Many participants in this symposium are intensively engaged in technical, scientific or managerial aspects of land use or land development in acid sulfate areas. It seems wise, therefore, to start with a discussion of the social and economic reasons for our work and the implications of our possible recommendations for the people and for the physical environment, before we concentrate on detailed scientific, technical and developmental aspects.

Changing an ecosystem needs to be approached with the greatest caution, to prevent social or economic damage to the families directly involved and to others nearby or elsewhere; and to prevent irreversible impoverishment of the natural diversity, which contains known and unknown resources.

After touching on the distribution and extent of the acid sulfate soils, I will discuss separately those in the salt-water and in the fresh-water zones. For the saline acid sulfate soils, the main problem is the question whether or not to protect and preserve them in their natural state. For the fresh-water acid sulfate soil areas, the main social and economic problem is to create an effective kind of development plan, that makes maximum use of the variability in the soils and the capabilities of the settlers, and that is designed for progressive change and improvement to correct for past mistakes.
The world is a well-populated place. People are living in a great variety of places, but not in all places. Where people can move freely, for example within a given country, they tend to distribute in such a way that productivity of labor becomes similar in different places. The great differences in population density from place to place then reflect, at least in part, income opportunities at the level of available technology and resources. Large empty areas may thus be useless at present technology. For each area empty or almost empty of people, there is a reason: for example, no water in the Empty Quarter of Saudi Arabia. Many such reasons can be summarized under a few major terms. Non-use occurs because there is no available technology or because there are better opportunities elsewhere for the people. In the short run, there are other reasons as well: these can be found in history, politics and physical infrastructure. But the longer-term reasons lie in the unavailability of technology appropriate to the land and in the presence of alternative opportunities of economic activity for the people by whom the area could be reached. Attempts at colonization without recognition of these facts have caused great hardship and loss of development capital in several cases.

The world-wide extent of acid sulfate soils is about 13 million hectares: about one percent of the world's cultivated land. When the extent of the acid sulfate soils is compared with the extent of some of the world's other problem soils (Table I), it is clear that peat soils or saline and sodic soils, for example, are far more extensive—and, incidentally, more persistent. Acid sulfate conditions constitute a problem that persists for a limited number of years, and that bedevils a small part of the earth's crust; a small part even of the total area of problem soils that the population of the world is faced with. Several of the other kinds of problem soils, however, mainly lie in areas that have other major problems as well and that are far away from great concentrations of people. The acid sulfate soils tend to occur under favourable
climates for food production (Table 2), often near densely populated coastal areas or river plains (Figure 1), and their development would thus be of immediate interest.

Table 1. World distribution of some problem soils\(^1\) (million ha)

<table>
<thead>
<tr>
<th>Type of soils</th>
<th>Region</th>
<th>Acid sulfate soils</th>
<th>Peat soils</th>
<th>Planosols</th>
<th>Saline and sodic soils</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Asia and Far East</td>
<td>6.7</td>
<td>23.5</td>
<td>2.7</td>
<td>19.5</td>
<td></td>
</tr>
<tr>
<td>Africa</td>
<td>3.7</td>
<td>12.2</td>
<td>15.9</td>
<td>69.5</td>
<td></td>
</tr>
<tr>
<td>Latin America</td>
<td>2.1</td>
<td>7.4</td>
<td>67.2</td>
<td>59.4</td>
<td></td>
</tr>
<tr>
<td>North America</td>
<td>0.1</td>
<td>117.8</td>
<td>12.3</td>
<td>16.0</td>
<td></td>
</tr>
<tr>
<td>Near and Middle East</td>
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<td>0.0</td>
<td>0.0</td>
<td>53.1</td>
<td></td>
</tr>
<tr>
<td>Australia</td>
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<td>49.3</td>
<td>84.7</td>
<td></td>
</tr>
<tr>
<td>Europe</td>
<td>0.0</td>
<td>75.0</td>
<td>4.0</td>
<td>20.7</td>
<td></td>
</tr>
<tr>
<td>World total</td>
<td>12.6</td>
<td>240.0</td>
<td>151.4</td>
<td>322.9</td>
<td></td>
</tr>
</tbody>
</table>

\(^1\) Adapted from Beek et al. (1980), based on data from FAO/Unesco Soil map of the World.

Table 2. World distribution of acid sulfate soils\(^1\) (million ha)

<table>
<thead>
<tr>
<th>Length of growing periods (days)</th>
<th>Region</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt; 90</td>
<td>Asia and Far East</td>
<td>6.7</td>
</tr>
<tr>
<td>90-180</td>
<td>Africa</td>
<td>3.7</td>
</tr>
<tr>
<td>180-300</td>
<td>Latin America</td>
<td>2.1</td>
</tr>
<tr>
<td>&gt; 300</td>
<td>North America</td>
<td>0.1</td>
</tr>
<tr>
<td></td>
<td>Other regions</td>
<td>0.0</td>
</tr>
<tr>
<td></td>
<td>World total</td>
<td>12.6</td>
</tr>
</tbody>
</table>

\(^1\) Adapted from Beek et al. (1980), based on data from FAO/Unesco Soil map of the World. Growing period data according to FAO Agro-ecological Zones Project, Rome.

In comparison with acid sulfate soils the extent of peat soils is larger (Figure 1). Some of the extensive, unused peat areas are enclosed by
Figure 1. Distribution of acid sulfate soils and peat soils in South and Southeast Asia. Simplified from Beek et al. (1980). Data from FAO/Unesco Soil Map of the World.
acid sulfate margins. These, in turn, generally adjoin more intensively used, better land. In this geographic sense, acid sulfate soils are marginal. There are not yet any economically or even technically valid recipes for the reclamation of certain central, large peat areas. Practical possibilities exist for the development of some acid sulfate soils, and not yet for others. In this sense, too, we are working on the margin of the technically and economically possible. This implies the chance of failure, partial or total, in specific land development efforts.

3 Reasons for development

Decisions on whether or not to develop given areas of acid sulfate soils, and on the direction which development should take, regrettably are often not based on their physical and chemical qualities. However, such decisions may be prompted by population pressure - in adjacent areas or further away - or by the need for employment possibilities or commodities which hopefully could be produced by the land.

The large acid sulfate areas along the northeastern coast of South America (Figure 2) generally lie between a strip of better land in the young coastal plain, toward the coast, and higher land further south. In Guyana, they have largely been developed into reservoirs: low-level seasonal lakes supplying irrigation water for sugar-cane and rice on the better land toward the coast. This extensive use, without any need for soil reclamation, was possible because there is a relative abundance of land compared with the small population. A similar situation occurs in some other parts of South America. The West African acid sulfate areas (Figure 2) are under a somewhat greater pressure for development. The ratio of population to available, usable land is much higher in South and Southeast Asia. Thus, large areas of acid sulfate soils have been reclaimed by the people, partly without the benefit of scientific advice, particularly in the Central Plain of Thailand. In Indonesia and Vietnam, too, there are heavy pressures on land and urgent needs for land development. These pressures and needs constitute an important reason why the Second International Symposium on Acid Sulfate Soils was convened in 1981.
Figure 2. Distribution of acid sulfate soils in Africa and the Americas. Simplified from Beek et al. (1980). Data from FAO/Unesco Soil Map of the World.
Possible uses and their socio-economic implications

There is a variety of possible uses of acid sulfate soils:
- for all types of acid sulfate soils, and including some adjacent peat areas: nature reserve, or low-level irrigation water storage and flood protection;
- for inland, fresh-water areas: wetland rice, rubber, oil palm or pineapple;
- for areas closer to the sea, mainly with mangrove and some with a palm vegetation: biomass production for energy, or wood and bark production;
- for the saline areas adjacent to the coast: brackish-water fishponds, or salt pans in climates with a dependable dry season;
- for the salt-water edges: nurseries for fish, shellfish and other marine life. This brings us back to the first use mentioned: protection of the natural ecosystem.

Two main kinds of acid sulfate soil areas can thus be distinguished, each having distinct development alternatives with very different socio-economic implications: the fresh-water and the salt-water zones.

4.1 The salt-water zone

The main socio-economic problems in the salt-water zone are those of choice. There are various development possibilities, each feasible when viewed by itself within a limited area. Each has a different impact on the local ecology and on the adjacent sea area, particularly in its fisheries aspect. These consequences need to be clearly considered and weighed before development decisions are taken.

The natural mangrove ecosystem, part of which occurs on potential acid sulfate soils, is ecologically and economically very important.

In The Philippines (Gonzales 1978), fish of more than 40 zoological families have been recorded from the mangrove area, as well as many species of prawn, crab and oyster. Milkfish and prawn fry are collected for rearing in ponds. The mangrove area is both a nursery and the start of a food chain for much marine life; the disappearance of a mangrove...
fringe from a coast-line could have serious or disastrous consequences for fishing activities off-shore. The mangrove and nipa palm forest by itself also yields several products, for example in the Philippines: viscose rayon for textile fibers, tannin for leather manufacture, firewood and charcoal for fuel, thatch and shingles for roofing and walls, palm sap for vinegar and wine, timber for construction and furniture. The main alternatives to keeping the area as a mangrove ecosystem are salt pans, brackish-water fishponds, and wetland rice fields. All three uses require land reclamation measures, involving changes made by engineering, water management and chemical inputs. All three produce large amounts of acids during the reclamation period, part of which will reach the sea. Where extensive areas are to be reclaimed, the impact of this on adjacent coastal fringes will need to be estimated in order to determine a safe rate of reclamation.

At this point I would like to quote some words of Jose Janolo, secretary of the Department of Natural Resources in Manila, on the occasion of the international workshop on mangrove and estuarine area development, in 1977.

'We must .. respect our environment and treat it with consideration and care .. There is a very real danger that, in our eagerness to produce and develop .., we may be overlooking the limits of the ecosystem. Have we paused to consider that no technology can ever recreate an extinct species or reconstitute fundamental chemical-biological cycles? .. Our approach to the development of mangrove and estuarine areas .. must be based on an awe and respect for the complex multifaceted and interconnected, but finite environment of which we are all inhabitants.' (Janolo 1978)

'Salt pans, rice fields or fishponds. If areas with saline acid sulfate soils are to be reclaimed, there are generally no great infrastructural problems. The main requirement is roads: for inputs and produce, as well as to get the people to services, and services to the people. In Bangladesh, for example, there is a small potential acid sulfate area called the Chakaria Sunderbans. This was covered by mangrove and was saline, tidal and not yet acid. It was developed (reclaimed) by local
people for rainfed wetland rice and rapidly became extremely acid as soon as the tidewater was excluded by dikes. The rice gave very low yields and failed in some fields. Then the people, who mainly lived on the higher land nearby, changed their poor and failing rice fields into salt pans. In local spots, extremely acid water welled up through the soil into the salt pans. Such spots were isolated and made harmless by separate small dikes. Even though the salt pans are only productive for about 4 months per year, in the dry season, annual incomes per ha were higher than even from good rainfed rice land.

In the Philippines, where much of the acid sulfate area is of the saline type, many of the individual patches are also small, and occur within a few km from schools and markets. Even in this relatively favorable situation, where there is a good infrastructure and where effective procedures for land reclamation and management are known at least to some technical experts, as well as to the land users in some parts of the country, there may still be major socio-economic problems. On coastal acid sulfate soils in Sorsogon, for example, on the southern tip of Luzon Island, wetland paddy yields of about 250 kg/ha are reported. Some farmers keep operating at this level because they have no other opportunities and because they have relatively large holdings.

Rice farming on such land generally appears to be losing ground in two ways: by farmers abandoning the land and migrating to towns, and by conversion of the land into brackish-water fishponds. The latter is a major engineering operating that requires considerable financial resources, but can result in an economically viable production system.

Although the conversion to fishponds appears to be economically sound, there is a major social danger. The conversion requires capital and unrestricted access to saline tidewater for every pond operator. Both these aspects carry the seeds for increasing social disparity, the rich getting richer and the poor being pushed out from the land. Such developments could be prevented by public canals open to tidewater, and by access to sources of medium-term credit for the poor farmer with little land.
4.2 The fresh-water zone

The potential acid sulfate soils in a fresh-water environment seem to constitute a less varied and less valuable natural ecosystem than the saline ones. The reclamation and use of fresh-water acid sulfate soils generally raise greater technical and infrastructural problems, as well as economic and social ones, than the acid sulfate soils in the saline coastal fringe. The individual areas are generally more extensive. In many, there is little or no tidal range to assist drainage and irrigation. There is no salt water to help speed up the removal of acids. Acid drainage water will need to be removed without damage to land downstream. Provision of access and services is generally more difficult and expensive. Known, technically sound procedures of reclamation for wetland or selected dryland crops are not necessarily economic even at low labor costs.

Because of the extent of the 'empty' areas, their large-scale colonization requires infrastructure locally, in the new land, since established services on the old land may be too far away. Similarly, a new network of social connections, support and organization needs to grow or to be developed in large, contiguous colonization areas.

Acid sulfate soil areas are not necessarily homogeneous throughout: they may vary in severity over short distances, and especially along rivers there generally are strips of land without acid sulfate problems. For the most severe acid sulfate soils there do not yet seem to be effective and economically feasible reclamation methods. For the less severe kinds there are practical development possibilities. Some of these have been found by scientists, but several have been developed by the people living and farming on the edges of the acid sulfate areas or within them.

Farmers in the Mekong Delta, for example, developed a system of shallow, broad drains at close intervals throughout the extent of the rainfed wetland rice fields on acid sulfate land. The first rains of the wet season wash much of the acid out of the surface soil into the drains. There it is immobilized by reduction or it is removed toward the rivers. By the time sufficient rain has fallen to raise the water level to the land surface, most of the acid has been removed from the upper few cm and the rest has been immobilized by reduction locally. Reported paddy
yields under this system are about 2.5 t/ha, compared with a previous average of about 0.5 t/ha.

5 Failures and successes
5.1 Holland in the last three centuries

In the year 1641, a famous Dutch engineer who became known by the name of Leeghwater (Empty-the-water) devised a plan to drain the largest lake in the Netherlands, 4 meters deep and with a clayey bottom. The task was too great for the windmills existing at that time; two centuries later, in 1848, the Dutch state undertook the work with English steam engines. The drainage was a success – the colonization by farmers was a disaster. Acid sulfate soils covered part of the empoldered lake bottom, and two generations of farmers abandoned the land or went destitute trying to wrest a living from their farms. Seen in a perspective of centuries, acid sulfate soils are a temporary phenomenon. In the natural, permanently wet state, the acid in them is hidden in the form of pyrite and the soils can exist essentially unchanged for long periods. After drainage, extreme acidity develops,excluding most of the relatively easy development possibilities of swamp areas with better soils. After several decades of leaching by rainfall or irrigation, if drainage has been maintained, much of the acid has been removed and the soil may have become moderately suited for some uses. After a century, it may even become good agricultural land: the former Dutch lake now is a prosperous area.

5.2 Settlement scheme

A more recent example is a polder developed shortly before 1960 in Guyana, South America, to the west of Georgetown. There, the colonists were rice farmers. After a few years, 90 percent of them had abandoned the land again: an enormous economic loss and a social disaster. At present, there are colonization schemes planned and under execution in acid sulfate areas. People in the planning-and-development investment sector now think of 'socio-economic' aspects of such schemes. We
technicians, and planners as well, firmly believe that we will never make mistakes as bad as our predecessors made. But can we bear the responsibility for the chance that they will become similar failures, with consequent social disruption? We should realize that the term 'social' or, worse, 'socio' is not a mere appendix to embellish 'economic'. Its basic meaning is linked with 'together' - not with provision of things from above. Let us examine a kind of organization and planning that may increase the chances of social and economic success.

5.3 Spontaneous colonization

There is a gradual, organic process of land development and homesteading going on in some areas with spontaneous colonization, for example, on Palawan Island in the Philippines (James 1978) and in the tidal swamp land of Kalimantan and Sumatera in Indonesia (Collier 1979). In the latter, a few Buginese settlers first dig a short section of main canal from a river, then a smaller cross canal serving land on both sides. As clearing proceeds and an economic base becomes established, family members or friends arrive, first stay with the original settlers and work on their land, then start clearing a section of land for themselves under the leadership of the original settler on the canal. Progressively, the main canal is extended and further cross canals are dug. Where problems arise, certain sections can be left unused: meanwhile, they are being drained by the presence of the canals and may in due course become usable. Such local, temporary failures can be absorbed by the social structure that has developed, and do not destroy the local economy. The new people arriving learn the methods of development and farming appropriate to the area from the earlier arrivals. They tend to stay even if there are partial failures because of their investment in money, working time and effort. As the cultivated area expands, there is time for concurrent development and improvement of local services and for the emergence of an effective social organization.
5.4 A Comparison

When we observe developments in large, one-shot reclamation and settlement projects by governments, a very different picture emerges. Total costs per hectare may be similar (or higher), but the rate of abandonment or other failures is higher than in the spontaneous settlements. Settlers in government projects tend to come from very different places. Those who become neighbors generally do not know each other, and all are new in the area, with no local support or experience to draw on. There is no social network or structure; the services provided by government are supposed to keep the people together and active until an economic basis and a social structure have evolved that will stabilize the new community.

This comparison does not intend to show that spontaneous migration would constitute an adequate answer to the economic and social ills of government-organized settlement. Often, the pioneer settlers are social leaders, independent souls, and belong to the relatively rich. The people resettled in government projects mainly belong to the poor, and had very few resources to draw on in their original location. Nevertheless, they should never be uprooted and transplanted, with government credit and fertilizer, into a social vacuum.

6 Development centered on farmers' capabilities

We need to use and adapt the strengths and valuable aspects out of the spontaneous migration experience to improve the government-stimulated programs. The people can protect themselves by their own active participation against some of the mistakes that politicians, planners and we scientists may make.

There is some recent experience with broad overall plans that have wide meshes, gaps, to be filled in later. Only a few of these meshes are filled in detail at the start. This kind of plan-structure allowing small-scale mistakes and progressive improvements would need physical space to correct such mistakes: a frontier situation would be desirable.

In a frontier situation, when there is enough land ready for development
between presently used and undeveloped areas, small-scale experiments can be made on different kinds of acid sulfate soils at limited cost, both by the farmers and by scientists on farmers' fields. Successes can be immediately applied on similar land, while failures hold up the advance of part of the reclamation frontier: a gradual and organic process, rather like the tide coming in on a flat beach, successive waves claiming more of the area: then here, then there, and with occasional long delays in certain places.

The settlers for a given project should not be appointed all at once. The first wave of settlers will need to be chosen very carefully. These pioneers should be selected primarily on their capabilities of management, innovation and farming. If possible, they should be chosen with the participation of the villages in which they live. The settlers for a given stretch of frontier should preferably come from villages near to each other and they should be prepared to work together. As more settlers gradually arrive, they find older as well as more recently established settlers in the new area, with a range of practical experience on how to reclaim and use the land.

The willingness to settle in the new land at first may have to be stimulated by considerable direct assistance, but will tend to increase with time, as information about the progress of reclamation filters back from the settlers to the villages of origin. This will increase the chances of success and decrease the amounts of public money that will need to be used for direct assistance. Thus, more resources are available for adequate development of the general infrastructure such as roads, main drains or main irrigation structures.

The crucial aspect in the reclamation of acid sulfate soils is mobilizing the strength of the community of people, creating the possibility for a broad base of experience. If the people moving into areas of new development are strengthened, not weakened, in their technical abilities, their social organization and their mutual support; if they have a stake in the development of the land rather than just being planted there with government credit and fertilizers, they will not sell their borrowed ploughs and roof-sheets and go, but they will jointly make a success of the development even of acid sulfate soils. Our present task is to help in shaping the technical tools for reclamation, making maximum use of the varied experience of the practical farmers.
Acknowledgements

I gratefully acknowledge the help readily given by G.E. Goodell and R.W. Herdt, both of the International Rice Research Institute, in developing and clarifying the thoughts on which major parts of this paper are based, and by T. Brinkman-Geilman in structuring the originally formless mass of text. The responsibility for any errors or misstatements rests on me.
References


FACTORS INFLUENCING THE FORMATION
OF POTENTIAL ACIDITY IN TIDAL
SWAMPS
L.J. Pons and N. van Breemen
Department of Soil Science and Geology,
Agricultural University
Wageningen, The Netherlands

Summary

An explanation is offered for the geographic distribution of potentially acid sulfate soil materials in relation to climatic zones and the physiography of coastal plains. For this purpose potential acidity is defined as an excess of pyrite over acid neutralizing components. The essential ingredients and environmental conditions for the formation, accumulation or sedimentation of pyrite and acid neutralizing components are listed and interpreted in terms of actual and past physiographic settings, illustrated by well-known situations. Potential acidity is built up predominantly in kaolinite-rich, non-calcareous sediments in tidal flats below mean high water level, with a dense mangrove vegetation, amply flushed by saline or brackish tides at a sedimentation rate allowing for the mangroves to persist well below mean high water level for at least several decades.

These conditions are favoured by a subsidence of the land relative to the sea level or by low sedimentation rates and by a tropical humid climate. A relative rise of the land or an increase in sedimentation rate lead to rapid siltation of tidal creeks and quick lateral accretion of closed shorelines at levels well above mean sea level minimizes the influence of tidal flushing and mangrove vegetation, and thereby will depress the rate of pyrite accumulation and of decarbonisation and consequently of the potential acidity in tidal deposits.
2 Introduction

Of the estimated 500 million hectares fine textured soils developed in marine and fluviatile sediments (FAO/UNESCO, Soil Map of the World 1971-1979: Fluvisols and Gleysols), about 12.5 million hectares are highly pyritic and will acidify upon aeration, or have already done so (Table 1). Still larger areas of pyritic sediments are continuously water-saturated and covered by peat or non-pyritic sediments. Moreover pre-Holocene pyritic coastal sediments, often in combination with peat, commonly give rise to serious acidity problems, especially as a result of open-cast mines in tertiary lignite deposits and coal of carboniferous age.

Table 1. Regional distribution of acid sulphate soils (based on data from FAO/UNESCO Soil Map of the World; length of growing periods according to FAO Agro-Ecological Zones Project, Rome)

<table>
<thead>
<tr>
<th>Region</th>
<th>Area (10^6 ha)</th>
<th>Area (million ha) per length of growing period</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>&lt; 90 days</td>
</tr>
<tr>
<td>Africa</td>
<td>3.7</td>
<td>0.4</td>
</tr>
<tr>
<td>Near and Middle East</td>
<td>-</td>
<td>-</td>
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<tr>
<td>Asia and Far East</td>
<td>6.7</td>
<td>-</td>
</tr>
<tr>
<td>Latin America</td>
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<td>N. America</td>
<td>0.1</td>
<td>-</td>
</tr>
<tr>
<td>Europe</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>World total</td>
<td>12.6</td>
<td>-</td>
</tr>
</tbody>
</table>

Potential soil acidity due to excess pyrite over neutralizing substances is formed mainly in tidal swamps and marshes, but sometimes also in sea bottom sediments. Up to now little is known about the reasons why pyritic contents are dangerously high in some areas and much lower in apparently similar adjacent areas. The aim of this article is to explain, sometimes rather speculatively, the distribution of potentially acid sulfate soils in relation to climatic zones and the physiography of the coastal plains. Such knowledge should help to solve problems in identification, cartography and reclamation of these soils. This article is similar in scope as the paper by Pons, Van Breemen and Driessen (in press).
Formation of potential soil sulfate acidity

Acid sulfate soils are formed by oxidation of sulfidic muds when the quantity of sulfuric acid, formed by oxidation of reduced S-compounds exceeds the acid-neutralizing capacity of adsorbed bases and easily weatherable minerals to the extent that the pH drops below 4.

Pyrite (cubic FeS₂) is quantitatively the most important sulfur mineral in such sediments. Accumulation of sedimentary pyrite requires (a) reduction of sulfate to sulfide, (b) partial oxidation of sulfide to polysulfides or to elementary S and (c) either formation of FeS (from Fe-oxides or Fe-silicates) followed by combination of FeS and S to FeS₂, or direct precipitation of FeS₂ from Fe⁺⁺ and polysulfides.

Regardless of the actual pathway, the following overall reaction describes complete pyritization of ferric oxide:

\[
\begin{align*}
Fe_2O_3(s) + 4SO_4^{2-}(aq) + 8CH_2O + \frac{1}{2}O_2(g) & \rightarrow 2FeS_2(s) + 8HCO_3^-(aq) + 4H_2O \\
\end{align*}
\]

(1)

The essential ingredients for the accumulation of pyrite are:
1) sulfate, continuously supplied over an appreciable period (e.g. with sea water);
2) iron-containing minerals present in the sediments;
3) metabolizable organic matter (CH₂O);
4) sulfate-reducing bacteria, which are practically always present;
5) an anaerobic environment;
6) limited aeration for oxidation of all sulfide to disulfide.

Potential acidity can develop only if at least a part of the alkalinity in the form of bicarbonate (HCO₃⁻), formed during sulfate reduction, is removed from the system. This requires leaching of the interstitial solution. Leaching is favoured strongly by tidal action and may further accelerate pyrite formation by breaking up diffusion-controlled rate-limiting processes and by supplying dissolved oxygen as well as sulfate from sea water. Removal of HCO₃⁻ also tends to depress the pH, giving slightly acid conditions which favour pyrite formation kinetically.

The pyrite content is a measure for the potential acidity, according to the reaction
\[ \text{FeS}_2 + \frac{15}{4} \text{O}_2 + \frac{7}{2} \text{H}_2\text{O} \rightarrow \text{Fe(OH)}_3 + 2\text{SO}_4^{2-} + 4\text{H}^+ \] (2)

If any bases present are represented by their oxide components, the neutralizing capacity follows from the equation

\[ M_{x+}^{2+} + x_z\text{H}_+ + x_M^{2+} + \frac{x_z}{2}\text{H}_2\text{O} \] (3)

The acid neutralizing capacity of soil material depends on the amount of exchangeable bases and the contents of easily weatherable silicates and of carbonates. If fine-textured marine clays contain appreciable amounts of smectitic clay and are saturated with bases, their exchange complex may inactivate acidity released by up to 0.5% pyrite-S and prevent a drop in pH below 4.0. An example of neutralization by silicates is the replacement of Mg from smectites by Fe(III) from oxidizing pyrite, sometimes up to the equivalent of 1% pyrite-S (Van Breemen 1980). Three per cent CaCO₃ balances the acidity produced by 1% pyrite.

Distribution of potential acidity

Potential acidity can be formed most readily in:
- poorly drained inland valleys, subject to influx of sulfate-rich water;
- bottoms of saline and brackish lagoons, seas and lakes; and
- saline and brackish tidal flats and tidal swamps.

Inland valleys, with potential acidity are relatively rare with the supply of sulfates as the limiting factor. Examples include the pyritic papyrus peats of Uganda (Chenery 1954), pyritic sandy gley soils in valleys in the Eastern Netherlands (Poelman 1973) and the sulfidic peat soils of Minnesota.

Bottoms of saline and brackish lagoons, seas and lakes, may be high in sulfides. Contents of primary (synsedimentary) organic matter usually limit sulfate reduction and the quantities of sulfides formed under these conditions (Berner 1971). Subaquatic sediments with potential acidity are generally limited to boreal and temperate climatic zones because there, contrary to tropical zones, decay of organic matter is slow and contents of primary organic matter in sediments are relatively
high (Pons 1965). Subaquatic sediments often contain relatively high amounts of iron monosulfides next to pyrite, resulting in black colours. This may be due to insufficient aeration of the bottom sediments for complete pyritization of sulfide. Examples are the bottom sediments of the Black Sea (Berner 1971) and of the former Littorina Sea (now the Baltic Sea) which contain more than 2% reduced sulfur and little or no carbonates (Wiklander et al. 1950). Isostatic rise of the land after the last glaciation resulted into drainage of considerable areas of Littorina sediments and caused the formation of acid sulfate soils along the Baltic coasts of Sweden and Finland. In the Netherlands, the bottom sediments of the former Zuyder Sea also contain more than 1% reduced sulfur (Ente 1964) but their relatively high carbonate contents prevent acidification upon reclamation.

**Pyrite formation in tidal flats and marshes.** Saline and brackish tidal flats and tidal swamps are quantitatively most important as a source of potential acid sulfate soils. The bare tidal flats and the lower parts of the swamps are regularly inundated with sulfate-rich water and permanently reduced. The highest parts near and above mean high tide, however, show predominantly aeration and little or no sulfate reduction.

In sediments of bare tidal flats and creek bottoms the content of primary organic matter may limit pyrite formation. They are generally low in organic matter (0.5-2%) in the tropics, but may be organic-rich in temperate regions, especially at high clay content. This explains the relatively high primary pyrite contents in temperate areas relative to those in the tropics (Pons 1965). On tidal marshes and swamps, however, a telmatophytic vegetation may add large quantities of organic matter to the primary organic matter. Telmatophytes which develop roots in reduced muds, include mangroves (Rhizophoraceae) in the tropics and reeds (Phragmites) and rushes (Scirpus) in temperate tidal marshes. Water temperature, salinity and duration of the inundations influence type and distribution of the vegetation, and thus control the supply of secondary organic matter to the mud. Figure 1 shows how the vegetation is adapted to the range of conditions in tidal marshes in different climates.
Adaption of the vegetation to lower topographic levels with longer inundations (and thus more reduced conditions) is greater in the tropics than in temperate and arctic zones and also greater in brackish than in saline conditions. In arid and semi-arid tropical coastal areas the growth of mangrove vegetations is hampered completely, perhaps due to very high salinities (Marius 1972).

Figure 1 illustrates that abundant supply of organic matter, favorable for pyrite accumulation can be expected in the 'low' brackish zone between mean sea level (MSL) and mean high water (MHW) in temperate areas with reeds (Phragmites) and rushes (Scirpus) and in the 'low' saline and brackish zone between mean low water (MLW) and mean high water (MHW) in tropical areas with Rhizophora and other mangrove trees.

Neutralizing compounds in tidal environments

Broadly speaking, the contents of neutralizing compounds of tidal
sediments at the time of deposition, viz. exchangeable bases, easily weatherable silicate minerals and carbonates, vary with climates. In the humid tropics, and especially in the smaller estuaries, kaolinite is often the dominant clay mineral in tidal sediments. These sediments are not only low in exchangeable bases but are also ineffective in neutralizing acid by weathering (Vieillefon 1973). Rivers from arid and semi-arid catchment areas supply mainly smectites to their estuaries, and, even though clay contents are often lower than in the humid tropics (Allen 1964), may neutralize an important fraction of the acidity formed upon oxidation. Those of the temperate areas have a mixed clay mineralogy with an appreciable exchangeable base content. Clayey sediments of large rivers of the humid tropics, including the Amazone and the Mekong, have moderate amounts of adsorbed bases and have a fair neutralizing capacity upon weathering.

Most volcanic catchment areas provide sediments rich in weatherable minerals. E.g. in tidal flats of the volcanic island of Java, in contrast to those of Sumatra and Kalimantan, the presence of such minerals lowers or prevents potential acidity (Driessen 1974).

Carbonates are practically absent in most coastal sediments in the humid tropics. Most rivers transport acidic water and non-calcareous sediments because their catchment areas include old, strongly weathered soils. Moreover coastal sea water in the tropics is often deluted with acid river water so any carbonate present runs the risk to be dissolved (Brinkman and Pons 1968). By contrast marine sediments in arid and semi-arid and in temperate zones frequently contain much more primary carbonates.

Summarizing (see also Table 2): the very fine textured clays of the large humid tropical estuaries show a moderately high neutralizing capacity. Sediments of arid, semi-arid and temperate areas and of volcanic regions have generally lower clay contents, but both because of a richer mineralogy and higher carbonate content, these sediments are highest in acid neutralizing capacity. Only the small estuaries in the humid tropics are generally very low in neutralizing materials and hence are often strongly acid or potentially acid.
Table 2. Occurrence of neutralizing ingredients in tidal deposits in environments favourable for pyrite accumulation (xxx abundant, xx fair, x rare, - none)

<table>
<thead>
<tr>
<th></th>
<th>Humid tropics</th>
<th>Humid temperate zone</th>
<th>Arid and semi-arid zone</th>
</tr>
</thead>
<tbody>
<tr>
<td>Regions with recent volcanism</td>
<td></td>
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<td></td>
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<tr>
<td>Small estuaries</td>
<td>xxx</td>
<td>x</td>
<td>x/xx</td>
</tr>
<tr>
<td>Large estuaries</td>
<td>xx</td>
<td>xx</td>
<td>xxx</td>
</tr>
<tr>
<td>Clayey deposits</td>
<td>x</td>
<td>x</td>
<td>xxx</td>
</tr>
<tr>
<td>Sandy deposits</td>
<td>xx</td>
<td>xx</td>
<td>xxx</td>
</tr>
</tbody>
</table>

Exchangeable bases

Weatherable silicate minerals

Primary carbonates

6 Dynamics of tidal environments and the formation of potential acidity

The time required for the formation of appreciable amounts of potential acidity (i.e. of pyrite) is probably in the order of decades to centuries. So, the tidal marsh vegetation has to persist at a given location for at least such a period of time in order to build up sufficient quantities of pyrite. This implies that sedimentation must be slow (Moormann and Pons 1974). Tidal environments with low sedimentation rates often have many well-developed creeks. Estuarine areas generally show numerous creeks in contrast to rapidly accreting coastal systems as in Malaysia (Diemont and Van Wijngaarden 1974) and along the Guyana coast (Brinkman and Pons 1968).

According to Diemont and Van Wijngaarden (1974) reduced substrata of large coastal swamps behind a closed accreting shore line in Malaysia have less than 0.5% pyrite-sulfur, are low in organic matter and show a field pH between 8 and 8.4, reflecting high concentrations of HCO$_3^-$ (10-26 mol/m$^3$) in the soil solution. Those of the estuarine swamps, dissected by tidal creeks, have 1-2.5% pyrite sulfur, are high in undecomposed organic matter and show field pH's between 6.2 and 6.8 in the upper meter, with interstitial water low in dissolved HCO$_3^-$. 

44
Iates.

If sedimentation is outweighed by accumulation of organic debris, (2-10 mol/m^3). Black FeS was locally found in sediments of the accreting coast, but not in estuarine sediments. During spring tides the concentrations of dissolved sulfide in the estuarine sediments dropped to undetectable levels whereas they remained almost constant along the accreting coast. These observations can be explained by much more effective tidal flushing in tidal marshes with a well-developed creek system. Tidal flushing would favour temporary limited aeration, necessary for the complete pyritization of ferric iron and leaching of interstitial water and evacuation of HCO_3^- so that a relatively low pH (6.5-7) is maintained.

In tidal environments, dissolution of CaCO_3 (secondary decalcification) may be much stronger than under terrestrial conditions (Van der Sluys 1970, Salomons 1974). This accelerated dissolution is also a result of tidal flushing combined with dissolution of CaCO_3 by CO_2 produced during the decomposition of plant remains. Oxidation of some pyrite during low tides would also remove CaCO_3 (Kooistra 1978).

Summarizing one may conclude that in saline and brackish marshes, dissected by creeks, leaching by tidal action may contribute to potential acidity, both by favouring pyrite formation and by removal of carbonates.

If sedimentation is outweighed by accumulation of organic debris, pyritic peats may develop. Pyritic mangrove peats are known from the Niger delta (ILACO), from Senegal (Vieillefon 1973), in Kenya (unpublished observations by Van Wijngaarden and Pons), and in Malaysia and Indonesia (Driessen 1974). Thin layers of pyritic reed and rush peats are very common e.g. in The Netherlands. In these peats, iron may become the limiting factor for pyrite formation. The same may be true for mangrove marshes composed dominantly of quartz sands (Vieillefon 1973).

During the last 3000 years many deltas, estuaries and coasts in Europe have witnessed a strongly accelerated sedimentation due to deforestation and land reclamation, especially since Roman times. Elsewhere, including in the humid tropics, this process is now becoming increasingly important. For this reason recent sediments often have a lower potential acidity than sub recent sediments. Moormann and Pons (1974) described the Mekong delta as an example.

Summarizing one may say, that from the point of dynamic development of
tidal environments many factors cooperate to result in high potential acidity in the humid tropics: dense vegetation, low sedimentation rates, and low primary and secondary carbonate contents in recent times increased soil erosion and concomitant accelerated sedimentation in tidal flats has somewhat decreased the rate of formation of potential acidity in many tropical areas.

7 The influence of relative sea level changes on tidal environments in relation with potential acidity

Both the formation of coastal land forms and the development of potential acidity in their sediments is strongly influenced by relative sea level changes. After the last glaciation the sea level rose by about 3–4 m per 1000 years (Blackwelder et al. 1979) and levelled off until a maximum was reached some 5,500 years BP and, apart from a slight drop some 5000 years ago (Fairbridge 1961) probably remained stable ever since. Slight differences in local tectonisms, however, resulted in different patterns of changes in the relative sea level as illustrated by Figure 2.
Fairbridge's curve applies to stable coasts, e.g. Senegal, Kenya, Australia, etc. The curve of Louwe Kooymans (1974) is not only characteristic for The Netherlands, where land subsidence caused continued rise in sea level after 5,500 years BP, but also for many other subsiding areas as the Orinoco delta, the Mississippi delta, etc. Along the Surinam coast the sea level remained constant during the last 5,500 years (Brinkman and Pons 1968). This pattern is also characteristic for many deltas e.g. the Bangkok plain and the Mekong delta.

Figure 3 illustrates how sea level changes and sediment supply may affect the formation of potential acidity in coastal areas. When the rise of sea level is high relative to the supply of sediment, transgression will take place.
Figure 3. Effect of changes in sea level and sediment supply on the accumulation of potential acidity in tidal swamps. Level of potential acidity is represented by relative density of dot distribution.

When sediment supply and relative sea level rise are more or less balanced a broad zone of stationary relatively low lying mangroves will occur (Brinkman and Pons 1968). Under these conditions vertical sedimentation predominates and potential acidity will be built up over considerable depths. If the sediment supply is relatively high the land area will grow by lateral accretion of the coast. Broad areas of relatively high-elevated tidal marshes are formed. The belt with mangroves and other salt and brackish marsh vegetations will shift rapidly seaward with the growing coast and only little potential acidity is formed (Moormann and Pons 1974).

After the last glaciation, in many areas with considerable supply of
sediments the rise in sea level during the early Holocene was approximately balanced by the sediment supply. This resulted in a vertical build-up of sediments under stationary tidal marsh conditions. The silting-up of creeks was also retarded and tidal flushing of the relative low mangrove and salt marshes was maintained during long periods giving rise to thick sediments with high potential acidity.

After the stabilisation of the sea level during the late Holocene the still considerable supply of sediments caused lateral coastal accretion in these areas. A zone with high-lying mangroves rapidly shifted seaward with the growing coast. Only limited time was available for the formation of potential acidity. In addition, less favourable chemical conditions in these relatively high lying sediments for both pyrite formation as well as for decarbonation, contributed to their generally low level of potential acidity.

Erosion caused by deforestation in watersheds during the last parts of the Late Holocene has further accelerated the already high rates of coastal accretion in many of these regions.

In areas of low sediment supply, where transgressions took place in early Holocene times, sea level stabilisation in late Holocene times brought about stationary coasts with low lying mangroves. In such areas potential acidity is formed at present. Examples are the estuary of the Siné-Saloum (Marius 1972), the estuary of the Casamance river where recent sedimentation is so slow that locally pyrite peats are formed (Vieillefon 1973), and the estuary of the Saigon river (Moormann and Pons 1974).
References


