6 Soil patterns

6.1 Potential acid sulphate environments

Soil variation is always a problem for land-use planning and management. Acid sulphate soils are notoriously localised. Even within a single area of acid sulphate soil, the severity of acidity, or potential acidity, can vary significantly from point to point.

Relationships between soil characteristics and other facets of the landscape operate from the largest scale to the smallest. In this section, some generalisations are developed to help in identifying those parts of the landscape where acid sulphate soils can be expected. Because the detailed soil pattern of each area will be unique, this section can only give samples of the local links between acid sulphate soils and landforms, climate, ecology, and management.

The combination of factors required for the accumulation of sulphides occurs in three distinct environments (Pons and van Breemen 1982):

- Marshy inland valleys and basins flushed by sulphate-rich waters draining from older sulphidic sediments. These are not extensive, but there are several local examples including sulphidic peats in Uganda (Chenery 1954) and Leningrad (Krym 1982), and sulphidic sands in The Netherlands (Poelman 1973);

- Bottoms of saline and brackish seas and lakes. Organic-rich sediments deposited in saline or brackish water may accumulate significant concentrations of reduced sulphur, both as Fe (II) monosulphide and pyrite. The Littorina bottom sediments of the Baltic contain up to 2 per cent reduced sulphur. Isostatic recovery of the land, following glaciation, has brought some of these sediments above sea level, leading to the development of acid sulphate soils in coastal areas of Sweden and Finland (Wicklander et al. 1950; Kivinen 1950);

- Saline and brackish water tidal swamp and marsh, which includes tidal flats, salt marsh, and mangrove swamp. This is the principal potential acid sulphate environment.

6.2 Soil patterns in the tidal zone

6.2.1 Landforms

Sulphidic soils develop most extensively where clayey sediment accretes slowly in saline and brackish water and, simultaneously, copious organic matter is supplied by swamp vegetation. The longer the duration of saline or brackish swamp conditions, and the greater the input of organic matter, the greater the accumulation of pyrite. Shelter from strong currents and wave action is conducive to the accumulation of mud and to its colonisation by vegetation. Favourable conditions occur in deltas, sheltered estuaries, coastlines protected by offshore islands and bars, and even open shores where wave energy is dissipated across a broad, gently-sloping coastal shelf.
The lowest parts of the inter-tidal zone are flooded most of the time, so these soils are permanently reduced. In the higher parts of the tidal landscape, the upper horizons of the soil are predominantly oxidised. The tidal range, and the effectiveness of drainage, determine the thickness of oxidised, non-sulphidic material that will accrete above the permanently reduced, sulphidic substratum. The greater the tidal range, the broader the tidal zone, and the thicker the ultimate development of the oxidised surface horizon.

Several hundreds of years seem to be needed for pyrite to accumulate in excess of the neutralising capacity of the soil. Therefore, potentially acid soils are likely to develop only in relatively stable systems, where sediment is accumulating slowly. Rapidly-accreting systems, or systems subject to alternate erosion and deposition, will not accumulate high concentrations of pyrite.

Sandy sediments generally occur in less stable tidal environments. They rarely contain large amounts of pyrite, but only a small proportion of pyrite will produce severe acidity in a quartz sand, because there is little neutralising capacity.

Striking differences in chemistry between soils of a relatively straight mudflat coast and an estuarine area dissected by tidal creeks are reported by Diemont and van Wijngaarden (1974), working in West Malaysia. In the reduced horizon of the straight coast, field pH values varied between 8 and 8.4, reflecting high concentrations of HCO$_3^-$ (10-26 mol m$^-3$) in the interstitial water, and pyrite S contents were less than 0.5 per cent. In contrast, in the estuarine swamps, pH values of the reduced horizon were between 6.2 and 6.8, interstitial water was lower in dissolved HCO$_3^-$ (2-10 mol m$^-3$), organic matter contents were higher, and pyrite S contents were between 1 and 2.5 per cent. Concentrations of dissolved sulphide were similar in the two environments, except during spring tides when they were reduced to undetectable levels in the estuarine soils.

Pons and van Breemen (1982) attribute the apparent removal of dissolved sulphide and bicarbonate, and the increased accumulation of pyrite, to more effective tidal flushing. Flushing will be enhanced by the network of tidal creeks, and by greater soil permeability associated with a higher content of organic matter. Tidal flushing should promote pyrite formation, by removing HCO$_3^-$, supplying the limited amount of dissolved oxygen necessary to form pyrite from reduced sulphide, and by accelerating rate-limiting processes that are otherwise dependent on diffusion.

The different pyrite contents found along the Malaysian coast may equally be explained by the differing stability of the coastline. The straight coast is subject to strong tidal currents, and appears to be continually eroding and rebuilding.

The rate of sedimentation, and the age and stability of the landscape determine the time available for the accumulation of pyrite. Where the rate of sedimentation is slow, and conditions for pyrite accumulation have persisted over a long period, very high reduced sulphur contents may occur (up to 25 kg S m$^-3$ under *Avicennia* mangrove in northern New Zealand; up to 50 kg S m$^-3$ under *Rhizophora* mangrove in The Gambia). Rapid sedimentation and a rapidly-aggrading coastline result in a much shorter period of favourable conditions for pyrite accumulation and, consequently, in sediments of low sulphur content.
6.2.2 Vegetation

Vegetation fuels the process of pyrite formation by supplying readily-decomposed organic matter, mainly through the decomposition of the root systems since most surface debris is carried away by the tide. Both climate and salinity effect remarkable contrasts in the ecology of the tidal zone. Temperate salt marsh is mainly herbaceous; absent or much reduced in winter; and confined to the upper tidal zone by a combination of low temperatures, wave action, flooding, and the turbidity of the water, which reduces the amount of sunlight received. In brackish water, salt marsh gives way to reed swamp, where the dense, robust roots and rhizomes contribute to a high organic content in the reduced mud. At the freshwater margin, if the supply of mineral alluvium is low, peat accumulates (Plate 6.1).

The characteristic vegetation of inter-tidal swamps in the tropics is mangrove forest. Mangroves range from shrubs less than 50 cm high, at the cool margins of their range, to trees greater than 30 m high (see Plate 1.7). In favourable conditions, their productivity is comparable to that of rain forest. Mangroves extend lower into the tidal zone than salt marsh, sometimes below mean sea level in brackish waters. Where rainfall is high, they are succeeded in the upper part of the tidal zone by swamp forest or reeds. As in temperate regions, peat may accumulate at the brackish or freshwater tidal margin if there is little mineral sedimentation. A long dry season severely restricts
inter-tidal vegetation, especially in the tropics, where extreme salinity develops on the higher tidal flats that remain exposed for long periods during neap tides (Plate 6.2).

The organic matter contents of marine sediments are generally low in the tropics (0.5 to 3 per cent), but may be higher in temperate regions (up to 10 per cent). On bare tidal flats, pyrite formation may be limited by low organic matter content. But once marsh or mangrove vegetation is established, the dense mass of fibrous roots provides a copious supply of easily-decomposed organic matter.

Individual species or plant associations exert no specific effect on pyrite accumulation. However, different species do occupy particular niches related to climate, exposure, depth of flooding, drainage, and salinity (Chapman 1976). In temperate regions, marsh vegetation is much reduced in winter and is usually restricted to the upper part of the inter-tidal zone, above mean sea level. The most diverse and productive tidal swamp vegetation occurs in the humid tropics with a mean annual rainfall greater than 2000 mm and no dry season. Here mangroves may colonise the entire inter-tidal zone, and are succeeded inland by freshwater swamp forest. In dryer regions, the range and diversity of mangrove vegetation is reduced by very high salinity in the upper part of the tidal zone, which is flooded only during spring tides. Groundwater salinity in excess of about 10 per cent excludes mangroves. During the dry season, salinities in excess of 25 per cent occur on the highest part of the inter-tidal zone, where mangroves are succeeded by salt marsh and barren salt flats (Plate 6.2).
In a particular locality, the different swamp and marsh species indicate current differences in microtopography, hydrology, or salinity, which can be significant in land reclamation or management, but are not necessarily related to the pyrite content of the underlying soil, which may have developed under somewhat different conditions. In general, the largest areas of high pyrite content (more than 30 kg S m\(^{-3}\)) are formed under big mangroves and *Nypa*, or other brackish water plant communities, succeeding mangrove. Very high pyrite contents also occur in peat soils that have been subject to a long period of brackish water flooding.

6.2.3 Changing sedimentary environments

The relationship between post-glacial sea levels, the rate of sedimentation, and the regional distribution of acid sulphate soils was introduced in Section 1.3. During the last glacial period, the world sea level stood some 80 m below its present level. From about 18 or 19 000 years ago, the sea level rose rapidly, reaching about 5 m below the present level about 7 000 years ago. During the last 7 000 years, the sea level has risen more slowly with cyclical fluctuations of about 1 m amplitude (Morner 1971; Tooley 1976; Blackwelder et al. 1979). Against this background of a eustatic rise in sea level, many areas have been subject to isostatic or tectonic uplift or subsidence, resulting in a variety of regional trends of relative sea level (see Figure 1.1).

In each sedimentary basin, the combined effects of sea level changes and rates of sedimentation have affected the sedimentary environment, and also the time available for pyrite accumulation. Where sedimentation keeps pace with a rising sea level, a broad, stationary zone of tidal swamp or marsh vegetation may develop; tidal flushing remains active, and thick layers of sulphidic material can accumulate. Even under a stable sea level, strongly sulphidic sediments may accumulate if the rate of sedimentation is slow — so that favourable conditions for pyrite accumulation persist over a long period. Under the influence of a falling sea level, or very rapid sedimentation, accumulation of pyrite may be limited by the shorter period of suitable environment.

Regional and local changes in sea level, sedimentation, hydrology, or water chemistry can result in the burial of sulphidic material by non-sulphidic alluvium or peat, so that potential acid sulphate soils may be found in freshwater or dryland environments, or pyrite may accumulate in peat or alluvium originally laid down in fresh water.

6.3 Regional soil patterns

Contrasting regional patterns in South East Asia, resulting from different rates of sedimentation and rising sea level, were described briefly in Section 1.3.3. Figure 6.1 shows the general soil pattern of the Chao Phraya Delta in Thailand. Here the sulphidic older marine clays, laid down in a broad, stationary tidal zone under a rapidly-rising sea level, are succeeded, about 40 km from the present coastline, by younger marine clays, laid down along a rapidly-advancing coastline. The younger clays are mostly not potentially acid.

Inland, some of the older sulphidic clays are covered by a blanket of non-sulphidic
river alluvium. The old marine clays that remain exposed have become acid sulphate soils, as a result of progressively falling watertables.

Figures 6.2 and 6.3 illustrate a very different soil pattern, in the middle reach of The Gambia estuary. Here the most recent sediments, accumulating in the broad tidal swamp on either side of the main river channel, are very sulphidic. The present tidal zone is flanked by low estuarine terraces, which suggests a recent slight fall in sea level. The terraces, which are still flooded at times during the wet season, carry ripe clays with only local occurrences of acid sulphate subsoils. Non-sulphidic half ripe

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clays in the upper part of the present tidal zone appear to be planed-off remnants of these terraces, which must have been laid down under some combination of lower salinity and/or more rapid sedimentation than the present-day swamp sediments.

Certainly the most intensively-studied area of acid sulphate soils is the North Sea basin, especially in The Netherlands, where their fundamental chemistry was first elucidated by van Kercshoff (1856) and van Bemmelen (1863; 1886). Here the sea level has continued to rise, intermittently, over the last 7000 years by a combination of eustatic rise of sea level and isostatic subsidence of the land (see Figure 1.1).

In both The Netherlands and East Anglia, the alternate formation and partial destruction of coastal sand dunes and spits has resulted in a complex pattern of sedimentation. Periods of subdued marine activity, during which extensive freshwater peat deposits accumulated, have alternated with marine incursions, when estuarine clays have been deposited and secondary pyrite accumulation has taken place in peats flooded by brackish water.

The general soil pattern of the Yare Flood Plain in East Anglia is shown by Figure 6.4. The most recent estuarine clay has been deposited broadly over the seaward part of the basin, and tongues inland along the tidal rivers. In the lower reaches, all the clay is calcareous. In the middle reaches, the clay is calcareous along the river and creek levees, but non-calcareous in the intervening basins, giving a complex pattern of potentially acid and non-acid soils (see Section 6.5.2).
Figure 6.3 Detailed soil pattern at Sankwia Tenda, The Gambia. Base map by permission of the Superintend-ent of Surveys, The Gambia (For legend, see Figure 6.2)

Legend to Figures 6.2 and 6.3

Soil pattern in the mid-Gambia

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Soil</th>
<th>Vegetation and land use</th>
<th>Landforms and hydrology</th>
</tr>
</thead>
<tbody>
<tr>
<td>S</td>
<td>Sandy and coarse loamy</td>
<td>Arable farming or woodland savanna</td>
<td>Colluvial valley slopes</td>
</tr>
<tr>
<td></td>
<td>sᵢC + sᵣC + sᵢC, Association of ripe clay, ripe saline clay, and riped clay with saline subsoil; rarely severely acid</td>
<td><em>Mitragyna-Acacia</em> savanna with tall grass-herb vegetation in depressions. Formerly widespread rice cultivation in depressions.</td>
<td>Freely drained</td>
</tr>
<tr>
<td>s₁Cw₂</td>
<td>Half ripe saline clay</td>
<td><em>Sesuvium</em> and salt-tolerant grasses and rushes. Some barren salt-flats in lower reaches; <em>Phragmites-Echinocloa</em> reed swamp in upper reaches where salinity is less. Extensive clearance for tidal rice.</td>
<td>Estuarine terrace. Depressions flooded in the wet season</td>
</tr>
</tbody>
</table>

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The soil patterns of the tidal zone evolve in concert with the sedimentary landscape. Regional soil patterns are related to changes in sea level and gross sedimentation. The characteristics of detailed patterns that are relevant to project feasibility and management commonly include:

- An intricate distribution pattern of acid and non-acid soils;
- Within any large area of acid sulphate or potential acid sulphate soils, a tenfold variation in pyrite content;
- Lower pyrite content in the topsoil than in the subsoil; variation in thickness of non-acid topsoil;
- Usually pyrite contents are greatest, and acid or potentially acid layers closest to the surface, in the lowest parts of the landscape (for example on the Bangkok Plain, van Breemen 1976);
- Depositional landforms, such as sand bars and levees, and erosional features, such as estuarine terraces and relict islands or shields of sediment deposited under a relatively higher sea level, are conspicuous features of the soil pattern (for example Andriesse and Sim 1968; Dent 1980).

Each sedimentary basin has a unique soil pattern. This is related to its particular environment and sedimentary history. The range of contrasting soil patterns is illustrated here by examples of detailed surveys from New Zealand and The Gambia.

In Northland, New Zealand (see Figure 4.6), relative sea level seems to have been fairly stable over the last 2000 years. Extensive tidal landscapes in wide harbours have developed an intricate pattern of meandering tidal creeks, levees, and backswamps, illustrated by Figure 6.5. A more disciplined pattern, representative of constricted tidal river landscapes, is illustrated by Figure 6.6.

In both landscapes, there is a correspondence between landform and soil morphology (Figures 6.7 and 6.8). Half ripe clays, with Go-Gro-Gr profiles, are developed on raised flats and levees that can drain quickly at low tide. Half ripe or unripe clays, with thick, sulphidic Gr horizons, are developed in the backswamps.

Soil profile morphology is indicative of a range of chemical and physical soil properties. Pyrite content has been discussed already in relation to the characteristic horizons of the tidal soils (see Section 4.2). A comparison between Figures 6.7 and 6.9 illustrate the field relationships of the important geotechnical property, shear strength. In this instance, the shear strength of the saturated tidal soils is determined firstly by soil texture; the characteristics of sandy materials are quite distinct from clays. Within the clay soils, shear strength is most closely related to ripeness.
Figure 6.4 Generalised soil pattern of the Yare Flood Plain, East Anglia, U.K. Shaded circles represent the depth at which acid or potentially acid material occurred in duplicate samples from each 1 km grid intersect (from Dent 1981)

Only a small proportion of the sediment deposited in an estuary is deposited above mean sea level. The soil maps and sections illustrate the way that sand banks, colonised first by shellfish then by mangrove and salt marsh vegetation, often act as nuclei for