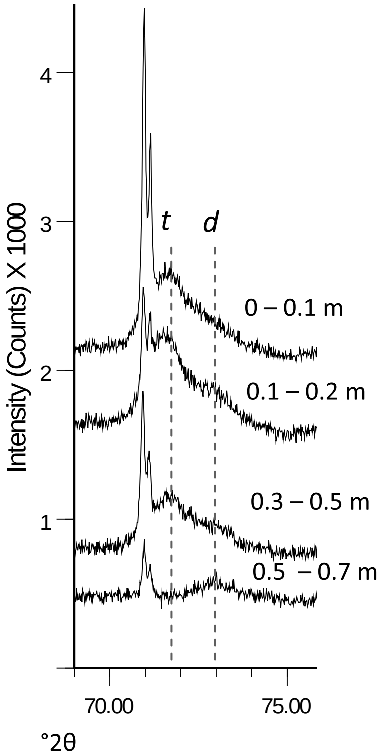

Fig. 4.14 XRD peaks for the 0 - 0.7m zone of profile T3, showing the presence of a trioctahedral (060) peak (*t*) in the 0 – 0.5 m horizons, and a dioctahedral (060) peak (*d*) in the 0.5 – 0.7 m horizon.

Another peak is also detected in some cases at 70.9 °2θ, corresponding to Fe-rich saponite. This generally occurs as a shoulder on the high angle side of a sharp peak that can be attributed to quartz. Furthermore, no peaks were detected for the 060 spacing of dioctahedral smectites, which is close to 1.50 Å (Fanning and Keramidas 1977) in the 0 - 0.1 m horizon (Fig. 4.14), confirming the presence of smectite as saponite in this horizon. This was also the case throughout the 0.1 – 0.5 m zone; however a slight, but broad peak is also visible on the high angle side of the trioctahedral 060 peak. Below this, in the 0.5 – 0.7 m horizon, a trioctahedral 060 peak was not detected, but a dioctahedral 060 peak was. Montmorillonite and beidelite are the two most common dioctahedral smectites found in soils (Churchman 2000) and this peak at 72.9 °2θ corresponds to the (060) 1.50 Å spacing for montmorillonite. XRD analysis of the <2 µm fraction shows a reduction in the intensity of the smectite peaks in the 0.5 – 1.0 m zones (Fig. 4.5), corresponding with the increased intensities of sepiolite and palygorskite peaks. Upon further investigation, it appears that the 0 – 0.5 m zone of T3 is the only part of any of the profiles to contain saponite (as confirmed by the trioctahedral 060 peak), and where this occurs, no sepiolite and palygorskite were detected by XRD. In all other profiles, as in other parts of T3, where a smectite peak is detected, in addition to sepiolite and palygorskite in the layer silicate region, only a dioctahedral 060 peak was found, indicating that the smectite is montmorillonite. In no cases were there strong peaks for both dioctahedral and trioctahedral smectites. This relationship was also found in a study of a saline lacustrine environment in Brazil; this feature was attributed to the position in the landscape, wherein the smectite minerals in the upper zone of the landscape (outside the level of seasonal lake variation) were found to be dioctahedral (ferribeidellite), and the smectites in the lower zones (within the area of seasonal lake level variation) were trioctahedral (stevensite and saponite) (Furquim *et al.* 2010).

Saponite, sepiolite and palygorskite have been shown to form either through direct precipitation from alkaline lake waters or authigenically from interstitial pore-water (Akbulut and Kadir 2003; Yeniyol 2007). Their formation commonly occurs in alkaline lacustrine environments at high pH, and is considered to be controlled by the concentration of Si, Mg, Al and Fe, rather than by mutual transformation. Palygorskite has however been found as a diagenetic transformation product of other inherited clay minerals where sepiolite and Mg-smectite were found as chemical precipitates in a lacustrine environment (Torres-Ruiz *et al.* 1994). It has also been concluded that palygorskite can feasibly form pedogenically from soil water, given the right elemental composition (Singer 1974). As seen in table 4.3, saponite occured in the absence of sepiolite, palygorskite and ankerite and contained very high elemental Mg. A similar observation was made by Leguey *et al.* (2010), who reported that the concentration of tri-octahedral smectites in a lacustrine sediment was the lowest when sepiolite was present in the highest concentrations.

Table 4.3 Key properties of the layer silicate minerals detected.
N.B. + = 0 – 3 %, ++ = 3 – 6 %, +++ = 6 – 9 %, ++++ >9 %, - = not present, P = present

Predominant minerals detected by XRD	$pH_{1:5}$ (H_2O)	Element composition as oxides (%)				Other mins. detected by XRD	
		MgO	Al_3O_2	Fe_2O_3	K_2O	Ankerite	Sep. and Paly.
Saponite	>9	++++	++	+	+	-	-
Montmorillonite	>9	++	++	+	+	P	P
Sepiolite and Palygorskite	>9	++	+++	++	+	P	P
Illite and Kaolinite	<9	++	++++	++	++	P	trace

Regardless of their genesis by direct precipitation or diagenetic transformation, the formation and stability of these minerals requires an alkaline environment and relatively high activities of Si and Mg (Neaman and Singer 2004); palygorskite also requires the input of Al. Nonetheless, ankerite is a (Fe-bearing) dolomite species and the observation that this mineral is absent in the presence of saponite is intriguing, indicating that Mg in solution is partitioned between carbonate and silicate phases. This phenomenon has been reported previously, where the Mg content of authigenic clays is relatively low when associated with widespread dolomite beds, and is much higher when only calcite is found (Alonso-Zarza 2003; Deocampo 2010). Two scenarios for saponite formation are therefore possible; the first is that saponite was a primary precipitate in the absence of ankerite, and the second is that ankerite was present, but has undergone dissolution. In the first scenario, highly evaporative conditions would predominate, first leading to the precipitation of calcite; the remaining Mg is therefore sufficiently high enough to lead to the precipitation of saponite. In the second scenario, Mg-rich calcite and ankerite were primary precipitates that succumbed to dissolution, releasing Ca, Mg and $C0_3$ into the system. This results in the formation of the nodular powdery carbonate that is ubiquitous in the 0 – 0.7 m zone of T3, and in the presence of high Si, supplies the additional Mg that is necessary for the neo-formation of saponite. Thus, saponite is either a primary precipitate that has formed in areas of the landscape where water persisted the longest i.e. in topographical lows on the western side of the Avenue Plain and in natural drainage lines, or is a neo-formed mineral, affected by the dissolution of ankerite. Nonetheless, both of these scenarios involve prolonged wetting and high Mg and Si activity in the surface, ground and pore waters.

Sepiolite and palygorskite are considered to be authigenic primary minerals in this case because of their ubiquitous presence in the profiles and their concomitant occurrence with lacustrine carbonates. Dioctahedral smectites have been reported as the diagenetic product of the dissolution of palygorskite when the mean annual rainfall exceeds 300 mm (Neaman and Singer 2004). The presence of dioctahedral smectite in this case is therefore attributed to the weathering of palygorskite and possibly also sepiolite. This conclusion is supported by the occurrence of high exchangeable Mg (Table 4.1) which is known to occur in soils where palygorskite has succumbed to weathering (Neaman and Singer 2004) .

4.4.2 Genesis of lacustrine, palustrine and calcrete carbonates on the Avenue Plain

Whereas the carbonate minerals detected in all of the samples were either Mg-rich carbonate or ankerite, the stable isotope and petrographic features identify the carbonates as being derived or altered in different climatic and environmental regimes.

Four main carbonate morphological types were intercepted in the profiles; these included an indurated carbonate horizon within 0.3 m of the surface; zones of powdery marl that often contained clay; indurated carbonates >0.7 m depth in the profile; and soft powdery nodules present within the soil matrix. In addition to $\delta^{13}C$ and $\delta^{18}O$ data for profiles T1, T2 and T3, stable isotope data were also collected for another five profiles from the study trench. The data from these samples has been sorted into four groups, representing the 4 carbonate morphological types, and are presented in Figure 4.15.

4.4.2.1 Palustrine limestones

The indurated carbonate horizon present in profile T1 (0.27 – 0.40 m) is classified as palustrine limestone. The minerals present in this horizon were identified by XRD as Mg-rich calcite and ankerite (Fig. 4.3) and aside from Si and Al, this horizon contained considerable Fe and K (Table 4.2). It is likely that a large part of the Fe was present as oxides due to remobilisation and precipitation and changes in the Eh of oscillating groundwater (Alonso-Zarza and Wright 2010a); this mechanism is supported by the orange staining / mottling observed in thin section (Fig. 4.9). Petrographic examination showed the section to be composed of peloids and intraclasts, cemented within a mottled micrite with multiple curved desiccation cracks of variable shapes and sizes. The pores were lined with clear carbonate of variable thickness, indicating the precipitation of secondary calcite from vadose meteoric waters. These characteristics are consistent with those observed in nodular and brecciated limestones (Freytet and Verrecchia 2002; Alonso-Zarza 2003; Alonso-Zarza and Wright 2010a), hence the designation of this horizon as a palustrine limestone.

The isotope values measured in this horizon may also support this conclusion. The covariance in $\delta^{18}O$ and $\delta^{13}C$ isotope data observed here (Fig. 4.15) suggests that these carbonates were formed in a hydrologically closed system. Subsequent alteration by diagenesis of the primary sediment and interaction with plants may account for the lighter isotope values observed in this zone.

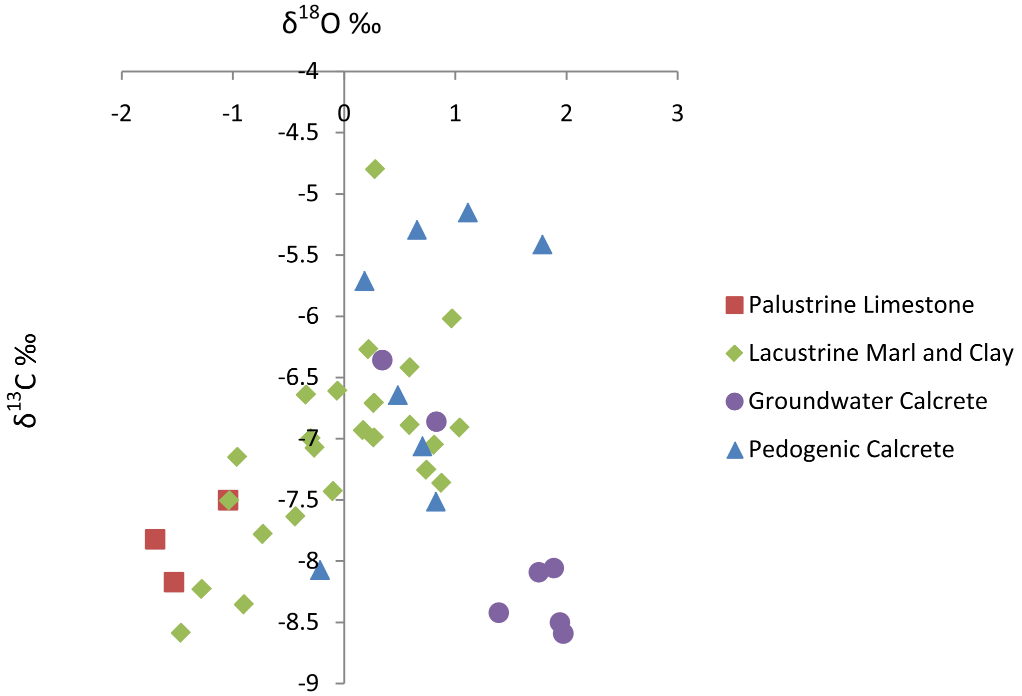

Fig. 4.15 Plot of $\delta^{13}C$ v's $\delta^{18}O$ for a range of different carbonate types found in the study area.

The range in carbon isotope values reported here reflect a change in climatic regime and/ or vegetation in the surrounding catchment. The $\delta^{13}C$ content of carbonates is affected by the proportions of plants that use C_3 (trees, most shrubs, cool season grasses), C_4 (warm season grasses and a few shrubs) and CAM (cacti and other succulents) photosynthetic pathways. When C_3 vegetation predominates in a region, lighter $\delta^{13}C$ values are generally observed in the carbonates due to their supply of highly negative carbon (- 32 to -25 ‰) (Zhou and Chafetz 2010). Heavier carbon isotope values therefore represent carbon inputs from C_4 plants (that record $\delta^{13}C$ values between -14 and -10 ‰), or greater atmospheric carbon input, both of which are related to increasing aridity. The highly negative $\delta^{18}O$ and $\delta^{13}C$ values recorded in this carbonate type (palustrine limestone) may suggest high biogenic activity in lacustrine waters, the input of highly negative plant derived carbon and limited atmospheric input, which would be consistent with the transition from a lacustrine to palustrine setting as plants colonise the exposed lacustrine sediments. It therefore appears that the primary lacustrine mud from which this limestone formed has undergone significant physical and chemical alteration due to sub-aerial exposure of the sediments and the interaction with plants and vadose waters.

4.4.2.2 Lacustrine marl and clay

Beneath the indurated horizon of T1, throughout 0.1 – 0.8 m of profile T2 and 0.5 – 0.7 m of T3, zones of unconsolidated marl were present that also contained considerable Al, Fe and K (Table 4.2). Mg-rich calcite and ankerite were the predominant minerals detected here, with $CaC0_3$ content ranging between 65 and 83 % and CEC values between 11 and 17 cmol (+) / kg (Table 4.1). There was more clay present in the marl of T1 than T2 and the mineralogy transitions from predominately illite and kaolinite to increasing amounts of smectite (as montmorillonite), palygorskite and sepiolite in all profiles (Figs. 4.3 and 4.5).

A wide range of $\delta^{18}O$ and $\delta^{13}C$ values were recorded for these carbonate types, which possibly reflects the alteration of this material through diagenetic[2] and pedogenic

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[2] Diagenetic processes refer to any chemical, physical or biological alteration of a sediment after its deposition

[3]processes. Whereas this marl was probably derived in a lacustrine setting (rather than being groundwater-related), given the ephemeral nature of the flood waters that were known to traverse this region seasonally (Holmes and Waterhouse 1983), the lack of microfossils, range in isotope values and ubiquitous presence of root hairs and visible pores in hand specimen, it is likely that this carbonate has undergone some form of diagenesis and weathering[4]. The petrography of this zone was not studied due to the unconsolidated nature of the material, therefore the degree of alteration of this sediment cannot be determined.

4.4.2.3 Groundwater calcretes / silcretes

Three horizons within the profiles have been identified as groundwater calcretes /silcretes due to their proximity to the watertable and their similar isotopic and mineralogical properties. However, their morphological properties differ significantly.

The highly indurated 0.95 – 1.1 m horizon of T1 was predominantly comprised of Mg-rich calcite and smectite, with trace amounts of sepiolite, illite, kaolinite and quartz (Figs. 4.3 and 4.5). The multi-faceted nature of this material is demonstrated in thin section, being characterised by intraclastic material embedded in a cloudy micrite matrix with up to 20% scattered porosity (Fig. 4.10). The pores were coated with a clear secondary carbonate that is mostly the same thickness in all directions, indicating their formation in a phreatic

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[3] Pedogenic processes refer to the alteration of near surface materials via their interaction with plants and vadose and meteoric waters

[4] Weathering refers to the alteration of near surface materials via their interaction with the atmosphere

environment (Freytet and Verrecchia 2002). Reference to another thin section from this horizon (Fig. 4.16*a)* shows essentially the same features of the previous thin section (Fig. 4.10), but particularly shows the feature of small circular voids within the secondary carbonates in many of the pores; these suggest the exploration of fine plant roots in this horizon. Fig. 4.16 (b) is a photograph of a soil core collected from a nearby location (from a similar depth) which also show large pores, suggesting the exploratory activity of plant roots at a larger scale. Many fine quartz grains were also visible in thin section, scattered randomly throughout the sample; quartz peak intensity was also very high in this horizon and below (Table 4.2). This indurated horizon is therefore concluded to be a groundwater calcrete / silcrete, albeit overlaid on a highly altered palustrine deposit, as indicated by its heterogeneous morphology (Fig. 4.10).

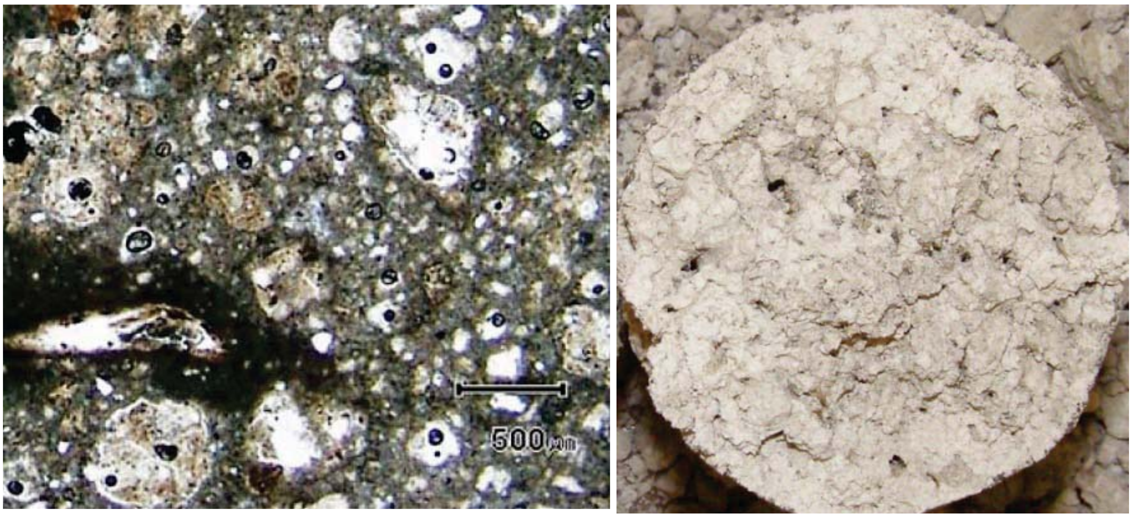

Fig. 4.16 (a) Thin section of T1 (0.9 – 1.1 m) showing small round voids within the pore fillings; and (b) a photograph showing similar voids within a soil core (2.5 cm width), indicating the exploration of plant roots.

Petrographic examination of the other highly indurated horizons (1.3 – 1.5 m of T1 and 0.7 – 1.0 m of T3) showed them to be massive with limited porosity; some pores are again lined with a thin uniform secondary carbonate (Figs. 4.11 and 4.12). These horizons have similar geochemical characteristics (especially isotopic values) and mineralogy; however, T3 also contained fossil fragments (mollusc) (Fig. 4.12). Such features suggest that these lacustrine sediments were subjected to only limited subaerial exposure and diagenesis; hence they maintain a homogenous and massive ‘alpha’ structure.

Interaction with the watertable influences the C and O isotopic signatures of these calcrete horizons; the range in values is consistent with those reported for calcretes (Alonso-Zarza 2003). The enrichment of ^{18}O seen here suggests increasing aridity in this environment and the precipitation of carbonates driven through evaporative processes in an open system (due to their inverse covariance). Whereas the groundwater calcretes are enriched in ^{18}O, δ^{13}C values remain in the range recorded for the lacustrine and palustrine limestones (Fig. 4.15). Stable carbon isotope values are controlled by inputs of atmospheric and soil CO_2, which in turn is affected by the type and extent of local plant cover. At these depths in the profile, however, it is unlikely that there is significant input of atmospheric or soil $C0_2$, hence the groundwater calcretes retain the isotopic carbon signature of the primary lacustrine sediment. In contrast, the oxygen isotope signature is altered to reflect the composition of current meteoric waters and precipitation driven by evaporative processes; this phenomenon has been reported previously (Leier *et al.* 2009).

Further indication of the complexity of these horizons is indicated by the presence of many small white particles throughout the thin sections (Fig. 4.10, 4.11 and 4.12), suggesting quite small crystals of quartz that would be consistent with an authigenic origin, and may suggest silicification of the calcretes, contributing to the induration that is observed. Calcrete – silcrete associations are commonly found in continental basins with arid or semi-arid climates, with their formation being controlled by variations in pH (although always around 9) and evaporation and also by variations of the salinity of groundwater (Bustillo and Alonso-Zarza 2007). Carbonate rocks can become silicified through diagenetic processes, resulting in the major replacement of carbonate minerals by silica minerals (including opaline phases, quartz and polymorphs of quartz) as well as silica cementation in voids (Bustillo 2010). Compared with amorphous silica, quartz tends to precipitate at lower Si concentrations in solutions (Bustillo 2010), but as pH increases the concentration of Si at which quartz precipitates also increases (Fig. 4.17).

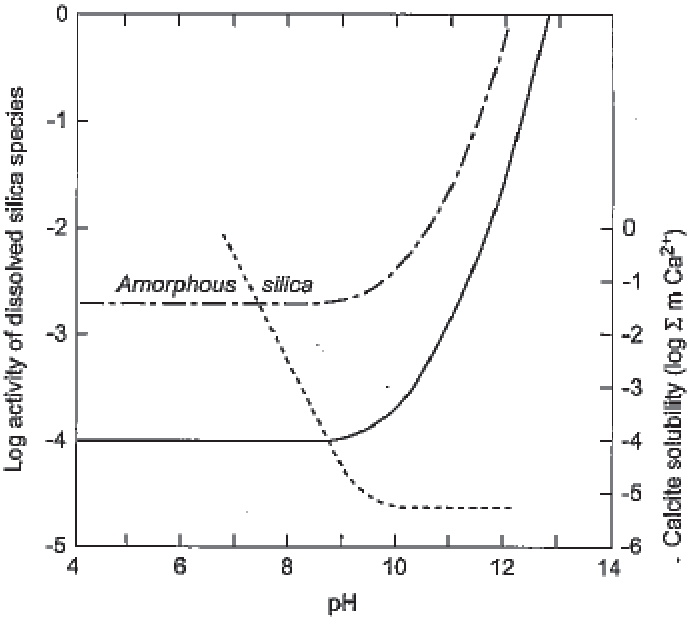

Fig. 4.17 Superposition of the solubility curves for the calcite and silica phases with respect to pH. The dashed line represents the solubility curve for calcite; the solid line represents the total dissolved silica concentration in equilibrium with quartz; the remaining line is that for amorphous silica. Sourced from Bustillo (2010).

Silica precipitation and carbonate dissolution sites commonly occur in the phreatic zone as a consequence of artesian upwelling and evaporative concentration and can also include areas where different groundwaters mix with more saline fluids in playas (Bustillo and Alonso-Zarza 2007). Such silcretes conserve the structure and texture of the carbonate host rock on which they form and many groundwater silcretes are formed directly from quartz without any intermediate opaline phase (Bustillo 2010). This process was illustrated by Bustillo and Alonso-Zarza (2007) in a study of palustrine deposits that indicated the psuedomorphic replacement of sepiolite by silica, with quartz subsequently appearing as a result of cementation and ageing.

The soil chemical, mineralogical and hydrological characteristics observed in this study therefore lend themselves to the silicification of groundwater calcretes. It is worthy to note that in the 0.9 – 1.1 m zone of T1, $CaC0_3$ content was only 60% (Table 4.1) and in XRD a significant quartz peak is detected in addition to Mg-rich calcite (Fig. 4.3); quartz grains of varying size were also clearly visible in thin section (Figs. 4.9, 4.10 and 4.11). In the 1.3 – 1.5 m horizon of T1 and 0.7 – 1.0 m horizon of T3, $CaC0_3$ content was 86.8 and 81.0 % respectively and quartz peak intensities also increased in these zones, and below, in the $CaCO_3$ free bulk samples that were analysed by XRD (Table 4.2). The hypothesis arising from these observations is that silicification of groundwater calcretes has occurred, albeit to different degrees in the three groundwater calcretes and is likely the cause of significant induration in these horizons. Given the implementation of drainage and recent period of declining rainfall, leading to the subsequent and continuing lowering of groundwater (Chapter 2), silicification of these sediments may be an ongoing process in this region.

4.4.2.4 Pedogenic calcretes

Soft white powdery carbonate nodules were found scattered throughout the profile in T3; the $CaCO_3$ content increases from 20 % in the surface, to >60 % in the 0.5 – 0.7 m zone. The soil in T3 was black (dry colour 5Y 2.5/1) the white carbonate presented a stark contrast. Due to its ubiquitous presence and soft powdery form, it is proposed that this carbonate is of pedogenic origin. The isotope data recorded for this profile supports this conclusion; the generally heaviest $\delta^{18}O$ and $\delta^{13}C$ values among the carbonates indicate highly evaporative conditions, a potential shift in vegetation types and increased inputs of atmospheric CO_2 which is consistent with the warm arid climate currently experienced in this region.

4.4.3 Development of soil profiles

Given all of the information presented here, the variability among authigenic clay minerals and carbonate types and their morphology are believed to be the result of historic geological changes in the depositional basin and source waters of this region, in addition to their current position in the landscape. Through our field observations, the eastern side of the Avenue Plain predominantly featured soil profiles similar to T1 (Chromosols). In this profile there was a unique combination of minerals (detrital clays, diatoms, feldspars) and distinct lack of $CaC0_3$ in the soil that overlies palustrine limestones; the transition between these horizons was often abrupt.

These features suggest a significant change in hydrology and source of input waters throughout this region since induration of the palustrine limestone occurred. Given the geological and volcanic history of this region, groundwater levels would have progressively dropped in association with the staged retreat of the ocean over the past 300 Ka (Huntley and Prescott 2001) and potentially is at least partly responsible for the exposure of lacustrine sediments. The distinct interface between indurated palustrine limestone and detrital alluvial materials may therefore represent a significant geological event (such as uplift of the coastal plain and retreat of the ocean) that led to a change in the hydrology of this interdunal plain, the sources and type of alluvial materials deposited here and the residence time of water on the surface of the soil.

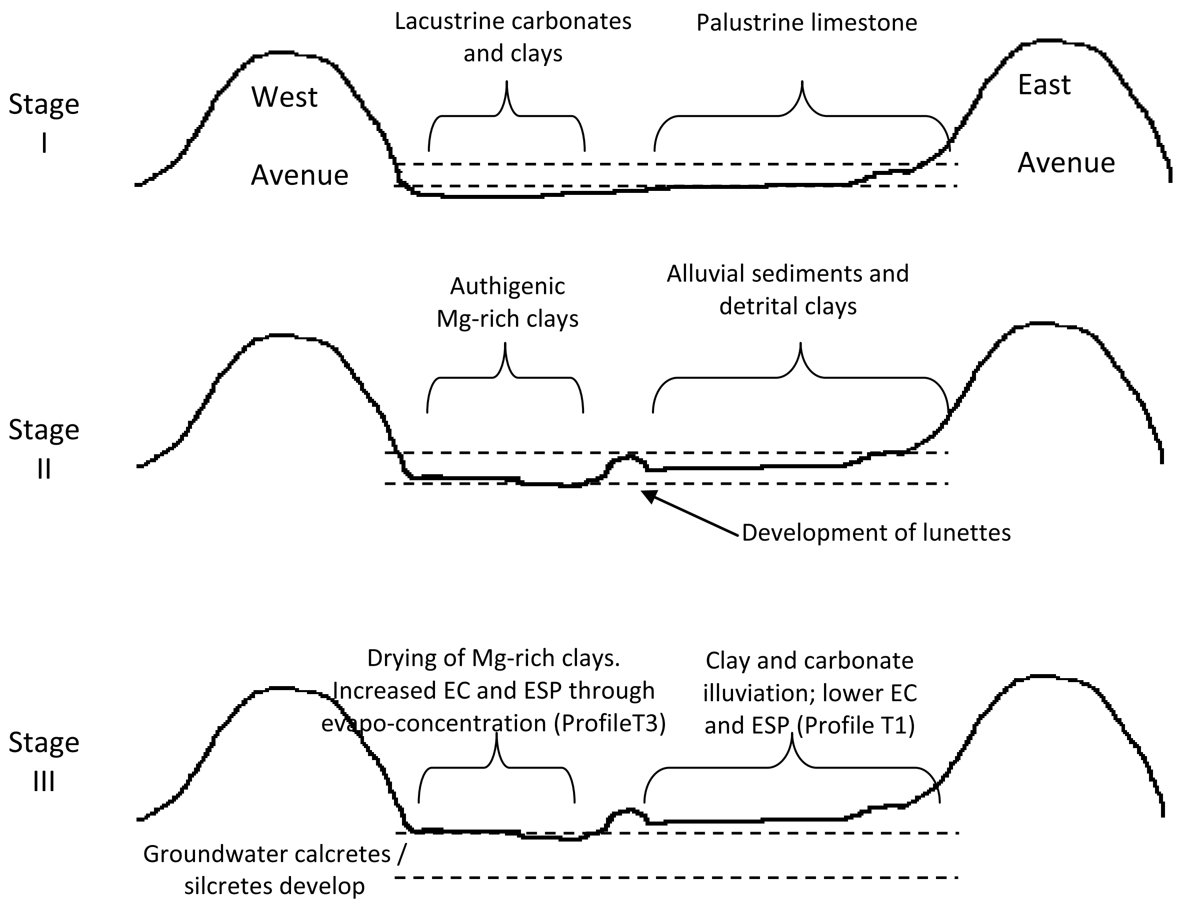

Fig. 4.18 Diagram of three stages of deposition and alteration of lacustrine sediments in the USE of SA. The vertical dashed lines represent the zones of surface / ground water fluctuation during each of the stages.

This process is represented in Figure 4.18, whereby the sediments deposited during Stage I were predominately lacustrine carbonates, marls and clays. When the areas of higher topographical position became exposed (largely on the eastern side of the plains), palustrine limestones formed through diagenetic and pedogenic alteration of the exposed primary sediment.

In Stage II it is proposed that the watertable retreated, facilitating the development of lunettes and the further induration of exposed lacustrine sediments. It is well documented that prevailing winds in this region were historically directed from the north-west, which resulted in the formation of 'lunettes' on the Avenue Plain (Twidale *et al.* 1983). These localised, elevated crescentic ridges are composed of aeolian material winnowed from the playa floors in areas where surface water inundation was prolonged (Twidale *et al.* 1983). These features were documented and mapped by Blackburn (1952) on the Avenue Plain and occur predominantly on the western side of the interdunal corridors, due to their north-westerly gradient, and currently coincide with the areas that feature soils similar to T3 (undulating, black, wet, poor plant cover, friable at the surface, wide and deep cracks, absence of shallow palustrine limestone i.e. Vertosols). As a result of these landscape features, the depressions that form on the windward side of the lunettes and the natural drainage lines on the far western side of the plains rarely dry out completely; the absence of palustrine limestone can be attributed to this factor, as these areas do not undergo sub-aerial exposure and desiccation to the same extent as expected for the sediments on the leeward side of the lunettes and across the flats. Mg-rich clays are therefore precipitated in the zones with prolonged surface water inundation. The alluvial materials subsequently transported into this area either remain stratified above the palustrine limestones, or are incorporated into the unconsolidated zones that feature Mg-rich clays.

In Stage III, the watertable retreats even further, exacerbated by European settlement and the widespread implementation of artificial drainage. Salts are now leached from the soils on the eastern side of the plain and those on the western side start to dry for the first time. Due to such fluctuations of surface and groundwaters, two distinct soil profiles therefore developed across this landscape. The main type, Chromosols, features predominately stratified detrital minerals overlying palustrine limetsones (such as T1, Table 4.4); some interstratified smectite/kaolin clay minerals may also be present. Soil types such as these can be identified within the zone of shoreline influence in the lunettes and across the interdunal plains.

Table 4.4 Key properties of the Chromosols that feature on the eastern side of the Avenue Plain. P= present and tr = trace

Profile T1	Zone (m)	Origin	Key Properties										
			<2µm fraction						Powder bulk sample				
			Sap	Mont	Se	P	I	K	Q	MCal	A	CEC	
	0.0 – 0.27	Detrital - alluvial	-	-	-	-	P	P	P	-	-	32	High exchangeable Mg (EMP). High elemental Al, Fe and K. Primary minerals, high quartz and diatoms detected by TEM. High clay content. Lightest δ^{18}O and δ^{13}C isotopic signatures.
	0.27 – 0.4	Palustrine Limestone	-	tr	-	-	P	tr	tr	P	tr	11	High EMP. High elemental Al, Fe and K. Heterogeneous matrix with irregular desiccation cracks and orange mottling. Covariance of δ^{18}O and δ^{13}C; very light δ^{18}O.
	0.4 – 0.65	Lacustrine Clay Marl	-	tr	-	-	tr	tr	tr	P	tr	17	Moderate ESP, high EMP. High elemental Al, Fe and K. More enriched with ^{18}O and ^{13}C.
	0.65 – 0.95	Lacustrine Clay Marl	-	tr	tr	tr	-	-	tr	P	tr	15	Similar to the 0.4 – 0.65 m zone, but lack of I and K and introduction of Se and P. High pH and high ESP. High elemental Ca, Na and Cl.
	0.95 – 1.1	GW calcrete / silcrete on palustrine host material	-	P	tr	-	tr	tr	tr	P	-	16	High pH, ESP and EMP. No ankerite detected. Heterogeneous matrix, many pores. Inverse covariance of δ^{18}O and δ^{13}C.
	1.1 – 1.3	Lacustrine Clay	-	tr	P	P	-	-	P	tr	tr	30	High clay content and CEC. High pH, ESP and EMP. High elemental Mg and Cl.
	1.3 – 1.5	Groundwater calcrete / silcrete	-	P	-	-	-	tr	tr	P	-	17	High pH and EMP; ESP lower. Mainly MCal detected. Low elemental Si, Al and Fe and high Mg, Ca and Cl. Much montmorillonite with sepiolite rods detected by TEM. Massive homogenous matrix with irregular pores. Inverse isotope covariance.

The other characteristic soil type features deep accumulations of Mg-rich smectites where surface water resided the longest, such as the Vertosol in profile T3 (Table 4.5). In the current environment, the high proportion of smectite (as saponite) throughout these soils, in addition to elevated Na$^+$ content, results in a high swelling potential of the soil. As a result, infiltration of water through the profile is reduced; salts and pedogenic carbonates are therefore retained throughout, resulting in the highly saline, sodic and alkaline conditions observed. In addition, a prolonged drying of these soils now occurs, resulting in depressions forming across the landscape that capture evapo-concentrated highly saline and alkaline surface waters, exacerbating their physicochemical constraints; plant growth is detrimentally affected as a result. Gradual transitions between these soil types also occur (T2, a Calcarosol), highlighting the complex interactions of surface and groundwaters in lacustrine and palustrine environments.

Table 4.5 Key properties of the soils that feature on the western side and lowest parts of the landscape.

<table>
<tr><th>Profile T3</th><th>Zone (m)</th><th>Origin</th><th colspan="10">Key Properties</th></tr>
<tr><td rowspan="14"></td><td rowspan="4">0.0 – 0.5</td><td rowspan="4">Authigenic / diagenetic saponite, pedogenic carbonates, detrital micas</td><td colspan="6"><2µm fraction</td><td colspan="4">Powder bulk sample</td></tr>
<tr><td>Sap</td><td>Mont</td><td>Se</td><td>P</td><td>I</td><td>K</td><td>Q</td><td>MCal</td><td>A</td><td>CEC</td></tr>
<tr><td>P</td><td>-</td><td>-</td><td>-</td><td>tr</td><td>tr</td><td>P</td><td>tr</td><td>-</td><td>35</td></tr>
<tr><td colspan="10">High pH, CEC, clay %, ESP and EMP. No Ankerite detected. Very high elemental Mg and Mg:Al. The carbonates present, up to 20%, are enriched in ${}^{18}O$ and ${}^{13}C$ indicating precipitation by evaporative processes and increasing aridity.</td></tr>
<tr><td rowspan="3">0.5 – 0.7</td><td rowspan="3">Lacustrine Clay Marl</td><td>Sap</td><td>Mont</td><td>Se</td><td>P</td><td>I</td><td>K</td><td>Q</td><td>MCal</td><td>A</td><td>CEC</td></tr>
<tr><td>-</td><td>P</td><td>tr</td><td>tr</td><td>-</td><td>-</td><td>tr</td><td>P</td><td>-</td><td>14</td></tr>
<tr><td colspan="10">High pH. Increasing carbonate %. High ESP. Se and P detected. Low Si, Al, Fe and K. High Ca, Na and Cl.</td></tr>
<tr><td rowspan="3">0.7 – 1.0</td><td rowspan="3">GW calcrete / silcrete formed on lacustrine host material</td><td>Sap</td><td>Mont</td><td>Se</td><td>P</td><td>I</td><td>K</td><td>Q</td><td>MCal</td><td>A</td><td>CEC</td></tr>
<tr><td>-</td><td>P</td><td>tr</td><td>tr</td><td>-</td><td>-</td><td>tr</td><td>P</td><td>tr</td><td>4</td></tr>
<tr><td colspan="10">High carbonate, low CEC and high ESP. High elemental Si and Si:Al. Low elemental Mg. Homogenous massive matrix with few pores; fossils and large quartz grains present.</td></tr>
<tr><td rowspan="3">1.0 – 1.4</td><td rowspan="3">Lacustrine Marl</td><td>Sap</td><td>Mont</td><td>Se</td><td>P</td><td>I</td><td>K</td><td>Q</td><td>MCal</td><td>A</td><td>CEC</td></tr>
<tr><td>-</td><td>P</td><td>tr</td><td>-</td><td>-</td><td>tr</td><td>tr</td><td>P</td><td>tr</td><td>8</td></tr>
<tr><td colspan="10">High pH, ESP and EMP. High elemental Si, Al, Fe and K and low Mg.</td></tr>
</table>

These conclusions, however, do not entirely concur with those of previous studies (Blackburn 1952; Norrish and Rogers 1956; Blackburn *et al.* 1965; Blackburn 1983) that mostly reported the soils in this landscape to be derived from the underlying parent material. In contrast, some of the minerals found here, such as sepiolite and palygorskite, are primary precipitates, whereas illite and kaolinite are most likely detrital components of the soil. Nonetheless, saponite may be an authigenic mineral. In addition, the dense capping that was intercepted at the interface of the surface soil and underlying limestones reported by previous authors (Blackburn *et al.* 1965) may in fact have been the product of palustrine alteration and induration, in addition to secondary carbonate accumulation.

4.5 CONCLUSION

Poor plant growth observed across isolated areas of this region is primarily the result of the mineralogy of the underlying soils. Whereas illite and kaolinite clay minerals are detrital in origin, the Mg-rich clay minerals: saponite, sepiolite and palygorskite, are authigenic minerals. These minerals formed either through direct precipitation from continental solutions and/or diagenesis, their formation and stability being related to the position in the landscape and subsequently the degree of sub aerial exposure of lacustrine sediments. In the zones that did not historically undergo a high degree of subaerial exposure and diagenesis (the western side of the plains), saponite is the dominant mineral present and shallow palustrine limestone is absent. There is however up to 20% pedogenic calcrete scattered throughout this soil type. The presence of saponite along with environmental solutions rich in NaCl, leads to high swelling in the clays when wet. This creates soils that have a low leaching capacity and the salts of Na and Ca are seen to accumulate throughout the profile. The topographical depressions created during the drying of these soil types results in evapo-concentrated surface waters accumulating in these soil types after periods of drying, intensifying the saline and sodic conditions. These soils subsequently became highly alkaline, highly saline and strongly sodic, adversely affecting plant growth.

In contrast, in the portion of the landscape that underwent the greatest degree of subaerial exposure (the eastern side of the plains), induration of palustrine limestone occurred which led to the stratification and preservation of detrital minerals. These soil types now support good plant growth as salts are more readily leached through the profile; in addition, the indurated horizons act as a barrier to capillary rise of saline groundwater from below. Due to deep drainage in this region and the lower position of the water table, some soils now support better plant growth than observed previously.

From these observations, it is concluded that the carbonates across this landscape are of lacustrine, palustrine, pedogenic and groundwater origin and are not simply clay and carbonate species formed on lacustrine parent materials, as once thought. Complex interactions exist within this landscape between the carbonate and clay species; both distinct and gradual boundaries between the types are observed across very small scales, reflecting this complexity.

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CHAPTER 5

ON-FARM RESEARCH IMPROVES FARMER KNOWLEDGE AND FACILITATES CHANGE

5.1 INTRODUCTION

In Australia and world-wide, the principles and practices of rural extension are often employed to communicate the outcomes of agricultural research and development. The goals of agricultural extension include the transfer of technology from researchers to farmers, advising farmers in their decision making and educating farmers on how to make better decisions, enabling them to clarify their own goals and possibilities and stimulating desirable agricultural developments (Anderson and Feder 2003). More specifically, the transfer of technology involves shifting new technical knowledge, ideas, inventions, services and products from the place of their creation, to where they can be put into use (Guerin 2000). Technology adoption is the application of this transferred knowledge and should be the main objective of applied agricultural research. The resultant adoption of technology, however, is governed by the research agency's ability to change or influence a farmer's knowledge, skills, aspirations and practices, thereby building their capacity, and is vital for the continued development of sustainable agricultural enterprise. The processes employed for transfer of technology (ToT) from researcher to farmer are therefore crucial for adoption to occur. The major emphasis of ToT, however, is on the one-way transfer of knowledge and technology from research institutions through extension to farmers and therefore contains some inherent limitations to uptake (Christodoulou 2000). The primary limitation is that the information and technology are developed by the research institutions and often delivered as generic products, without considering that the farmer can also contribute to the development of knowledge and technology. The information generated by such research therefore is often not site-or problem-specific and the researcher may not have a thorough understanding of the barriers to implementation within the farming system (economic, social, environmental), resulting in minimal uptake. Participatory research, in contrast, is a mechanism that can help catalyse the generation of new innovation in collaboration with farmers that is necessary for the sustainable development of Australian agriculture (Christodoulou 2000).

Research conducted on-farm is one participatory method that can be utilised to investigate local problems while also building relationships. On-farm research (OFR) encourages two-way knowledge sharing and learning between researchers and farmers to help them make better decisions (Lawrence *et al.* 2007). OFR sites can become the meeting place for local growers to learn about a problem, discuss their own experiences and help to identify solutions and lines of investigation. The farmer can provide the researcher with the context to the problem and the limitations or opportunities of their farming system and the researcher can design OFR with relevance and rigour, enabling all parties to reach the desired outcome (Lawrence *et al.* 2007).

In 2005 a research project was initiated between the University of Adelaide and the Keilira Farm Management Group (KFMG) to determine whether soil physicochemical constraints were responsible for an observed decline in plant growth on their farms. The project aim was to establish if the soils were affected by salinity and sodicity and if artificial drainage was affecting the expression of these constraints. To complement this research the local salt-land agronomist from the South East Natural Resource Management Board (SENRM), Mr Jack England, also conducted OFR, with a range of pasture species and gypsum application rates trialled. Our joint objective therefore was to help the growers understand not only what the problem was, but also how to manage it in their environment. The incorporation of an extension component into the project therefore seemed crucial if we were to meet this objective. One of the hypotheses for the project, therefore, was that farmer knowledge of the problem, and how to manage it, could be improved.

5.2 METHODS AND ACTIVITIES

On-farm research was conducted on three properties initially, named South, Central and North, and was subsequently concentrated solely on the South site. The farmers at each site contributed to the selection of affected sites and provided valuable insight about land management history and catchment hydrology. At each site, the agronomist assessed a range of gypsum application rates and pasture species that were planted for demonstration and redox probes were also installed in particularly degraded soils. Trench excavation and soil sampling, analysis and interpretation was provided by the University. Extension and communication activities associated with the project were conducted with the KFMG, local consultants and the general public and included field walks at the three OFR sites in September 2005 and June 2006 and again at the South site in November 2007 (Table 5.1).

In order to test the hypothesis that farmer knowledge of the problem and how to manage it could be improved, a comprehensive evaluation was conducted with the three key landholders involved in the project upon commencement and completion of the work. The full suite of questions is presented in the results section.

Table 5.1 Extension and communication activities conducted in conjunction with the project

Date	Activity
September 2005	'Identifying the presence of sodicity, its effects on soil structure and implications for land management' KFMG field day, Keilira, USE SA, visit 3 research sites Presenters: Melissa Fraser and Jack England
June 2006	'Managing Sodicity – Pasture species and gypsum trial update' KFMG field day, Keilira, USE SA, visit 2 research sites Presenters: Melissa Fraser, Pichu Rengasamy, Jack England, Tim Prance - PIRSA
June 2007	'Soil management for the future: finding the hidden barriers to root growth' 48th Annual Conference of the Grassland Society of South Australia Murray Bridge, SA Presenters: Mark Thomas (CSIRO), Richard Merry (CSIRO), Melissa Fraser
November 2007	'Getting to the bottom of an Australian sodic Vertosol: a study in breadth, depth and scale' KFMG research update and field walk, Keilira, USE SA Presenters: Melissa Fraser and Jack England
March 2008	'Getting to the bottom of an Australian sodic Vertosol: a study in breadth, depth and scale' Lucindale Field Day, USE SA Future Farm Industries CRC stand
March 2008	'Beating Salinity and Sodicity' Best management practice brochure Distributed to 2000 households in the USE Author: Jack England
May 2009	'Helping farmers develop their *own* solutions to a salty problem' ABC SA Country Hour

The purpose of the survey was to gauge the farmer's current level of awareness, knowledge and management of salinity and sodicity, and how this changed through participation in the project. The survey was initially conducted in June 2005 and was then repeated in November 2010. In hindsight, it is acknowledged that evaluations could also have been conducted with participants attending each of the extension activities (field days etc.), but this unfortunately was not done. The results gleaned from the farmers involved with the project have been presented anonymously and are referred to as Farmer 1, Farmer 2 and Farmer 3 for this purpose. In some cases their direct responses to the survey questions, as recorded by them, have been presented here.

5.3 RESULTS AND DISCUSSION

The three farmers were first asked a series of questions in the surveys to gauge their understanding of salinity and sodicity and how this had changed from 2005 to 2010, ranking their responses accordingly as very low, low, moderate, high and very high. A series of statements were also presented upon completion of the project, with the farmers stating how strongly they agreed or disagreed with these (strongly disagree, disagree, neither agree nor disagree, agree and strongly agree). In addition, a set of questions to assess current management and amelioration strategies and how these had changed throughout the life of the project were also asked. The effectiveness of the extension and communication methods was also determined. The results from the surveys are presented in the following sections: Knowledge of salinity and sodicity; Management practices, productivity and sustainability; Community perception and the drainage schemes; and On-farm research and extension methods.

5.3.1 Knowledge of salinity and sodicity

Whereas all of the farmers rated their understanding of salinity and sodicity as moderate to high at the outset and completion of the project, every farmer also agreed/strongly agreed that participation in this project had increased their knowledge of these constraints (Table 5.2), in addition to improving their knowledge of soil variability across their farms.

Farmer 1 reported that dryland salinity has reduced from moderate-high to low-moderate in the last 5 years, with dryland salinity now causing a reduction of 10-20 % of dry-matter production. The spread of sodicity was considered to have stopped but when asked about the proportion of time and money they believed should be apportioned to controlling these issues, the farmer commented *'It is essential to provide enough time and money to maintain sodicity at low levels. Salinity will be minimised by the maintenance of deep drains and sodicity control'.*

Table 5.2 Questions related to farmer knowledge of salinity and sodicity.

1) How would you rate your current understanding of dryland salinity?			
	Farmer 1	**Farmer 2**	**Farmer 3**
2005	High	Moderate	Very High
2010	High	High	Very High
2) Through participation in this project, my knowledge of dryland salinity has increased.			
2010	Strongly agree	Agree	Strongly agree
3) How would you rate your current understanding of soil sodicity?			
2005	High	Moderate	Moderate
2010	High	High	Very High
4) Through my participation in this project, my knowledge of sodicity has increased.			
2010	Strongly agree	Agree	Strongly agree
5) Through my participation in this project, my knowledge of soil variability across my farm has increased.			
2010	Strongly agree	Strongly agree	Strongly agree
6) I once thought sodicity was a major problem that would spread across my farm, I now realise that it is related to soil types and therefore will have the greatest affect on isolated patches.			
2010	Strongly agree	Agree	Strongly agree

Farmer 2 reported that salinity affected approximately 30 % of their farm in 2005, but that this area had not increased in the following 5 years; according to the farmer this was probably brought about by successive years of drought and the natural lowering of groundwater levels. Sodicity was also believed to exist in patches on the western side of this farm in 2005, but at the time the farmer was not sure of the extent or if the problem would spread. In 2010, however, he reported that sodicity was restricted to isolated specific areas and had not spread across their farm as once feared, adding *'the patches become more conspicuous with grazing, and especially so when cattle pug those areas up. The major effect of salinity and sodicity is to limit the range of pasture species that can be grown and to reduce the length of the growing season'*.

In 2005, Farmer 3, reported that salinity was restricting pasture growth on approximately 20% of their property and felt that sodicity was spreading dramatically. Through involvement in this project and the conduct of OFR, the farmer commented that salinity and sodicity are most prominent in the soils that do not have a shallow indurated limestone horizon and that pasture productivity is severely affected in these areas. Farmer 3 also added: *'It will take many more years to ameliorate the bad saline sodic patches and it is uneconomic to do so. We have focussed on establishing perennial pastures on the rest of our property as they have been extremely profitable and will also reduce the onset of sodic soils in other susceptible areas. The areas of sodicity are getting bigger in other paddocks'*.

The responses and observations made by each of the farmers confirm that their knowledge of the interactions between salinity, sodicity and soil variability has been improved through involvement in this project. Furthermore, the knowledge gained has improved their capacity to identify these constraints on their farms and to understand the resultant effects to soil health and pasture productivity and longevity.

5.3.2 Management practices, production and sustainability

In a set of questions asked about management practices, productivity and sustainability it became evident that the new knowledge gained about salinity, sodicity, soil variability and the benefits of perennial pastures had led to management and practice change on the three farms (Table 5.3). At the outset of the project, the farmers were asked to identify their objectives for farm management (question 10 a, b and c, Table 5.3). Involvement in the project enabled the farmers to meet many of these objectives. The establishment of perennial pasture species, application of gypsum or variations in gypsum application rates and grazing/pasture practices were the most commonly reported changes in management that resulted in meeting these objectives. The implementation of these practices resulted in a perceived increase in productivity on tow out of three of the properties, with Farmer 2 reporting that drought conditions in 2006 and 2007, followed by significant inundation in 2009 resulted in pasture productivity remaining the same. The increase in productivity is attributed to the establishment of summer active perennials that capitalise on summer rainfall, prolonging the availability of green feed.

Each of the farmers also agreed that the sustainability of their enterprises had increased as a result of participation in the project. Economically, it was noted that the increased feed availability resulted in higher profitability as the need to source off-farm supplemental feed is reduced. Environmentally it was recognised that soil health is improved through the management of salinity and sodicity and the removal of salts from the landscape. Greater time to spend on off-farm activities was one of the improvements socially, with Farmer 1 reporting that he feels more confident in continuing their current farming operation and for future generations.

Table 5.3 Questions relating to farm management, productivity and sustainability.

7) Through my participation in this project, my management of dryland salinity has changed.			
	Farmer 1	**Farmer 2**	**Farmer 3**
2010	Strongly agree	Agree	Strongly agree
8) Through my participation in this project, my management of sodicity has changed.			
2010	Strongly agree	Agree	Strongly agree
9) What level of commitment do you have to solving these issues?			
2005	High	High	Very high
2010	High	High	Very high
10 a) Farmer 1 At the beginning of this project you identified your objectives for the short and medium term as: • To determine the best method to treat the problem, i.e. gypsum. And if so, what application rates? • To maintain the current levels of production (2005), as you feared that things would get worse if you didn't do anything. • To plant summer active perennials. Do you believe you are meeting/have met these objectives, have they changed, and/or is there still more to be done?			
Still evaluating the gypsum levels. About 1 t/ha on apparently unaffected soil is fine, but I don't yet know how many years a single application will last for (hopefully >5yrs). Much larger rates are needed (up to 20 t/ha) on the bad patches with no pasture cover in order to be able to establish pasture. We have definitely maintained or increased our 2005 levels of production. We have planted perennials on about half of the possible affected land (and more still to do). Trying to evaluate how long each species will persist in our soils.			
10 b) Farmer 2 At the beginning of this project you identified your objectives for the short and medium term as: • Increased productivity on available land through increasing stocking rates, species selection and pasture rejuvenation. • Improve 10% of the property's pastures each year • Increase stocking times due to implemented drainage Do you believe you are meeting/have met these objectives, have they changed, and/or is there still more to be done?			

I still think that these provide the basis of our objectives; they have at times been varied due to tough seasonal conditions etc. I would also add that we are placing a higher emphasis on sustainable grazing. Increased internal fencing/paddock subdivision to allow better grazing pressure where they graze for less time before moving, rather than set-stocking.

10 c) Farmer 3

At the beginning of this project you identified your objectives for the short and medium term as:

- 12 months: identify good pasture species for affected areas
- 2 years: persistence of those species and increased stocking rates
- 5 and 10 years: soils stabilised and sodicity being managed. Regular soil tests to check for further amendments required.

Do you believe you are meeting/have met these objectives, have they changed, and/or is there still more to be done?

First two objectives met. Problem with third is that it is very costly to ameliorate the sodic soils. We have found that if 2.5 t/ha of gypsum is added at sowing time that most of the pasture species in our perennial composition have colonised the bad patches. Cattle are excluded for the first year and while these areas fail to produce even quarter as much as the surrounding good areas, this is better than what was previously there. Cattle simply need to be excluded in the winter time so they don't mash the living perennials. No more work needs to be done.

11) What amelioration techniques are you currently using for salinity and sodicity and has this changed in the last 5 years?

Farmer 1:

- *Gypsum and perennials.*
- *Also trying to maintain soil cover on annual pasture land until mid – late autumn.*
- *Have had the same policy in place for at least the last 3 to 4 years.*

Farmer 2:

- *Try to maintain adequate ground cover in sodic areas until well into autumn.*
- *Less set stocking.*
- *Maintain our annual fertiliser program of 75 – 100 kg/ha of single P super.*
- *A ground water drain has now been dug across our farm.*

Farmer 3:

- *Nothing has changed except we are not putting as much gypsum out on the worst saline/sodic patches but would rather use the funds to establish more perennial ground cover.*

12) Has your cropping/grazing program changed in the last 5 years? If so, how, and was this due to your direct involvement in the project?

Farmer 1:

- *Yes.*
- *Planting summer perennials in increased levels.*
- *Grazing management has been altered to try to manage perennials to best suit production and longevity of stands.*

Farmer 2:	• *More rotational type grazing i.e. large mob sizes with less time being spent in each paddock. However, as with all systems I have learned that it is important to be flexible and adaptable according to seasonal and environmental conditions.* • *This change is due partially to what I have learned with sodic soils not being left bare, leaving pasture residue to reduce soil damage.*
Farmer 3:	• *It hasn't. We were already cleaning up grass and broadleaf weeds with a cropping rotation before sowing perennials. We have, however, stopped using perennial herbs in our pasture mix as they provide too much competition to sensitive perennial grasses during establishment and then doesn't last/ remain productive for more than 5 years.* • *The perennial herbs have been replaced with tall fescue which will grow if the Lucerne drowns in a wet year.* *The perennial pastures pay for the establishment cost in the first year and then increased production by up to $500/ha if 2-3 inches of summer rain is received (which has now happened in the last 4 years).*
13) How has your productivity changed in the last 5 years as a result of these management changes?	
Farmer 1:	• *Considerably better due to green feed from perennials in summer/autumn, but still nearly the same winter production as before we planted perennials.* • *Possibly the economic value is greater than the dry matter increase due to pastures of top quality being available to fill the 'feed gap' in an annual system.*
Farmer 2:	• *Productivity is probably the same which is put down to a few poor seasons (2006/07 drought) and massive winter inundation that killed pastures July – late October in 2009 (the property was not yet drained).*
Farmer 3:	• *Depends on summer rain. On average, DSE's have increased from 10 to 19 and have even further increased with opportunistic grazing during summer rainfall events.* *Not only have stocking rates increased significantly, stock are not being supplementary fed and they are putting weight on where they otherwise wouldn't on annual pastures.*
14) Has this project helped to increase your triple bottom line sustainability (economic, social, environmental), and if so, how?	
Farmer 1:	• *Yes.* • *Definite improvement in economics of farm.* • *I believe a definite improvement in environmental sustainability, but also think 5 yrs is way too short a time span for good evaluation. I think another 20 years is needed for proof.* • *Socially? I feel much better in my ability to continue farming here and future generations and hope my efforts have helped*

	others see and attend to their problems.
Farmer 2:	• *Yes. It has given me a greater education and awareness of what salinity and sodicity are doing to our flats.* • *At this stage I don’t know how to quantify or measure these, but now, post-drainage, I hope that this will be more significant as we hope to improve our overall grazing system.*
Farmer 3:	• *Definitely. The environment wins with salts being removed by the drains which allows for perennial ground cover. The plants with deeper roots use more water to a greater depth which not only increases production significantly (especially with summer rainfall), it provides a bigger “water sponge” for the winter rainfall in the following years. More water for plant growth with less osmotic pressure equals more pasture = more money.* • *Social life has improved as I can go to the pub instead of feeding weaner lambs on annual pastures. Lucerne provides out of season green feed. More time to socialise or do more work is more productive.*

5.3.3 On-farm research and extension methods

The results of soil chemistry, gypsum applications and perennial pasture assessments were primarily communicated through the conduct of field-walks/days and with the distribution of written material. All of the farmers strongly agreed that the combination of applied on-farm research and practical field-walks was beneficial to their learning.

Touring other properties, having scientists on hand, conducting on farm trials and having an active Farmer group were also reportedly beneficial to helping the farmers investigate and solve problems on their own farms. Jack England is now a local Keilira farmer himself, and although no longer officially employed as the Salt-land Agronomist, he is still a key contact for these farmers, in addition to staff from Primary Industries and Resources SA (PIRSA) and the South Australian Research and Development Institute (SARDI) and other local Agronomists.

Table 5.5 Evaluation of the methods used for research and extension of project outcomes.

19) The combination of applied on-farm research with practical field-walks and field-days was beneficial to my learning.

	Farmer 1	**Farmer 2**	**Farmer 3**
2010	Strongly agree	Strongly agree	Strongly agree

20) Universities and other research institutions should make more effort to extend their research outcomes to farmers, and conduct more research on-farm.

	Farmer 1	**Farmer 2**	**Farmer 3**
2010	Agree	Agree	Strongly agree

21) What level of support do you believe is available for helping to solve these issues?

	Farmer 1	**Farmer 2**	**Farmer 3**
2005	Moderate	High	Moderate
2010	Moderate	High	High

22) In relation to this project, what approaches/activities do you believe helped in solving/exploring these problems?

Farmer 1:	• Farm tours of neighbouring properties with the same problems helped. • On-farm experiments with gypsum trials at 0 – 10 t/ha plus planting perennials in association with expert advice from soil scientists.
Farmer 2:	• An active farm management group. • Externally funded plot and paddock sized demonstrations. • Farm tours / workshops and having access on such days to experts in geology, soils in the South East, plant experts etc all combine to bounce theories/ideas off each other. • Postgraduate student passionate about their field of study – that find supportive theories to the local peculiarities that define our region.
Farmer 3:	• Gypsum trials in conjunction with pasture species trials. • Redox electrodes which really identified the lack of ideal growing conditions combined with soil testing and ground penetration radar all helped with the overall understanding. • Having a PhD student really kicked things along as well.

23) How much do you think the field trials on yours and neighbouring properties have influenced your decision making and management of salinity and sodicity?

Farmer 1:	• Very big influence – to my knowledge the advice we got was not available readily by other avenues.
Farmer 2:	• 100%
Farmer 3:	• We had already started to sow perennials prior to the project but after the completion of the project and seeing the production figures of the perennials we were much more confident in striving ahead with sowing more. We are still cautious about a wet winter which is why varying pasture species have been selected. Lots of neighbours are now attempting to do the same thing as us which gives me confidence to keep going.

24) Who is currently your preferred contact to help you solve problems on your property?

Farmer 1:	• PIRSA pasture agronomist and local agronomist.

Farmer 2:	• SARDI and PIRSA plus the work that Jack England has done locally with salt-land agronomy. • Our local CRT rural merchandise store provides agronomic advice free of charge who we have got advice for pasture species, mixes etc.
Farmer 3:	• Jack England, who was the Salt-land agronomist.
25) Do you believe there is adequate help and expertise available?	
Farmer 1:	• Yes, but only if you actually seek out help which means you need to have an idea of what help you need.
Farmer 2:	• Yes; plus local and relevant trials and research conducted, some of which is still ongoing.
Farmer 3:	• After the study that was completed I believe the landholders and demonstration sites are suitable enough to spread the word.

Fig. 5.1 Local members of the Keilira Farm Management Group inspecting a soil pit and learning about salinity and sodicity at a field walk in June 2006.

These responses confirm that the methods employed to educate the farmers about the deleterious effects of salinity and sodicity and the beneficial effects of gypsum and perennial pastures were effective in helping the farmers to explore and solve their issues on-farm. All of the farmers also agreed that Universities and other research institutions should make more effort to extend their research outcomes to farmers and to conduct more research on-farm. All of the farmers also acknowledged the benefit of having a dedicated postgraduate student; this interaction and communication should be encouraged for any student conducting applied research.

5.3.4 Community perception and the drainage schemes

The implementation and extension of the artificial drainage schemes throughout the Upper South East of SA has divided the local community, with land owners developing very strong arguments for and against the systems. From speaking with numerous local farmers it was evident that some believed that the water balance of the region should not be interfered with, while others strongly believed that the drainage schemes facilitate significant environmental and economic benefit. In addition, the three farmers also had conflicting beliefs about the local community's awareness of salinity and sodicity and their level of commitment to ameliorating these constraints (Table 5.4).

Table 5.4 Community perception and the drainage schemes

15) What level of awareness do you believe the local community has about salinity?			
	Farmer 1	**Farmer 2**	**Farmer 3**
2005	Moderate	High	Moderate
2010	Moderate	High	Moderate
16) What level of awareness do you believe the local community has about sodicity?			
2005	Low	Low	Low
2010	Very Low	Moderate	Moderate
17) What level of commitment do you believe the local community has to solving these issues?			
2005	Low	High	Moderate
2010	Low	High	Moderate
18) Overall, deep drainage is an effective management tool that will result in increased productivity and profitability on my farm, and throughout this region.			
2010	Strongly agree	Strongly agree	Strongly agree

The three farmers did, however, all strongly agree that artificial deep drainage is an effective management tool that results in increased productivity and profitability on their farms and throughout the region. These responses indicate that the Government organisations such PIRSA, SARDI, the South East Natural Resources Management Board and local Council all need to continue a community awareness and education program that highlights the physicochemical constraints that exist in the soils of this region and how the implementation of the drainage schemes can facilitate the removal of salts and lower groundwater levels, thereby improving soil health and farm productivity.

5.4 CONCLUSIONS

An evaluation survey was conducted with three farmers that were involved with a research project in Upper South East South Australia. The purpose of the survey was to determine whether the suite of extension and communication activities associated with the project were successful in improving farmer knowledge of soil constraints and how to manage them on their farms. The survey revealed that all three farmers involved in the project acquired a better understanding of salinity, sodicity and soil variability on their farms. In addition, their management practices also changed as a result of their acquired knowledge. The main practices employed were the application of gypsum and the establishment of perennial pastures to ameliorate the effects of sodicity and to improve the utilisation of soil water and to maintain cover on the surface of the soil. All of the farmers agreed that the combination of on-farm research and extension activities was beneficial to their learning and impacted on their decision making and management skills.

Clearly more work can be done to further educate the local community about the soil constraints that exist in USE SA and the beneficial effects that artificial drainage can have on soil and environmental health.

5.5 REFERENCES

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CHAPTER 6

GENERAL DISCUSSION AND CONCLUSIONS

6.1 INTRODUCTION

Soils in the Upper South East of South Australia have historically been saline. The expression of salinity, coupled with seasonal inundation, had a detrimental effect on agricultural productivity in some parts of the landscape. Mitigation strategies to overcome this problem were instigated throughout the region primarily from the 1950s to the late 1990s. Artificial drainage was one of the main tools employed, with the aim of intercepting surface flood waters and lowering groundwater levels, thereby facilitating the leaching of salts and lowering soil salinity. Across Australia's agricultural land, however, an equally important and more prevalent threat occurs: sodicity, which is brought about by damaging concentrations of sodium as an exchange ion in the soil (Rengasamy and Olsson 1991). When soils are both saline and sodic, the deleterious effects of sodicity are often expressed when mitigation strategies for salinity are employed. The lowering of soil EC can enable swelling to occur in smectitic soils, and in the presence of high exchangeable Na, complete clay dispersion can occur in soils with a wide range of mineralogies (Churchman *et al.* 1993). The presence and type of clay minerals in soils can therefore affect the degree of degradation a sodic soil will undergo if the salt load in the soil is reduced.

Since the Fairview drain was dug across the Avenue Plain in SA's USE, local growers noticed patches of declining plant growth and feared that the tracts of land adjacent to the drains would become barren. However, areas of declining plant growth were also being observed on sites that were not artificially drained. This study was instigated to investigate the soils in the local district of Keilira to help the farmers understand what was causing the decline in plant growth. The broad hypothesis of this research was that a range of soil physicochemical constraints existed in the soils, including salinity, sodicity and alkalinity, and that the artificial drains and resultant leaching had affected these soil properties. By incorporating an extension and communication component into the work it was also hypothesised that a change in knowledge, awareness and management of these soil constraints could be achieved with the three farmers primarily involved in the project. The work presented in this thesis was conducted to test these hypotheses.

6.2 SUMMARY OF RESEARCH AND CONTRIBUTION TO KNOWLEDGE

An initial study was conducted in 2005 on three separate properties in the Keilira District, (named South, Central and North in this thesis) with the aim of determining the effects of artificial drainage on groundwater levels and soil physicochemical condition. Deep drains had been dug across the South and Central sites during the 1950s and late 1990s respectively to lower groundwater levels and facilitate the leaching of salts, whereas no artificial drainage had been implemented at the North site. Standing water levels (SWL) in two observation wells from each site were assessed and soil pits were excavated across zones of good and poor pasture growth. The data collected was compared with historic soil samples (following re-analysis) that were retrieved from the CSIRO archives in Canberra.

Results showed that SWL are highly responsive to artificial drainage and also to fluctuations in annual rainfall. Data from wells surrounding the Blackford and Fairview drains indicated that these drains effectively lower groundwater in this region. At the North site (undrained) SWL have also declined due to a reduction in annual rainfall but there was no indication that this area is directly affected by the drainage schemes. It is therefore likely that the lowering of SWL in this region, both through a reduction in annual rainfall, and the implementation of artificial drainage, has facilitated the leaching of salts from the soils at both drained and undrained sites.

Investigations of the soils from each site confirmed that salinity, sodicity and alkalinity all existed, having a detrimental effect on plant growth. The expression of sodicity was governed primarily by soil EC and clay mineralogy; the effects of sodicity were particularly prevalent at the recently drained Central site. Soils with the highest EC, ESP and pH were located at the undrained North site, yet no effects of sodicity on soil structure were expressed, owing to the extreme salinity of the soil. Lower EC values recorded for soils at the South and Central sites are attributed to the implementation of artificial drainage. Nonetheless, when current soil chemical data was compared to data from historic samples it was found that soil salinity was lower at both drained and un-drained sites following the implementation of artificial drainage throughout this region. Whereas the soils were probably always saline and sodic, the expression of sodicity and resultant poor pasture growth across the landscape appears to be primarily as a consequence of lowering soil EC. In some cases, however, plant growth was also affected by high soil EC (North ‘poor’ and South ‘poor’ soils). In addition, two distinct mineralogical associations were found to occur, both within and across sites that also affected the type and extent of degradation observed. These comprised soils dominated by illite and kaolinite clay minerals that were prone to dispersion, and soils dominated by smectite clay minerals that were moderately to extremely saline.

The aim of Chapter 3 was to investigate soil physicochemical variability on a larger scale at a single site to better understand its cause. A study area (200 m x 200 m) was selected in association with the managers of the South site, approximately 1 km from the soil pit that was examined in the 2005 study (at this site). Patches of soil in this area were starting to exhibit large cracks, micro-relief and salt-efflorescence and supported limited plant growth; however, the majority of the area, especially the north-east quadrant, supported good plant growth and a range of pasture species. A crescentic limestone ridge colonised by eucalyptus trees was present in the far south-east corner of the study site.

Due to the size of the area and the high cost involved with traditional soil survey, a preliminary electromagnetic induction and ground penetrating radar (GPR) survey of this area was conducted to identify zones of greatest EC_a and soil morphological variability. Soil samples were also collected in conjunction with the surveys; analysis of this information helped to locate a large study trench (60 m long and up to 1.8 m deep), that intersected zones of low and high EC_a and multiple radargram features.

Upon excavation it appeared that two distinct soil types occurred within the trench (Fig. 6.1). The majority of the trench featured Chromosols with shallow grey surface soils overlying indurated carbonate; these soils supported good pasture growth (profile T1 was selected as representative). The second distinct soil type was a deep Vertosol that was extremely saline, strongly sodic and very strongly alkaline and supported only poor pasture growth (profile T3). Transitions between the two types also occurred, such as T2 (Calcarosols).

Fig. 6.1 Photographs taken within the trench showing the major soil type, Chromosol, (left) and the deep black Vertosol that occurred in isolated areas within the trench (right).

Two distinct indurated carbonate horizons were also evident in the study trench at the South site; a shallow accumulation was generally located within 0.3 m of the surface and a second was intercepted >0.7 m in the profile, and in some cases a third also. Petrographic and isotopic analysis of these carbonates was conducted, as discussed in a subsequent study (Chapter 4), revealing that the shallow layer was a palustrine limestone, whereas the deeper accumulations were considered to be groundwater calcrete/silcrete. Their presence at the South site was detected by GPR and the extent of each type is depicted in the 0.18 m and 0.78 m time-depth coverages for the survey area respectively (Fig. 6.2 and 6.3).

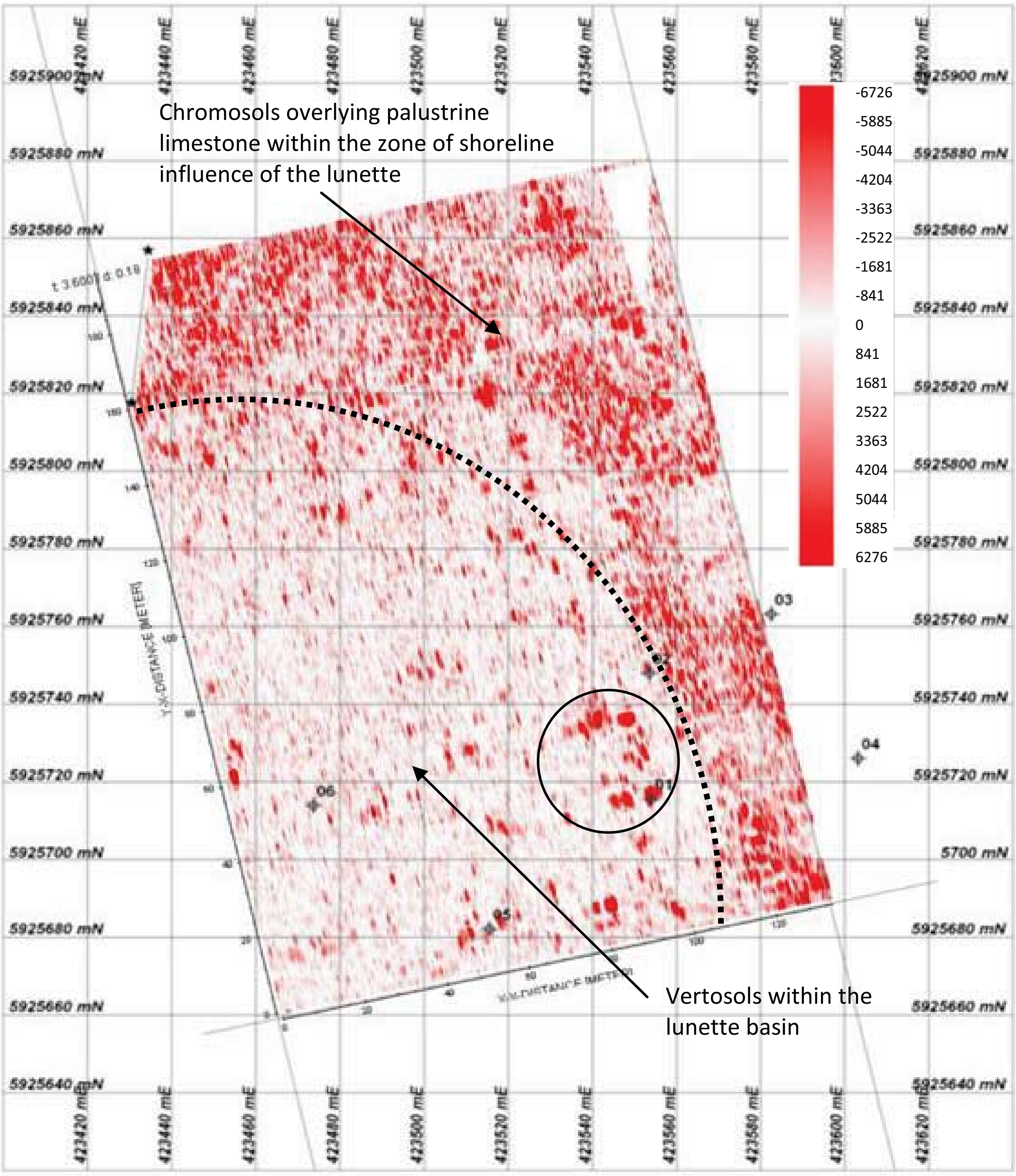

Fig. 6.2 GPR time - depth coverage for 0.18 m depicting the distribution of palustrine limestone across the study area indicating the zone of shoreline influence within the lunette. The large red areas highlighted in the circle correspond to patches of highly degraded saline-sodic Vertosols that created vertical streaks through the radargrams, not to palustrine limestone.

In the more recent study (Chapter 4) this site was concluded to be the basin of a lacustrine lunette; the palustrine limestone depicted in Figure 6.2 therefore identifies the zone of shoreline influence within the lunette i.e. the zone of greatest subaerial exposure, leading to the significant physical and chemical diagenesis observed in thin section for this carbonate type.

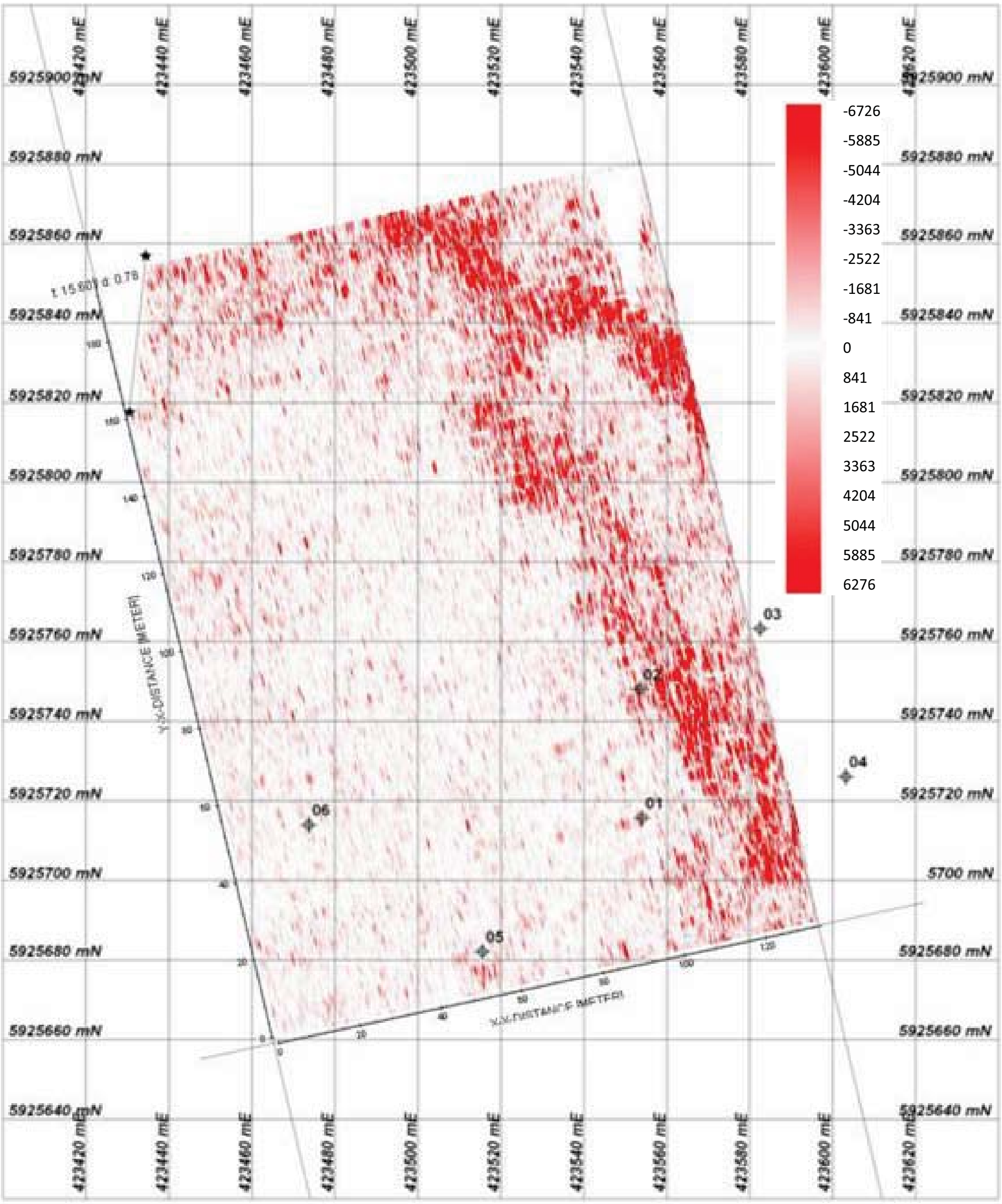

Fig. 6.3 GPR time - depth coverage for 0.78 m depicting thick accumulations of groundwater calcrete/silcrete.

This feature extends in an arc from the south-east corner to the north-west corner of the survey area (Fig. 6.2), flanked on the eastern side by the lunette ridge. Field observations and data collected in conjunction with the geophysical surveys (soil samples 1 – 6, Tables 6.1 and 6.2) showed that the characteristics of the soils located within the zone of shoreline influence (samples 2, 3 and 4) in the lunette were consistent with the physical and chemical properties of profile T1 (in the trench); soils within this zone supported prolific pasture growth.

Table 6.1 pH, EC and ESP values for the surface 0.3 m of soil for the illite/kaolinite-rich soils sampled in the studies.

Illite / Kaolinite-rich soils	Depth (m)	$pH_{1:5}$	$EC_{1:5}$ (dSm^{-1})	ESP %
South 'good'	0.0 – 0.1	7.5	0.25	4.5
	0.1 – 0.2	9.0	0.31	11.8
	0.2 – 0.3	9.5	0.43	24.4
Central 'good'	0.0 – 0.1	7.8	0.33	16.1
	0.1 – 0.2	9.5	0.62	44.0
	0.2 – 0.3	10.1	0.92	52.3
Central 'poor'	0.0 – 0.1	7.2	0.18	5.5
	0.1 – 0.2	8.3	0.10	12.8
	0.2 – 0.3	8.9	0.17	22.8
Soil Association R (sample collected by Blackburn in 1950)	0.0 – 0.025	10.2	0.58	-
	0.025 – 0.05	9.9	0.15	-
	0.063 – 0.1	9.3	0.60	-
	0.11 – 0.15	8.8	2.38	-
South 'Profile 2'	0.0 – 0.1	7.5	0.61	0.6
	0.1 – 0.2	8.3	0.34	0.9
South 'Profile 3'	0.0 – 0.1	7.5	0.41	0.3
	0.1 – 0.2	8.3	0.33	1.0
	0.2 – 0.3	8.7	0.32	1.4
South 'Profile 4'	0.0 – 0.1	7.4	0.76	0.9
	0.1 – 0.2	7.8	0.43	0.9
South 'T1'	0.0 – 0.1	7.7	0.57	1.2
	0.1 – 0.27	8.4	0.39	1.7

In contrast, soils sampled in the south-west zone of the survey area (samples 1, 5 and 6) were similar to profile T3 intercepted in the trench (Vertosol), in that they were deep and black but the pH, EC and ESP in these soils was generally lower in the surface 0.2m than those recorded for T3, hence, this area supported fair plant growth; the most recently observed (Nov 2010) condition of soils in this zone can be seen in Fig. 6.4. The highly degraded features seen in T3 are therefore the result of higher pH, EC and ESP of this soil (Table 6.2). The isolated areas of deep black extremely saline and strongly sodic Vertosols were also identified by GPR, returning a sharp vertical streak on the GPR radargram, owing to their high salt and clay content (Fig. 6.2).

Table 6.2 pH, EC and ESP values for the surface 0.3 m of soil for the smectite rich soils sampled in the studies.

Smectite-rich soils	Depth (m)	$pH_{1:5}$	$EC_{1:5}$ (dSm^{-1})	ESP %
South 'poor'	0.0 – 0.1	7.3	0.52	2.1
	0.1 – 0.2	8.1	0.14	3.1
	0.2 – 0.3	9.1	0.11	5.9
North 'good'	0.0 – 0.1	9.9	0.73	45.6
	0.1 – 0.2	9.9	1.07	48.2
	0.2 – 0.3	10.0	1.39	57.4
North 'poor'	0.0 – 0.1	9.0	5.65	67.3
	0.1 – 0.2	9.5	1.61	47.4
	0.2 – 0.3	9.4	1.91	43.9
Soil Association J (Sample collected by Blackburn in 1950)	0.0 – 0.01	8.6	8.30	-
	0.01 – 0.02	8.7	3.71	-
	0.05 – 0.075	8.0	1.62	-
	0.1 – 0.17	7.9	2.19	-
	0.3 – 0.375	8.6	5.7	-
South 'Profile 1'	0.0 – 0.1	8.3	0.64	6.4
	0.1 – 0.2	8.6	0.89	14.4
	0.2 – 0.3	8.2	3.38	30.5
South 'Profile 5'	0.0 – 0.1	8.0	0.72	6.6
	0.1 – 0.2	8.6	1.15	24.4
	0.2 – 0.3	8.7	2.33	46.9
South 'Profile 6'	0.0 – 0.1	8.0	1.33	3.1
	0.1 – 0.2	8.4	0.54	6.4
	0.2 – 0.3	9.0	0.76	19.0
South 'T3'	0.0 – 0.1	8.9	1.01	18.8
	0.1 – 0.3	9.5	2.22	41.3

These findings led to the conclusion that the poor plant growth observed in this area is related primarily to the presence of isolated patches of extremely saline, strongly sodic and very strongly alkaline Vertosols. Areas that supported good plant growth were generally Chromosols with surface horizons that were mildly to moderately alkaline, low to moderately saline and non-sodic that overlay shallow indurated palustrine limestone.

Fig. 6.4 Photograph of a Vertosol at the South site in November 2010; notice the surface crust and fractures/cracks.

The aim of Chapter 4 was to describe mineralogical, geochemical and morphological analyses of the clay minerals and carbonate types found within the study trench at the South site to attempt to determine the cause of their genesis in the landscape. Three key profiles that were selected in the previous study (Chapter 3) were examined in more detail (T1, T2 and T3 respectively). Clay mineralogy was assessed by XRD, XRF and TEM, whereas the carbonates were subjected to XRD, stable isotope and petrographic analyses. Stable isotope investigations were conducted on both indurated and unconsolidated carbonate types, and petrography was assessed on four highly indurated horizons, with results confirming that these carbonates were principally precipitated in a lacustrine environment. However, the effects of significant chemical and physical diagenesis were evident in some of the samples, suggesting that some zones of the profile had undergone subaerial exposure and alteration, resulting in the development of palustrine limestones. This carbonate type was intercepted in profile T1, and throughout much of the study area, as previously discussed, but was noticeably absent in profile T3. The indurated carbonates intercepted in the lower zones of all profiles were identified as groundwater calcretes, with silicification also likely to be occurring. The unconsolidated carbonates scattered throughout profile T3 were concluded to be pedogenic due to their soft nodular form, their ubiquitous presence throughout the profile and their heavier oxygen and carbon isotopic signatures.

Mineralogical results for the clay fraction of the soils confirmed that similar associations existed as those found in the initial investigations of this project, viz. the Chromosols were dominated by illite and kaolinite clay minerals at the surface, whereas the Vertosols were smectite-dominant throughout. XRD and TEM analysis of Profile T1 from the South site, however, also revealed the presence of sepiolite and palygorskite in the soil profiles, two clay minerals that are rich in Mg and are known to form in lacustrine environments. These minerals were detected in the highest proportions below palustrine limestone and occurred concurrently with the carbonates Mg-rich calcite and ankerite; minor concentrations of dioctahedral smectite (montmorillonite) were also detected. Sepiolite was also previously detected in the profiles at the Central and North study sites (2005). It was concluded that sepiolite and palygorskite are authigenic minerals that were directly precipitated in a lacustrine environment, whereas illite and kaolinite were considered to be mostly detrital in origin. However, the asymmetry of XRD peaks for both illite and kaolinite in some samples, coupled with CECs that are abnormally high for these mineral types, may indicate the occurrence of interstratification, which also supports the formation of these minerals through diagenesis of other clay minerals (smectite, palygorskite and/or sepiolite).

An interesting aspect of Vertosol at the South site (T3), was the occurrence of the Mg-rich trioctahedral smectite mineral saponite; it occurs in the absence of sepiolite, palygorskite, ankerite and montmorillonite in this case, indicating that Mg in solution is partitioned between carbonate and silicate phases. In lacustrine environments saponite has been found to form through both direct precipitation and by diagenetic transformation; the genesis of saponite cannot be conclusively established in this case. Nonetheless, the formation and stability of saponite requires an alkaline environment with prolonged wetting and high activities of Si and Mg. These conditions prevail in the lowest parts of the landscape; hence, saponite can be expected to be found within the basins of lunettes that are prevalent on the western side of the Avenue Plain and throughout natural drainage lines that do not succumb to extensive subaerial exposure. The site selected for this study was concluded to be a lacustrine lunette.

These findings led to the conclusion that poor plant growth observed in isolated areas throughout the South site are primarily the result of the underlying mineralogy of the soils, which in turn is related to their position in the landscape and the hydrological regime of this region. Areas of the landscape that underwent the greatest degree of subaerial exposure supported the development of moderately to highly indurated palustrine limestone which has led to the stratification and preservation of detrital minerals at the surface. These soil types are typically identified as Chromosols. In contrast, in portions of the landscape that supported prolonged surface water inundation, smectite minerals were found to predominate throughout the solum; the physical and chemical properties of these soils can be unfavourable for pasture growth.

The aim of Chapter 5 was to determine whether farmer knowledge and management of soil physicochemical constraints could be improved through active participation in this project. The three farmers principally involved with the project (owners of the South, Central and North study sites) were surveyed upon commencement of the project to determine their level of knowledge of soil physicochemical constraints and their management and aspirations at that time. Throughout the project a range of extension activities were conducted and an active dialogue was maintained between researcher and farmer. A second survey was conducted with the farmers upon completion of the project to determine how their understanding of soil issues and management had changed through involvement in the project.

Results from the survey confirmed that all three farmers involved in the project acquired a better understanding of salinity, sodicity and soil variability on their farms. In addition, their management practices also changed as a result of their acquired knowledge. The main practices employed were the application of gypsum and the establishment of perennial pastures to ameliorate the effects of sodicity and to improve the utilisation of soil water and to maintain cover on the surface of the soil. All of the farmers agreed that the combination of on-farm research and extension activities was beneficial to their learning and impacted on their decision making and management skills.

6.3 GENERAL DISCUSSION

Given the conclusions made in each of the studies discussed above, it has become apparent that two distinct soils types exist in this landscape which are primarily a function of their position in the landscape and the historic hydrological regime of the region. Given the current physicochemical condition of these soils and the existing and proposed expansion of the artificial drainage network throughout the USE, some important implications for management should be considered for each of these soil types.

6.3.1 Illite- and Kaolinite-rich soils

Soils with surface horizons dominated with illite and kaolinite clay minerals were found at the South site in the preliminary study and also across the sampling area and within the trench in the main Study. They were also the only soils intercepted and investigated at the Central study site in the preliminary study. Typical profiles for these soil types exhibit shallow grey surface soils 0.2 – 0.3 m deep with an increasing clay content with depth, that overlie moderately to highly indurated palustrine limestone; their physical and morphological properties are consistent with the major soil type identified in the central region of the Avenue Plain by Blackburn (1952) prior to broad scale agricultural development (Soil Association R). In Blackburn's study these soils were flanked by Soil Association S on the far eastern side of the plain, which were identified as 'variable soils of the plains' and Soil Association J on the western side of the plains, which were 'variable grey and black soils, mainly saline, of the uneven lagoon-lunette areas'. They can be classified as Chromosols, Sodosols or Calcarosols depending on their physicochemical properties.

These soil types exhibit a range of pH, EC and ESP values and have been affected by artificial drainage (Table 6.1). Soils at the South site were less sodic in the surface 0.3 m than the soils at the Central site which is attributed to >50 years of artificial drainage and the regular application of gypsum. Due to the mineralogy, soil structure at the Central site was particularly unstable and dense surface soils were encountered due to clay dispersion.

In addition to clay mineralogy, the leaching of salts and soil structural decline of these soil types may also be affected by the morphology of the underlying carbonate. When highly indurated forms were present (South ‘good’ and Central ‘poor’) the EC of the overlying soil was generally lower than when the carbonate was fractured and marly (Central ‘good’). The highly indurated forms are not conducive to the capillary rise of saline groundwater; hence the leaching of salts is enhanced in these soil types, resulting in the expression of sodicity through lowering soil EC. The recently drained soil at the Central site with these morphological characteristics exhibited a highly compacted form and columnar structure at the surface due to dispersion (Central ‘poor’). An example of this can be seen in Figure 6.5 which is a photograph of the soil in close vicinity to the Central ‘poor’ profile. It shows dense soil structure at the surface and large columns that intergrades to sub-angular blocky smaller peds as the EC of the soil increases with depth; the boundary to palustrine limestone is sharp.

Fig. 6.5 Photograph taken adjacent to the Central 'poor' site, showing dense columnar structure, with a sharp boundary to indurated palustrine limestone.

However, given the effectiveness of the Fairview and Blackford drains to consistently reduce groundwater levels in the vicinity of the Central and South study sites, it is probable that these soils can be remediated with a regular application of gypsum, maintenance of good plant growth and hence, additions of organic matter (Churchman 2002), as seen at the South site. In areas that are currently undrained that feature these soil types, the application of gypsum prior to the implementation of drainage is recommended to avert the expression of sodicity. Upon drainage, it is vital that traffic is also minimised on these soils types following heavy rainfall as this soil type is prone to both spontaneous and mechanical dispersion, leading to the development of very dense surface soils that are not capable of self-mulching, unlike their Vertosol counterparts.

6.3.2 Smectite-rich soils

Soils that were dominated by smectite clay minerals were intercepted and investigated at both the South and North study sites; they have also subsequently been found at the Central site. These soils were generally much deeper than the illite- and kaolinite-rich soils, owing to the absence of shallow palustrine limestone. Artificial drainage appeared to have a large impact on the EC, ESP and pH of these soils in the preliminary study when great variability was observed between the drained soils at the South site and the undrained soils at the North. However isolated areas that were extremely saline and strongly sodic and very strongly alkaline were also detected at the South site in the main study. ESPs were lower at the South site, however, which is most likely due to the regular application of gypsum at this site and the long-term employment of artificial drainage. The undrained smectite soils (North site), were extremely saline, strongly sodic (ESP>40 % in all cases) and very strongly alkaline (Table 6.2), yet exhibited good aggregation and prolific root exploration; this factor is attributed at least partly to its extreme salinity and the presence of salt tolerant vegetation at this site.

One of the major concerns of the farmers at the outset of this project was that their whole farms would become barren as a result of artificial drainage. This proposal can be thoroughly disregarded, as the degradation observed has been found to be primarily related to clay mineralogy and not directly to the implementation of the drainage schemes. The variability in soil types has always existed across these farms; however, the current managers were not fully aware of such variability or the consequence for pasture production. This is mostly brought about as the low lying areas (basins of the lunettes and natural drainage lines) are typically inundated with surface water in the winter and spring months, so the degradation of pasture growth was not previously noted. It is the expansion of artificial drainage, coupled with the consistent decline in annual rainfall that has resulted in the extensive drying of these soils and the subsequent expression of salinity and sodicity for the first time in the current managers' experience. Observations in the 1950s concluded that these variable grey and black clay-rich salt-affected soils (assumed to be smectite dominant in this study) were colonised by salt tolerant vegetation such as thatching grass, salt-water tea tree and samphire. Since this land has been cleared of native vegetation and developed for agricultural purposes, these original native vegetative indicators of soil mineralogical variability are no longer evident across this landscape.

Given the extreme ESP observed in some of the studied soils, it is highly likely that they will succumb to the deleterious effects of sodicity if/when the leaching of salts is facilitated. The effects of slaking and dispersion on soil physical properties and eventual crop yield was discussed and modelled by So and Aylmore (1995). Their model depicts how dispersion leads to surface sealing, reduced infiltration, surface waterlogging, high initial evaporation and crusting, followed by reduced subsequent evaporation and drying; the subsoil therefore remains wet. These phenomena were seen to occur at numerous sites in this study; an example can be seen in Figure 6.7 that shows the crust that has formed following rainfall and the emergence of a seedling that had recently germinated, but was incapable of breaking through the impeding layer. XRD analysis of the white surface material revealed it to be pure quartz; its accumulation at the surface is brought about by the dispersion and eluviation of the clay fraction.

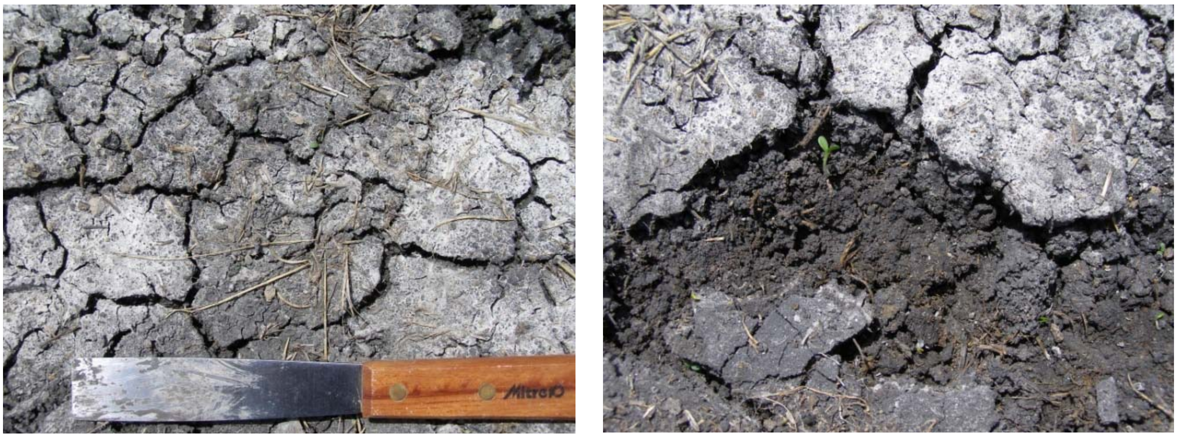

Fig. 6.7 Photograph of a Vertosol following rainfall, showing the formation of a hard surface crust (left) and the impeded emergence of a recently germinated plant (right).

It was also observed that these soil types were often moist below 0.1 m when sampled (except for the surfaces of large columnar peds that are created through drying and the formation of large cracks), regardless of the season and rainfall history. Given the reduced hydraulic conductivity often created through these processes, the leaching of salts from these soils may therefore be difficult to adequately achieve; it is likely that these soils will always be saline and sodic at some point in the profile, with surface salinity increasing in the dry months due to capillary rise and evapo-concentration, subsequently followed by dispersion in the surface in the wetter months.

Whereas the illite/kaolinite soils were observed to develop dense soil structure and large columns upon dispersion and drying (Fig 6.5), the smectite soils did not typically exhibit this feature in the surface which can be attributed to the shrink-swell, and hence self-mulching, nature of these soil types (Mermut *et al.* 1996). While this shrink-swell behaviour may be beneficial for soil structure, the significant shrinking and crack formation of the soil that occurs upon drying often leads to the development of noticeable microrelief features across the soil surface, often referred to as gilgai (Mermut *et al.* 1996). These depressions are then prone to the further accumulation of salts as they attract and capture evapo-concentrated saline surface waters, thereby exacerbating their hostile chemical properties. These processes may be the cause of the highly degraded features and complete lack of plant growth seen in profile T3 in comparison to the Vertosols in the surrounding area.

Management and amelioration of the isolated patches of Vertosols that are highly degraded may therefore be difficult to achieve. It will be vital to establish and maintain plant cover on the surface of the soil to minimise dispersion by raindrop impact and subsequent evaporation; the colonisation of deep rooted, salt tolerant perennial pasture is recommended in this case. Regular applications of gypsum are also recommended to overcome sodicity and stabilise soil structure and deep artificial drainage should be employed to maintain the saline groundwater at a lower level. The highly sodic patches of Vertosols will also be particularly prone to mechanical dispersion, hence, machinery operations and livestock traffic should be avoided when these soils are wet.

In the event of the extension of artificial drainage through areas that feature Vertosols, gypsum application should be employed prior to and following the implementation of drainage. In addition it would be beneficial to establish deep rooted perennial pasture species that can help to stabilise soil structure in the event of dispersion occurring. An active program of soil testing should also be employed to monitor EC, ESP and pH to determine the change in soil physicochemical conditions and to prescribe gypsum and nutrient recommendations to ensure adequate plant survival and proliferation.

6.4 LIMITATIONS OF THE STUDY AND RECOMMENDATIONS FOR FUTURE RESEARCH

Some of the discussion for the soil types reported in this study was based on visual observations of the soils in the paddock and the laboratory. Knowing what the author now knows about the soils in this landscape, there are analyses that could be performed that will strengthen the arguments and conclusions made here. Bulk density of the soil horizons could be performed to quantify the degradative effects of sodicity and dispersion on soil structure in the paddock. Percent plant cover could also be measured to better quantify the effects of soil physicochemical constraints on pasture growth. Boron toxicity is also a known chemical constraint in sodic soils and this too could be measured in these soils to determine if one soil type is more prone to the accumulation of boron than another. XRD analysis also could be performed on Blackburn's samples retrieved from the CSIRO archives to confirm that Soil Associations J and R are smectite dominant and illite/kaolinite dominant respectively. To confirm kaolin-smectite interstratification, high resolution TEM and infra-red spectroscopy analyses could also be performed to show diagnostic peaks for kaolinite (Churchman *et al.* 1994). To confirm the occurrence of illite-smectite interstratification, TEM and EDAX analyses could be used to indicate the K content of the clay structures.

For the carbonates, SEM and microprobe analyses could be used to assess the degree of silicification of the groundwater calcretes, and analysis of ground water samples for Si content could also be performed to support this. Petrographic assessment could also be conducted on more samples of palustrine limestone to confirm its uniform presence across this landscape.

An active soil monitoring program is also recommended for the northern area of the Keilira District, including the North study site. Since this project commenced, the extension of the drainage schemes has continued in the USE; in July 2010 the Bald Hills drain was excavated through the northern section of the Avenue Plain, intersecting the property ‘Cherita’ which was the North study site in the 2005 investigations. A visit was made to this property in November 2010 to inspect the excavated drain and the exposed soil profile. Much of the drain intersected soils with characteristics similar to the Chromosols that are common on the Avenue Plain; an example of this can be seen in Fig. 6.8. In contrast, the drain also intersected the eastern edge of a natural drainage line that featured Vertosols, the pasture colonised on this area (Sea Barley grass) had prematurely senesced, potentially owing to the hostile chemical conditions previously recorded for these soils at the North site. The photo shown in Figure 6.9 was taken at this time on the eastern edge of the Bald Hill drain (that transects the Avenue Plain North – South in this area), looking west, and shows the distinct change in soil type; the West Avenue Range can be seen in the background.

Investigations of standing water levels (SWL) in the observation wells near the Fairview drain showed that it effectively maintained lower SWL upon excavation and it is highly likely that the Bald Hills drain will have the same effect. The leaching of salts may be facilitated in this case and the structural decline of the soils at the North site is highly probable given the strongly sodic conditions previously reported.

Fig. 6.8 Typical grey soils of the Avenue Plain that that support good plant growth.

Fig. 6.9 Natural drainage lines at the North site contain Vertosols that are extremely saline, strongly sodic and very strongly alkaline. Plant growth on these soil types is restricted to Sea Barley Grass, as seen in the photo (Nov 2010).

Soil monitoring should be conducted at least annually, if not seasonally, to determine the rate of removal of salts in each of the soil types and the subsequent gypsum application rates that will be required to avert the expression of sodicity on this farm; every effort should also be made to maintain plant cover. The installation of piezometers across this northern sector is also recommended to determine the effects of the drain on SWL.

In addition, the proportion of dioctahedral versus trioctahedral smectite should be assessed at the North site, and more extensively in salt-affected soils from the South site. Investigations reported in Chapters 3 and 4 of this thesis found that the soils in the south-west zone of the survey area at the South site were Vertosols that were formed in the basin of a lacustrine lunette. Further conclusions made in Chapter 4 of this thesis reported that the isolated patches within this zone with highly degraded physical and chemical form were Vertosols dominated by saponite clay minerals (trioctahedral) in the surface 0.5m. Mineralogical analysis of another soil profile sampled within this zone (not previously reported in this thesis) showed that it was dominated by montmorillonite (dioctahedral) in the surface 0.5 m, and not saponite (Fig. 6.6). In contrast to profile T3, the surface 0.3 m of this profile (Trench sample 201; Appendix 3) was only moderately saline, non-sodic and was moderately alkaline. Saponite was, however, strongly detected in the 0.6 – 0.9 m horizon of this profile (Fig. 6.10) and was also highly saline (0.7 dSm^{-1}), strongly sodic (46.1 %) and very strongly alkaline, with a pH of 9.9.

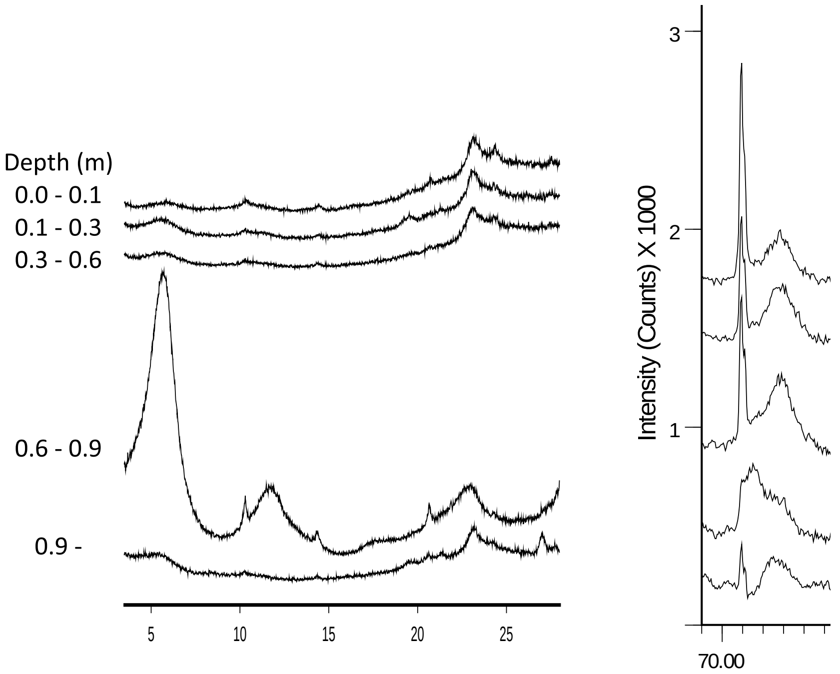

Fig. 6.10 XRD peaks for the clay fraction and bulk soil of a Vertosol within the lunette basin at the South site.

Another observation made was that when saponite was present (as indicated by the trioctahedral peak), strong smectite peaks were recorded in the absence of sepiolite and palygorskite, as demonstrated in Fig. 6.10 (and also Fig 4.5). In contrast, when smaller broad peaks were observed, dioctahedral smectites (montmorillonite) were present, often in addition to sepiolite and palygorskite, suggesting that dioctahedral smectites are interstratified with other clay minerals such as illite and/or kaolinite. In addition, it is now also observed that the ESP is often higher when the soils are dominated by saponite, than when dominated by montmorillonite. This is brought about not only by an increase in exchangeable sodium, but also is often due to a decrease in exchangeable Mg. This phenomenon may at least partly be attributed to the mineralogy of the soil, whereby a greater proportion of Mg is present in the structure of the clay minerals (saponite) therefore resulting in less Mg being available on the exchange complex, thereby increasing the ESP. The proportion of dioctahedral versus trioctahedral smectite in the surface of the soils is therefore an important factor that contributes to the degradation of these soils when salt-affected. The dioctahedral versus trioctahedral composition of the smectite-dominant soils at the North site was not determined in the current investigations, however distinct differences were observed in the XRD patterns at the North site for the clay fractions, despite them both being smectite dominant (Fig. 2.6). The ‘good’ soil from this site was much less saline and sodic at the surface than the ‘poor’ soil and contained smectite and sepiolite throughout, whereas the ‘poor’ end, in contrast, exhibited strong smectite peaks in the absence of sepiolite in the surface 0.3 m and was extremely saline and strongly sodic at the surface; given the observations for EC, ESP and mineralogy made in other soils, these data suggest that the soil at the ‘poor’ end of the trench may have been dominated by trioctahedral, rather than dioctahedral, smectite. This theory could be tested with further XRD analysis, not only at this site, but also for other patches of soil that are particularly degraded at the surface.

6.5 CONCLUSIONS

The aim of this study was to help the local farmers at Keilira to determine the cause of a decline in plant growth that was occurring in isolated areas across their farms. The combination of observations and data reported in this thesis has led to the conclusion that the areas within this landscape that exhibit poor plant growth are primarily indicative of isolated patches of smectite-dominant deep clay soils that are extremely saline, strongly sodic and very strongly alkaline. These soils are found to occur in the lowest parts of the landscape, primarily in the basins of lunettes and throughout natural drainage lines; the development of smectite-dominant soils and the absence of shallow indurated palustrine limestone is the result of prolonged surface water inundation and high activities of Si and Mg in an alkaline environment. The clay minerals and carbonate types studied here are consistent with those of lacustrine and palustrine origin.

Poor plant growth may also be observed in soils that are dominated by illite and kaolinite clay minerals. If sodic, these soil types are prone to dispersion and the development of dense soil structure when the soil EC is reduced through leaching. Given the effectiveness of the drainage schemes and the morphology of the underlying limestone, these soil types can be remediated with the regular application of gypsum, as seen at the South site, provided saline ground waters do not breach the shallow limestone.

In the areas that feature Vertosols, a management program that includes the establishment of salt-tolerant perennial pastures and sustained applications of gypsum should help to stabilise these soils and lead to better physicochemical condition, albeit complete amelioration may take longer to achieve than for the Chromosols. It is important that local farmers at Keilira and across the Avenue Plain conduct thorough surveys of their farms to determine the areas of each soil type and individually manage each of these areas appropriately.

In addition, the combination of on-farm research and extension activities enabled the three farmers involved in this project to improve their knowledge of salinity, sodicity and soil variability across their farms. This acquired knowledge led to the implementation of new management practices on each of the farms, with all of the farmers reporting increased triple bottom line sustainability as a result of their participation in the project.

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APPENDIX 1

NOTE:
This map is included on page 201
of the print copy of the thesis held in
the University of Adelaide Library.

Appendix 1.1 Map of key geological features of South East South Australia. Source: SECWMB (2003).

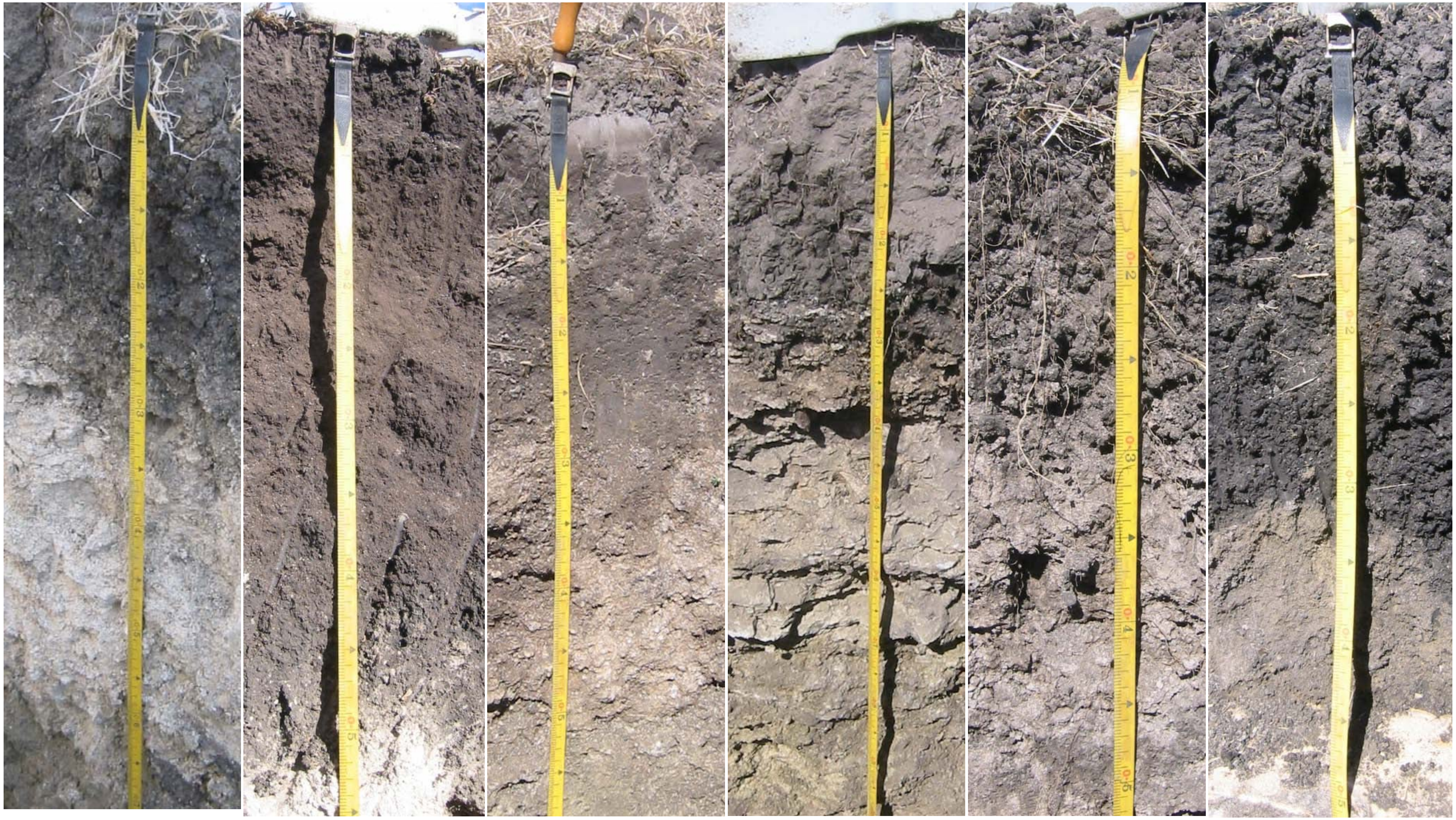
NOTE:
This map is included on page 202
of the print copy of the thesis held in
the University of Adelaide Library.

Appendix 1.2 Surface water flow paths in South East South Australia. Source: SECWMB (2003).

NOTE:
This map is included on page 203
of the print copy of the thesis held in
the University of Adelaide Library.

Appendix 1.3 Flooding and inundation experienced prior to drainage. Source: SECWMB (2003)

APPENDIX 2



(a) South 'Good' (b) South 'Poor' (c) Central 'Good' (d) Central 'Poor' (e) North 'Good' (f) North 'Poor'

Photographs of the profiles sampled in conjunction with Chapter 2

APPENDIX 3

Trench Location	Sample number	Depth m	Moisture %	Ratio	pH$_{1:5}$ Water	pH$_{1:5}$ CaCl	EC$_{1:5}$ dS/m	EC corrected	Cl mg/Kg	TOC %	Exch.Cations pH 8.5 I---------- cmol(+)/kg ----------I					C.E.C. (NH$_4$)	ESP %	EMP %	Carbonate %	Clay <2µm %	Silt 2-20µm %	Sand 20-2000µm %
											Ca	Mg	Na	K	Total							
101	1	0.0 - 0.1	8.2	1:5	7.93	7.65	0.42	0.42	124.35	-	15.4	5.8	0.6	3.7	26	26	2.3	22.8	-	-	-	-
101	2	0.1 - 0.3	19.0	1:5	8.38	8.06	0.69	0.69	141.75	-	13.1	12.2	1.2	2.5	29	28	4.2	42.0	-	-	-	-
101	3	0.3 - 0.5	9.1	1:5	8.81	8.36	0.54	0.54	112.5	-	6.5	13.2	1.5	1.4	23	20	6.7	58.3	-	-	-	-
101	4	0.5 - 0.75	11.6	1:5	8.94	8.31	0.39	0.39	112.95	-	4.5	9.8	1.7	1.4	17	17	9.9	56.3	-	-	-	-
101	5	0.75 - 0.87	9.8	1:5	9.14	8.32	0.36	0.36	159.15	-	3.5	7.3	1.8	0.8	14	13	13.6	54.3	-	-	-	-
101	6	0.87 - 0.94	1.3	R	-	-	-	-	-	-	3.0	5.6	3.3	0.9	13	11	25.9	43.7	-	-	-	-
101	7	0.94 - 1.02	-	R	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
101	8	1.02 - 1.2	9.1	1:5	9.53	8.52	0.68	0.68	561.6	-	6.1	16.4	7.8	1.3	32	31	24.7	51.9	-	-	-	-
101	9	1.2 - 1.4	-	R	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
101	10	1.4 - 1.5	10.7	1:5	9.49	8.25	0.54	0.54	495	-	1.3	3.2	2.2	0.5	7	7	30.7	44.9	-	-	-	-
103	1	0.0 - 0.1	5.3	1:5	7.68	7.29	0.57	0.57	20	2.61	12.3	9.3	0.3	2.6	24.5	27.3	1.2	37.9	2.6	32.1	27.2	40.8
103	2	0.1 - 0.27	8.9	1:5	8.39	7.94	0.40	0.40	26	0.84	12.8	18.8	0.6	4.5	36.7	37.1	1.7	51.2	8.0	93.2	3.3	3.5
103	3	0.27 - 0.4	4.4	R	-	-	-	-	-	0.36	3.4	5.9	0.5	1.5	11.3	11.3	4.7	52.0	73.9	55.9	3.7	40.4
103	4	0.4 - 0.65	5.9	1:5	9.18	8.29	0.27	0.27	19	0.31	4.1	10.1	1.4	1.8	17.5	17.0	7.9	58.1	65.1	83.4	4.0	12.6
103	5	0.65 - 0.95	10.7	1:5	9.42	8.23	0.36	0.36	28	0.27	3.3	8.2	3.0	1.1	15.5	14.9	19.1	53.0	70.6	87.7	5.2	7.2
103	6	0.95 - 1.1	6.3	R	-	-	-	-	-	0.24	2.9	7.0	5.8	1.0	16.7	15.9	34.7	41.8	66.1	83.0	7.3	9.7
103	7	1.1 - 1.3	30.2	1:5	9.46	8.64	1.23	1.23	1087	0.21	4.5	14.0	12.5	1.8	32.7	30.5	38.2	42.7	22.1	87.3	2.4	10.3
103	8	1.3 - 1.5		1:5	9.38	8.33	0.80	0.80	734	0.20	3.4	8.3	5.0	1.1	17.9	16.6	28.2	46.7	86.8	70.6	7.3	22.1
106	1	0.0 - 0.08	2.5	1:5	7.20	6.74	0.25	0.25	39	-	11.8	6.0	0.2	1.8	20	26	1.3	30.3	-	-	-	-
106	2	0.08 - 0.28	9.7	1:5	7.73	7.23	0.28	0.28	29	-	13.6	19.2	0.4	2.9	36	38	1.2	53.2	-	-	-	-
106	3	0.28 - 0.38	13.5	1:5	8.25	7.69	0.27	0.27	34	-	14.9	21.9	0.9	2.4	40	46	2.2	54.6	-	-	-	-
106	4	0.38 - 0.43	6.0	1:5	8.90	8.12	0.27	0.27	22	-	9.9	17.3	3.0	3.5	34	34	8.8	51.3	-	-	-	-
106	5	0.43 - 0.56	8.4	1:5	8.99	8.15	0.27	0.27	18	-	5.3	9.3	1.9	1.9	18	17	10.2	50.5	-	-	-	-
106	6	0.56 - 0.8	16.7	1:5	8.97	8.19	0.32	0.32	26	-	5.9	10.3	3.1	2.2	22	23	14.6	47.9	-	-	-	-
106	7	0.8 - 1.0	12.8	1:5	9.05	8.19	0.32	0.32	28	-	4.5	7.9	2.8	1.6	17	18	16.8	46.8	-	-	-	-
106	8	1.0 - 1.25	2.8	R	-	-	-	-	-	-	1.9	3.3	1.2	0.6	7	6	17.5	47.0	-	-	-	-
106	9	1.25 - 1.5	33.5	1:5	9.17	8.35	0.70	0.70	353	-	10.3	22.8	9.1	1.6	44	47	20.7	52.0	-	-	-	-
110	1	0.0 - 0.1	5.8	1:5	8.38	7.89	0.34	0.34	19	1.75	19.0	8.5	0.7	2.3	30.5	35.7	2.4	28.0	21.5	68.6	10.6	20.8
110	2	0.1 - 0.2	7.2	1:5	8.9	8.21	0.41	0.41	28	0.51	4.2	8.1	1.1	0.7	14.1	12.5	7.6	57.5	73.2	81.1	8.6	10.3
110	3	0.2 - 0.5	3.4	1:5	9.48	8.41	0.42	0.42	42	0.33	1.9	7.4	2.5	0.5	12.3	11.3	20.5	60.4	82.7	86.1	2.8	11.1
110	4	0.5 - 0.8	9.9	1:5	9.5	8.29	0.45	0.45	47	0.23	1.8	5.0	3.3	0.5	10.6	10.1	31.1	47.1	74.9	83.9	3.8	12.4
110	5	0.8 - 0.87	2.0	R	-	-	-	-	-	0.22	1.0	2.5	2.5	0.4	6.4	7.9	38.5	38.5	84.7	55.5	10.7	33.8
110	6	0.87 - 0.9	13.9	1:5	9.37	8.42	0.70	0.70	73	0.31	4.4	12.2	8.8	1.3	26.7	27.0	33.1	45.5	17.0	61.2	14.3	24.6

Trench Location	Sample number	Depth m	Moisture %	Ratio	pH Water	pH CaCl	EC dS/m	EC corrected	Cl mg/Kg	TOC %	Exch.Cations pH 8.5 I---------------------- cmol(+)/kg ---------------------I					C.E.C. (NH_4)	ESP %	EMP %	Carbonate %	Clay <2µm %	Silt 2-20µm %	Sand 20-2000µm %
											Ca	Mg	Na	K	Total							
112	1	0.0 - 0.1	11.5	1:5	8.89	8.24	1.01	1.01	350	1.71	15.4	17.0	7.8	1.3	41.6	35.8	18.8	40.9	21.3	45.0	38.5	16.5
112	2	0.1 - 0.3	9.9	1:10	9.45	8.6	1.11	2.22	651	0.74	7.4	15.0	16.8	1.5	40.7	37.8	41.3	36.9	31.5	74.9	20.8	4.3
112	3	0.3 - 0.5	6.6	1:10	9.79	8.81	1.09	2.18	843	0.76	3.6	10.3	19.0	1.1	34.0	29.9	55.9	30.3	34.4	77.0	19.3	3.7
112	4	0.5 - 0.7	9.8	1:5	9.61	8.6	1.36	1.36	609	0.40	2.5	5.4	9.3	0.7	17.9	13.8	52.0	30.2	61.8	76.6	13.7	9.8
112	5	0.7 - 1.0	1.0	R	-	-	-	-	-	0.32	0.9	1.1	1.9	0.4	4.3	4.1	44.5	25.8	81.0	51.3	9.3	39.4
112	6	1.0 - 1.4	3.2	1:5	9.73	8.28	0.48	0.48	155	0.15	1.3	2.9	3.0	0.5	7.7	7.5	39.3	36.9	79.9	45.1	7.1	47.8
113	1	0.0 - 0.1	12.3	1:5	8.64	8.01	0.49	0.49	104	-	24.6	14.5	3.4	2.1	45	44	7.7	32.5	-	-	-	-
113	2	0.1 - 0.25	11.7	1:5	8.99	8.28	0.91	0.91	292	-	15.2	15.6	9.3	1.9	42	41	22.1	37.3	-	-	-	-
113	3	0.25 - 0.55	4.2	1:10	9.77	8.56	0.86	1.71	549	-	3.6	10.8	15.2	0.8	30	26	49.8	35.6	-	-	-	-
113	4	0.55 - 0.7	13.1	1:10	9.84	8.61	0.86	1.72	433	-	3.2	8.2	13.6	0.5	26	23	53.5	32.0	-	-	-	-
114	1	0.0 - 0.1	9.8	1:5	8.32	7.88	0.29	0.29	33	-	26.6	12.8	0.6	2.1	42	41	1.4	30.5	-	-	-	-
114	2	0.1 - 0.2	15.1	1:5	8.56	8.03	0.37	0.37	31	-	17.4	15.3	0.8	1.0	34	32	2.2	44.5	-	-	-	-
114	3	0.2 - 0.4	5.9	1:5	8.96	8.29	0.31	0.31	22	-	7.0	10.9	1.1	0.3	19	18	5.7	56.6	-	-	-	-
114	4	0.4 - 0.6	5.2	1:5	9.15	8.33	0.28	0.28	24	-	4.7	12.6	1.8	0.3	19	19	9.3	64.8	-	-	-	-
114	4	0.6 - 0.82	4.4	1:5	8.95	8.19	0.42	0.42	81	-	6.9	14.3	3.1	1.1	25	27	12.2	56.4	-	-	-	-
114	6	0.82 - 1.2	6.1	1:5	9.56	8.34	0.45	0.45	103	-	3.2	6.7	3.4	0.6	14	14	24.4	47.9	-	-	-	-
201	1	0.0 - 0.1	7.0	1:5	8.3	7.78	0.30	0.30	37	3.63	25.1	8.9	0.5	1.6	36.2	36.0	1.3	24.7	9.1	48.2	20.5	31.3
201	2	0.1 - 0.3	14.9	1:5	8.6	8.01	0.39	0.39	41	1.23	17.5	15.5	1.9	1.4	36.3	33.9	5.4	42.7	23.4	66.4	11.2	22.4
201	3	0.3 - 0.6	21.9	1:5	9.4	8.74	1.06	1.06	173	0.68	6.0	25.3	15.4	2.9	49.6	47.8	31.1	51.0	6.5	62.4	19.5	18.1
201	4	0.6 - 0.9	3.1	1:10	9.86	8.68	0.70	1.40	122	0.45	2.4	13.5	14.3	0.8	31.0	28.0	46.1	43.7	39.2	92.1	2.2	5.7
201	5	0.9 - 1.2	10.4	R	-	-	-	-	-	0.28	1.0	2.1	2.7	0.5	6.2	6.1	42.9	33.3	77.6	72.1	8.6	19.3
301	1	0.0 - 0.08	2.7	1:5	7.54	7.07	0.21	0.21	51	2.69	13.6	8.6	0.4	3.0	25.6	31.7	1.4	33.6	4.0	60.0	16.0	24.0
301	2	0.08 - 0.18	8.7	1:5	7.75	7.16	0.13	0.13	36	0.78	10.6	18.6	0.4	4.3	33.9	37.5	1.2	54.8	2.5	90.4	5.0	4.6
301	3	0.18 - 0.28	13.4	1:5	8.23	7.74	0.28	0.28	36	1.21	12.4	20.8	1.0	4.5	38.7	39.1	2.7	53.7	5.5	96.5	1.5	2.1
301	4	0.28 - 1.0	4.9	1:5	9.02	8.21	0.39	0.39	242	0.29	3.1	6.7	1.8	1.1	12.8	13.0	14.3	52.5	67.8	54.0	17.2	28.8
301	5	1.0 - 1.3	3.8	R	-	-	-	-	-	0.20	3.5	7.7	6.1	0.9	18.3	24.5	33.5	42.0	24.0	44.1	40.8	15.1

Cells shaded grey are the three main profiles selected as being representative of soils in the trench. T1 = 103 T2 = 110 T3 = 112