MOUNT TORRENS, EASTERN MOUNT LOFTY RANGES, SOUTH AUSTRALIA

R.W. Fitzpatrick and M.S. Skwarnecki

CRC LEME, CSIRO Land & Water, Private Bag 2, Glen Osmond, SA 5064

Rob.Fitzpatrick@csiro.au

INTRODUCTION

Initial work was based on detailed soil sampling and fieldwork in the Herrmanns and Dairy Creek catchments (14 km^2) near Mount Torrens, 45 km northeast of Adelaide in the eastern Mount Lofty Ranges ~~at~~, South Australia (Figure 1; 34^{o}53'15"S 139^{o}00'18"E; ADELAIDE 1:250 000 sheet SI54-09) (e.g. Fritsch and Fitzpatrick, 1994; Fitzpatrick *et al*., 1996; Skwarnecki *et al*., 2002). Regional studies were also conducted of areas surrounding these catchments covering 80 km^2 (Fitzpatrick *et al*., 1999) and 1000 km^2 (Skwarnecki and Fitzpatrick, 2003). Landscapes in this region host base metal mineralization and are contributing to degraded saline seepages and poor stream water quality, which are major constraints to agricultural production in the region.

To understand how soil-water-landscape process models can be used for explaining causes of land degradation or sampling tools in mineral exploration, knowledge of hydrology and its relationship to soil-regolith macro-morphological features (e.g. mottling patterns) are essential. Unfortunately, soil-regolith macro-morphological features can reflect both past as well as present hydrology in ancient landscapes such as in the eastern Mount Lofty Ranges. Construction of appropriate 3D and 4D soil-water-landscape models will, however, permit distinction between past (relict) and current hydro-pedological processes.

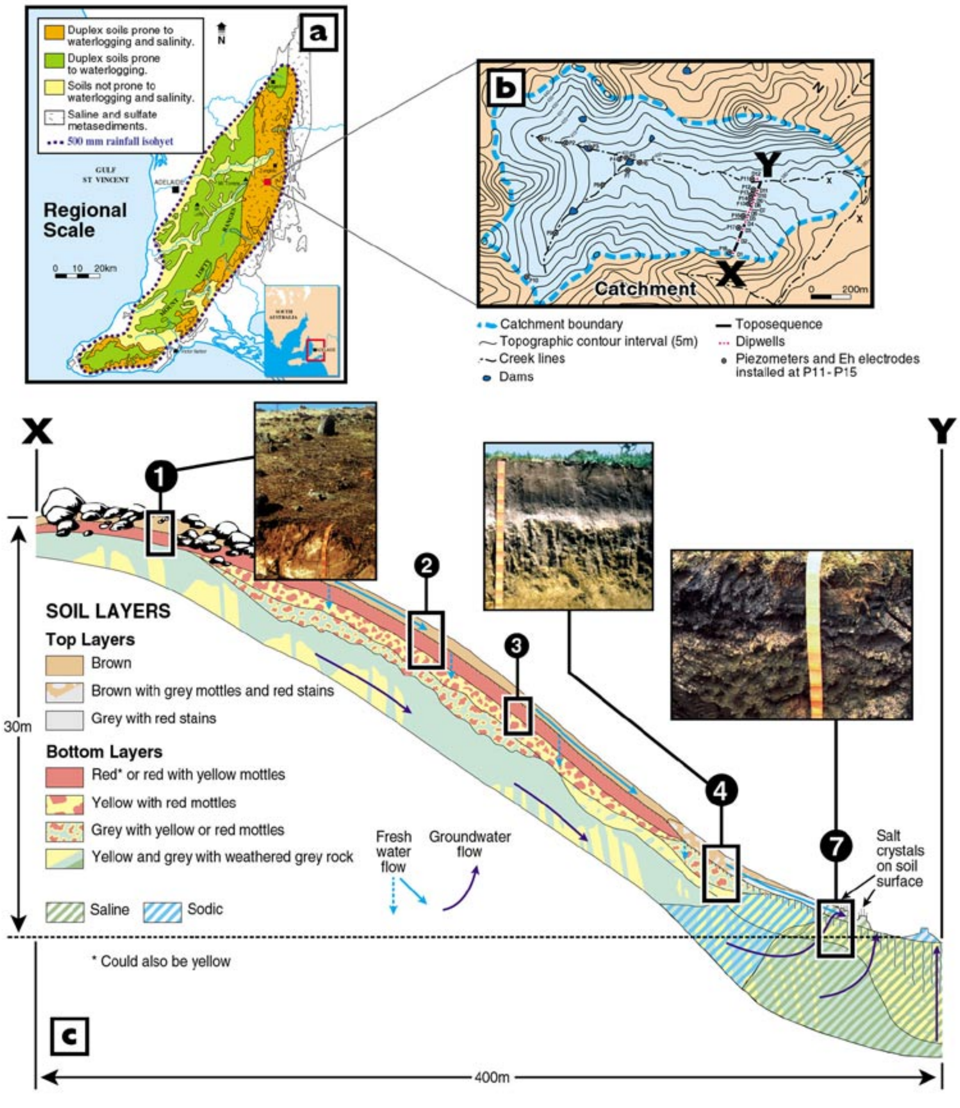

Figure 1. (a) Regional map of the Mount Lofty Ranges with generalised rainfall, geology, and soil pattern; (b) Herrmanns focus sub-catchment; (c) *Descriptive* soil-regolith model showing toposequence with three selected soil profiles, soil features (e.g. relict purple mottles and current very poorly drained saline soils with grey with red stains) and direction of perched fresh water flow and groundwater flow. (Modified from Fritsch and Fitzpatrick, 1994; Fitzpatrick *et al.,* 1997)

PHYSICAL SETTING

Geology and Geomorphology

The landscape of much of the eastern Mount Lofty Ranges region is undulating low hills; the altitude ranges from 400 to 500 m and local relief from about 30 to 50 m. A northeast to southwest topographic high east of Mount Torrens bisects the area; small catchments to the west drain into the Onkaparinga and Torrens catchment systems; catchments to the east form part of the Murray–Darling Basin system (Figure 1). These subcatchments are mostly underlain by rocks of Cambrian Kanmantoo Group, which includes units (such as the Nairne Pyrite Member) with relatively high amounts of S-, Cl- and Na -bearing minerals.

Erosional regime: Units of the erosional regime occur on rolling hills, where thin soils overlie bedrock, saprock or ferruginous saprolite. Outcrops of bedrock are common. Ferruginous saprolite, derived from Tapanappa Formation and Talisker Calc-siltstone rocks, outcrop on low hills in central parts of the area. There is generally no saprolite preserved over sandstones of the Backstairs Passage Formation in the west. Gossans crop out locally in a zone 200 m long at the base of low hills formed of Nairne Pyrite Member. Gossans are superficially very similar in appearance to ferruginous saprolite. However, on fractured surfaces, bright yellow mottles or patches (dominantly plumbojarosite, minor plumbogummite) occur in a reddish-purple matrix (mainly hematite). Gossans with boxworks after pyrite occur locally and are weathered equivalents of barren pyrite-rich mineralisation. Gossans also contain barite, kaolinite, jarosite, natrojarosite, Fe oxides with adsorbed Pb, anglesite, iodargyrite, gorceixite, anatase and native gold. In Dairy Creek, a galena-rich vein outcropping in the creek bed has been weathered to cerussite.

Depositional regime: Alluvium and colluvium occur along the valleys of Dairy Creek and its tributaries. Saprolite derived from Tapanappa Formation rocks is exposed where the creeks are deeply incised. Ferricrete occurs along the valley floor to the east of the subcatchments and has cemented alluvium, colluvium and lag derived from quartz veins and ferruginous saprolite. The Fe oxides were derived from erosion of ferruginous material from surrounding hills, where patches of ferruginous saprolite are still preserved.

Climate and vegetation

The climate is Mediterranean and representative of the eastern part of the Mount Lofty Ranges, with a mean annual rainfall of 650–700 mm falling in winter (May to September) and hot, dry summers (December to February). The vegetative cover before clearing for agriculture and for timber was *Eucalyptus camaldulensis* woodland. This was replaced by pasture, mainly comprising ryegrass and subterranean clover.

Soils, hydrology and land use

Relationships between landform elements, soil types, drainage, waterlogging, salinity and acidity are summarised in Figure 1. Soils are derived from strongly weathered micaceous sandstones and schists of the underlying metasedimentary rocks. On upper slopes outcrops of bedrock are common and thin soils may overlie bedrock, saprock or ferruginous saprolite. Soils of the middle and upper slopes are characterised by abrupt textural boundaries between sandy- and loamy-textured surface horizons (A and E horizons) and clayey subsurface horizons (B horizons) with mottled and/or sodic properties and classify mostly as Palexeralfs according to Soil Taxonomy (Soil Survey Staff, 1999). Lower slopes, terraces and valley floors frequently have sodic (Natrixeralfs) and alluvial soils (Entisols), and wet soils (Aquents) in saline groundwater discharge areas with perched wetlands. Soils of the groundwater discharge areas are frequently saline and sulfidic — these are potential acid sulfate soils (Fitzpatrick *et al.*, 1996). After oxidation of the sulfidic materials, such soils become actual acid sulfate soils (ASS) that contribute to degraded water quality through leakage of salts and acid weathering products. The clayey B horizons of sodic soils that have developed in areas where saline groundwater discharge has occurred often disperse and erode.

Land use in this area is predominantly sheep or cattle grazing on pasture. Increasingly, land is being used for more intensive purposes such as viticulture and cereal cropping. Commercial pine plantations have been established in areas of the Torrens River catchment, which is an important source of urban water supply.

REGOLITH-LANDFORM RELATIONSHIPS

Soil–regolith process model development

Soil–regolith process models are a simplification or abstraction of the mechanisms that occur in a particular geological-pedological cross-section or toposequence under study so that it can be more easily handled either physically or mentally for a specific purpose (e.g. Dijkerman, 1974). Several kinds of simplification or abstraction may be used; for example, in creating conceptual models that *describe*, *explain* or *predict* particular aspects of soil–regolith processes. Because more than one kind of simplification or abstraction is often used to design models, different models are not necessarily mutually exclusive. Here, we will show how the *descriptive* model is used as the precursor or framework for developing the *explanatory* model (3D), which in turn is used to help develop the *predictive* model (4D) for the eastern Mount Lofty Ranges region. Consequently, the *predictive* model (4D) consists of a collage of figures, which illustrates several cycles of evolutionally soil-regolith events.

SOIL-REGOLITH CHARACTERISATION

Descriptive soil-regolith models

Colour photographs of three typical profiles at different parts down the landscape slope or toposequence at the Herrmanns catchment are shown in Figure 1. Key soil morphological and physico-chemical features of profiles are also summarised in Figure 1. To understand the lateral linkages and relationships

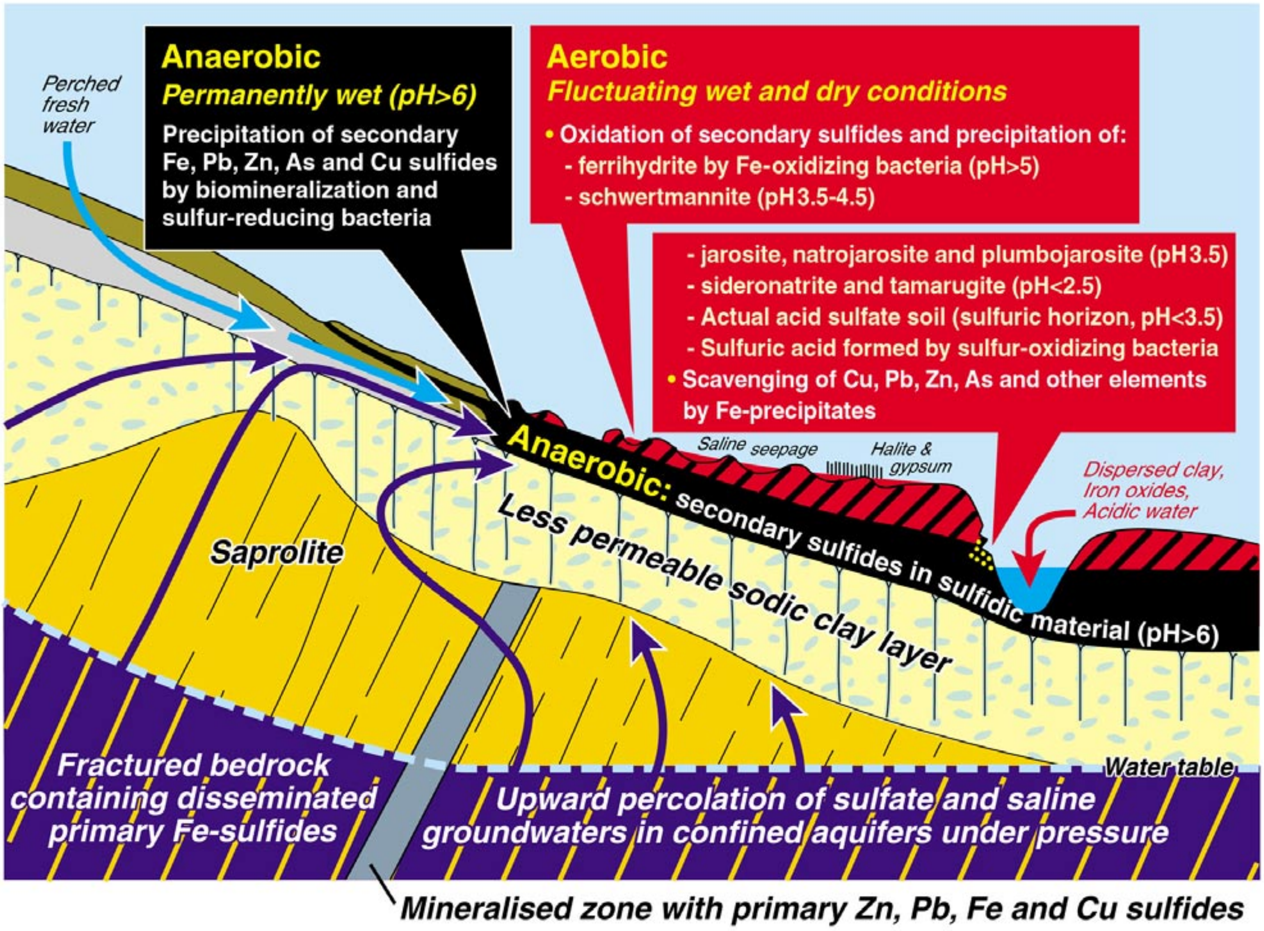

Figure 2. *Explanatory* soil–regolith model showing geochemical dispersion and erosion processes in saline seepages and formation of secondary sulfides in potential acid sulfate soils in a perched wetland and actual acid sulfate soils along eroded drainage lines. (Modified from Fitzpatrick *et al.,* 1996)

between soil profile features down landscape slopes, we used the systematic structural approach (Fritsch and Fitzpatrick, 1994) to identify and describe, by depth interval, all similar soil features (i.e. soil components with similar consistency, colour, textural and structural patterns, and physico-chemical and mineralogical properties). Similar soil features were grouped into fewer soil layers using nested or concordant relationships to group soil features, and discordant relationships to separate them and draw boundaries around similar features to link them down the toposequence, and map them at toposequence scale in cross section (Figure 1).

Each soil layer displayed in the cross section or toposequence was linked to soil and hydrological processes (e.g. water flow paths, salinity and sodicity). In Figure 1, we used mostly soil colour (together with other morphological, chemical and mineralogical indicators) and hydrology measurements in the toposequence (piezometers and dipwells; Fitzpatrick *et al*., 1996; Cox *et al*., 1996) to construct the 2D linkages that describe water flow paths and development of salinity (descriptive soil-regolith models). Some visual indicators are obvious (e.g. occurrences of thick black accumulations of organic matter on soil surfaces) but some are more subtle (e.g. subsoil mottling patterns). Subsoil waterlogging can occur without any evidence on the surface. In Figure 1 cross hatching and shading represents soil sodicity and salinity with the dark arrows indicating salt groundwater flow and light arrows freshwater flow.

The *descriptive* process model characterizes catchment-scale variability of relict (past geomorphological processes in development of deep weathering and erosion) and current (saline, sodic and acid sulfate soils) soil forming processes in order to help develop practical solutions for ameliorating soils at farm scale and for possible use in mineral exploration.

Explanatory soil-regolith models

The *descriptive* soil-regolith toposequence model (Figure 1) was used to construct the *explanatory* soil-landscape process model, which explains the contemporary geochemical dispersion and erosion mechanisms present in the lower parts of the toposequence (Figure 2). The mechanistic *explanatory* soil-landscape 3D model explains the formation and degradation of acid sulfate soils (ASS) in a single diagram. The model illustrates the pedological, geological, biogeochemical, mineralogical and hydrological processes involved in catchments east of Mount Torrens where the co-dominant anions in saline groundwaters and soils are sulfate and chloride. The combination of saline groundwaters enriched in sulfate (with other elements sourced from mineralised zones) seeping up through soils, anaerobic conditions and organic carbon in saturated soils yield pyrite-enriched sulfidic material containing

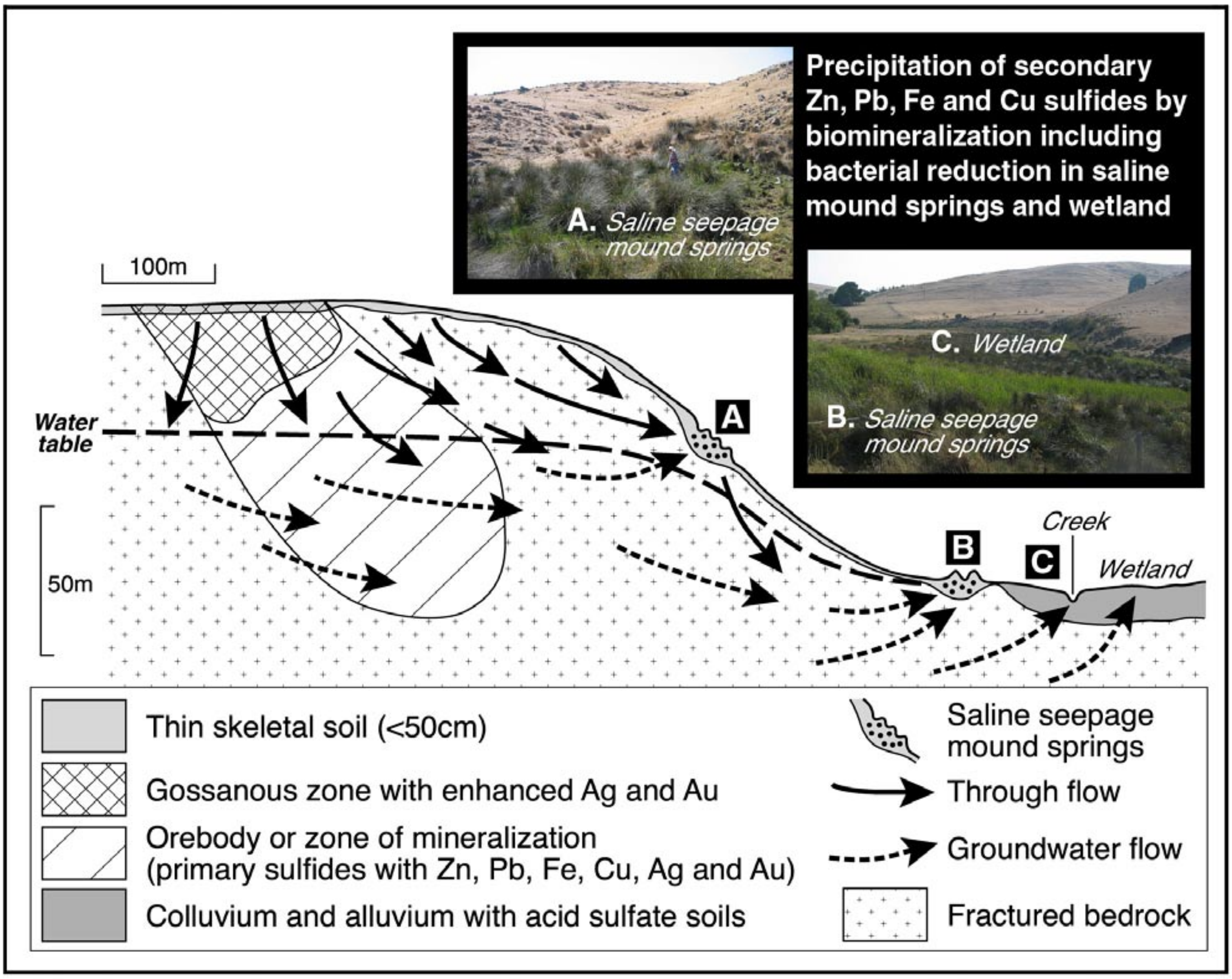

Figure 3. *Explanatory* soil–regolith model showing geochemical dispersion from mineralized zones into acid sulfate soil materials in seeps, springs and wetlands, eastern Mount Lofty Ranges zone. (from Skwarnecki and Fitzpatrick, 2003)

pyrite framboids through anaerobic bacterial reduction of sulfate. When these sulfidic materials are eroded and exposed to air, pyrite is oxidised producing sulfuric acid, which dissolves soil minerals and leads to precipitation of mineral combinations:

- sideronatrite, tamarugite, copiapite, halite and gypsum in sandy sulfuric horizons with pH <2.5, and
- natrojarosite, jarosite and plumbojarosite in clay-rich sulfuric horizons with pH 3.5-4,
- schwertmannite (orange; pH 4); ferrihydrite (reddish-brown; pH >6), akaganéite (reddish-orange) and colloidal (nanoparticulate) poorly crystalline/pseudoboehmite-like (white) precipitates.

Formation of these complex salts of sulfates of Fe, Al, Na, Pb, Ca, As, Zn, jarosites, oxyhydroxysulfates and oxyhydroxides of Fe are indicative of rapidly changing local environments and variations in redox, pH and rates of availability of Fe, S and other elements. Regional sampling of ASS has shown that a range of materials associated with ASS (e.g. sulfidic materials, sulfuric horizons, salt efflorescences, and Fe- and Al-rich precipitates) are anomalous in elements such as As, Bi, Cd, Cu, Pb, Tl and Zn where they are spatially related to the incidence of mineralization, thus constituting a new sampling medium for mineral exploration (Figure 3). From an exploration viewpoint, the evolution of ASS conditions carries indications of the presence of blind or concealed ore deposits (Figure 3).

Predictive soil-regolith models: landscape evolutionary processes

Stage 1*:* As indicated in Figures 2 and 3, saline groundwater enriched in sulfate (SO_4^{2-}) can seep up through the soil, along with other ions in solution such as Na^+, Ca^{2+}, Mg^{2+}, AsO_4^{2-}, I^- and Cl^-, and concentrate by evaporation to form various mineral precipitates within and on top of the soil (Figure 4a). The combination of rising sulfate-rich groundwater, anaerobic conditions associated with saturated soils, agricultural activity and fractured rocks relatively enriched in Fe, S, Pb, Zn, etc. can lead to the formation of potential acid sulfate soil (PASS) conditions and precipitation of anomalous concentrations of Pb and Zn. If the soil is wet and contains sufficient organic carbon, anaerobic bacteria use the oxygen associated with the sulfate (SO_4^{2-}) ions during the assimilation of carbon from organic matter. This process produces pyrite (FeS_2) and forms "sulfidic materials" (Figure 4a). The pyrite-enriched soils are termed PASS because they have all the ingredients necessary to form actual acid sulfate soils (AASS).

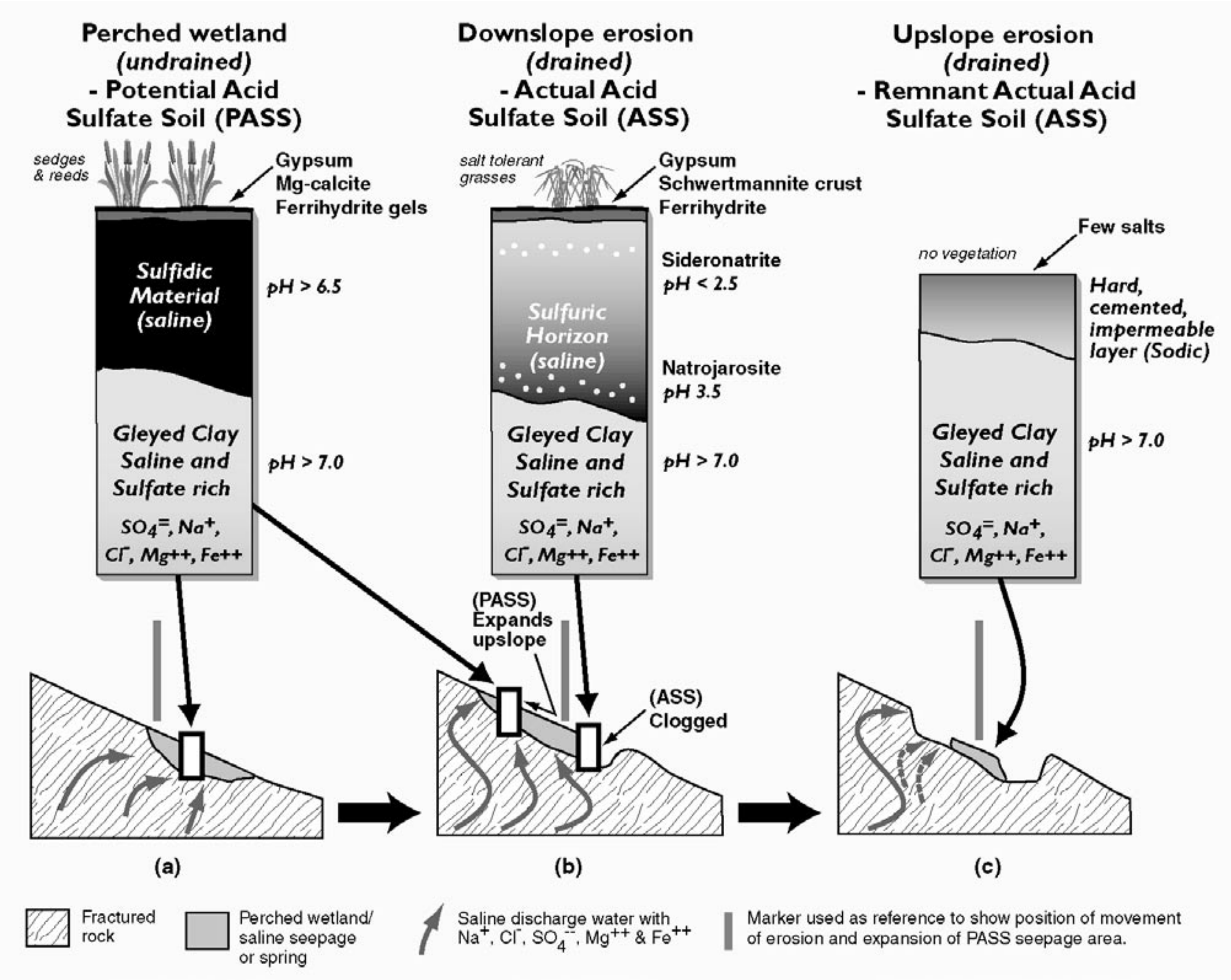

Figure 4. *Predictive* soil-regolith model showing the hydrogeochemical processes, which transform potential acid sulfate soils (PASS) in a perched wetland to highly saline actual acid sulfate soils (ASS). (Modified from Fitzpatrick *et al*., 2000)

Stage 2: Actual acid sulfate soils result when pugging from animals, drainage works or other disruptions expose the pyrite in previously saturated soils to oxygen in the air. When this happens, pyrite is oxidised to sulfuric acid and various iron sulfate-rich minerals, and AASS forms (Figure 4b). When sulfuric acid forms, the soil pH can drop from neutral (pH 7) to below 4; locally pH may attain values as low as 2.5 to form a "sulfuric horizon" (Figure 4b). The sulfuric acid dissolves the clay particles in soil, causing basic cations and associated anions (e.g., Na^+, Mg^{2+}, Ca^{2+}, Ba^{2+}, Cl^-, SO_4^{2-}, SiO_4^{4-}), trace elements, and metal ions such as Fe^{3+} and Al^{3+} to be released onto the soil surface and into stream waters. As the regolith structure degrades due to the accompanying sodicity, soils become clogged with dispersed clay and iron precipitates and they lose their permeability and groundcover. This prevents the groundwater below from discharging and forces it to move sideways or upslope (Figure 4b). Soil around the clogged area eventually erodes, sending acid, metal ions and salts into waterways and dams, and a new area of PASS develops upslope or adjacent to the original AASS zone. If cattle or other activities continue to disturb the soil around the newly created PASS, the area affected continues to expand upslope (Figure 4b).

Stage 3: If these processes express on the surface of the soil, bare eroded saline scalds surrounding a core of slowly permeable, highly saline, eroded AASS result (Figure 4c). These saline landscapes are characterised by slimy red or white ooze and scalds with impermeable iron-rich crusts. As shown in Figs. 4a and 4b, when the potential acid sulfate soils undergo changes, different salt and iron minerals form because of differences in pH and salt concentrations. In the final stage of formation, a hard soil layer remains, with only few salts (Figure 4c). The acidification process accelerates the decomposition and formation of minerals in the soils and underlying rocks and can cause an increase in salinity and carbonate formation.

CONCLUSIONS

This paper summarises the concepts of using the "toposequence approach" as a vehicle for constructing and presenting results of spatially-based conceptual process models. These models can be constructed at three levels of complexity. In the simple *descriptive* model only the most important soil-regolith and hydrological features are displayed. In the more complex *explanatory* model the relationships and behaviour between soil-regolith, geochemical and hydrological processes are displayed that take into account changes in land management practices. In the most complex four-dimensional or *predictive* model predicted biogeochemical and hydrological changes are indicated when ASS are drained or disturbed (e.g. eroded). By combining these soil-regolith models with digital terrain analysis, geophysical remote sensing, and direct field measurement, regional maps of waterlogging, acidity, salinity and catchment health have been developed (Fitzpatrick *et al*., 1999).

Finally, these soil-regolith models have been used to:

(i) produce practical soil-landscape and vegetation field keys for Landcare groups; the keys provide details of land-use options to prevent the irreversible spread of acidic, saline and sodic conditions (Fitzpatrick *et al*., 2003); (ii) indicate how saline scalds with associated ASS containing iron precipitates, sulfidic materials and mottled sulfuric horizons provide a geochemical sampling medium for the detection of mineral or ore deposits.

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