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Wetland sediments and soils on the Swan Coastal Plain, southwestern Australia: types, distribution, susceptibility to combustion, and implications for fire management

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Abstract

The main types of end-member sediments constituting wetland fill on the Swan Coastal Plain are diatomite, calcilutite (carbonate mud), peat, quartz sand, and kaolinite-dominated mud. There is also a range of intermediate sediments formed as mixtures between end-member sediment types, *viz.*, diatomaceous peat, organic matter enriched diatomite, organic matter enriched calcilutite, and various types of muddy sand. Humified equivalents of these sediments and humified basement quartz sand are the main wetland soils. There is a relationship between composition of the sedimentary fill, landscape setting, hydrochemical setting, and wetland type. Channels and wetland flats associated with the Pinjarra Plain bordering the Darling Scarp, or wetlands in the Pinjarra Plain to Bassendean Dunes transition are underlain by extrabasinal sediments, such as sand and kaolinite-dominated mud and muddy sand, reflecting their delivery and sedimentation by fluvial processes. Basin wetlands in the Bassendean Dunes are underlain by intrabasinal peat, diatomaceous peat, and diatomite, and their intermediates, or by soils composed of humic quartz sand (basement sand). Those in the Spearwood Dunes, within a terrain of quartz sand or limestone, are underlain by intrabasinal peat, diatomaceous peat, or calcilutite, often interlayered. Basin wetlands in the Quindalup Dunes are underlain by intrabasinal calcilutite, calcilutaceous sand, and some peat. Climate influences the distribution of the type of the wetland sediments in a south to north latitudinal gradient along the Swan Coastal Plain (*i.e.*, for a given geomorphic setting, peat tends to be more abundant in wetland basins in southern humid environments, and diatomite and calcilutite fills are more abundant in northern semi-arid environments). Climate also influences the temporal variation in material flammability as related to fluctuating or declining water tables. The various wetland sedimentary fills are mineralogic, geochemical and biochemical reservoirs that have varying response to combustion, producing different types of smoke and dust, factors important in designing fire management strategies. Pre-emptive and operational management of fire in wetland sediments and soils should be based on knowledge of their organic carbon content, their mineralogy, geochemistry and biochemistry, their hydrology, the potential of the sediments to combust in relation to annual water table fluctuations and longer term climatic patterns, the extent of flammable material across a wetland, the nature of stratigraphic interlayering along wetland margins, and the distribution of wetland sediment types both across the Swan Coastal Plain and along the climatic gradient of the length of the Swan Coastal Plain.

Keywords: wetland sediments, fire, pyrosediments, wetland hydrology, climate changes, Swan Coastal Plain wetlands

Introduction

Whereas fires in dryland environments consume vegetation and litter (Luke & McArthur 1978; Gill *et al* 1981), and in high temperature combustions may rapidly oxidise and remove humic soils, wetlands with organic matter rich substrates that become dry and flammable in the summer add another dimension to fire management, *i.e.*, how fires are ignited, fuelled and sustained, what remains as combustion residues, and what biochemical, geochemical, and mineralogic species are mobilised into the smoke or remain as ash. In the first instance, for example, while material such as peat may be more flammable than other wetland sediments, the opportunity for its combustion is closely related to the dynamics of the water table. For wetlands of the Swan Coastal Plain, one of the important tools in the management of fires thus is information on the distribution of flammable materials in the wetland systems, and the likelihood that such materials will be ignited. In this context, information on wetland sediments, wetland stratigraphy (*i.e.*, the thickness, sequences and types of wetland sediments and their mineralogy and geochemistry), surficial soils, and hydrology, (*i.e.*, the annual to long-term dynamics of inundation and waterlogging), should form cornerstones to an understanding of fire dynamics in wetlands and the development of strategies for managing fires in these environments.

This paper, as part of the Workshop on Fire Management in Wetlands held in Perth in March 2004, presents information on the types and distribution of wetland sediments and soils on the Swan Coastal Plain in order to identify those that are organic-rich and susceptible to combustion. As such, the paper describes the following: (1) the types of sediment and soils encountered in wetlands; (2) the stratigraphic fill of these wetlands in a geomorphic and climatic setting; (3) some of the responses of wetland sediments and soils to fire; (4) the various types of sediments and soils in wetlands in relation to their geomorphic setting and occurrence in natural wetland groups (consanguineous suites) across the Swan Coastal Plain and along a south to north climate gradient; and (5) the role of short-term or long-term groundwater fluctuations as factors in producing dry, flammable organic-rich sediments and soils that will be susceptible to combustion.

Information in this paper is drawn from the study of wetlands and sediments in consanguineous suites across the Swan Coastal Plain (Semeniuk 1988), the description of sediments, soils and stratigraphy in wetland basins across the Swan Coastal Plain (Semeniuk & Semeniuk 2004, 2005a,b), the detailed study of the stratigraphy, hydrology, vegetation and history of the Becher Suite wetlands (Semeniuk 2005), the climate patterns in coastal Western Australia (Semeniuk 1995a), and on R&D data collected over 30 years on the sediments, wetland sedimentary and diagenetic mineralogy, geochemistry, wetland stratigraphy and wetland hydrology by the V & C Semeniuk Research Group (Semeniuk & Semeniuk, 2005c).

From a stratigraphic and hydrologic perspective, the ignition and ongoing combustion of flammable materials in wetlands spatially and temporally are related to four factors: 1. the type and state of combustible materials resident in wetlands (Fig. 1); 2. the stratigraphic distribution of flammable materials across a wetland and down the stratigraphic profile; 3. the distribution of such materials, which is related to geomorphic setting and climate setting; and 4. the seasonal patterns, or longer term climatic patterns that result in potentially flammable materials drying out.

Materials and methods

A wide-ranging sediment/soil sampling programme was undertaken by Semeniuk & Semeniuk (2004) at the surface and in the stratigraphic sequence of 143 wetlands, from Bunbury to the Moore River, across the width and along the length of the central Swan Coastal Plain in the different geomorphic, hydrologic and hydrochemical settings, in order to fully capture potential variability in these materials. The details of methods used in the study of wetland sediment/soils are provided by Semeniuk & Semeniuk (2004, 2005a), but a summary is provided here.

In the laboratory, the samples of sediment/soils were described and analysed using various levels of detail to provide a comprehensive view of the variety of wetland sediment and soil types on the Swan Coastal Plain (Semeniuk & Semeniuk 2004, 2005a): stereomicroscope and a light transmitting microscopy; chemical analyses for various alkali metals, heavy metals, and S; determination of carbonate by acid digestion and high temperature combustion; C determination by combustion; selected analyses of some 50 samples at the CSIRO laboratories by Scanning Electron Microscope (SEM), supplemented by use of Back-scattered Electron Emissions (BSE), Energy Dispersive Spectroscopy (EDS), and XRD; routine spot analyses of numerous (5–15) particles within each SEM field of view, using EDS, which allowed determination of relative element content of individual particles and identification of diatoms, very fine and ultra-fine-grained diatom fragments, sponge spicules, invertebrate skeletons/tests and fragments, quartz silt, mud-sized phyllosilicate minerals, organic carbon, plant detritus, calcite, and framboidal pyrite, and in the ash, alkaline metal salts.

The effects of fire on sediment/soils were studied using natural materials in the field, and using laboratory procedures. In the first instance, during the 30 years of monitoring and studying wetlands stratigraphically on the Swan Coastal Plain and elsewhere, numerous wetlands through natural or anthropogenic agencies had been burnt during late summer. The water tables in these wetlands at the time of the fires generally were low, and surface sediments and soils were invariably dry. Forty seven of these had been sampled for surface sediments and eight had been sampled for soils before the combustion event, and had been analysed in terms of organic matter, diatoms, and carbonate mud as part of a regional study (Semeniuk & Semeniuk 2004). The responses of the surface materials to these fires were observed (*i.e.*, whether or not they had combusted), and the nature of the post-combustion residue or ash remaining analysed texturally, mineralogically, and in terms of elemental composition, and thus could be compared with pre-combustion sediments. In relation to laboratory procedures, a range of experiments were conducted to determine the effects of fire on particular grain types and minerals in various materials (*e.g.*, peat, spongolitic peat, peaty diatomite, peaty calcilutite, and other organic rich sediments, as well as diatomite, sponge spicules, pyrite, a pyrite/diatomite powder mix, and wood). Separate sample batches of these materials were combusted for 1 hour and for 2 hours at 250° C, 500° C, 750° C, and 1000° C to ascertain in the laboratory the textural and mineralogic transformations that may occur with the high temperatures achieved during natural combustion in wildfires. For the sediments, the pre-combustion and post-combustion samples were digested in perchloric acid and nitric acid, and analysed for Na, K, Ca, Mg, Fe, As, Pb, and S by Atomic Absorption Spectroscopy or ICP-MS, and selected pre-combustion and post-combustion samples were analysed by XRD. Pre-combustion and post-combustion samples were also examined as grain-mounts under petrographic microscope. The alkaline metal content of vegetation was determined by combusting various plant species, digesting the ash in perchloric acid and nitric acid, and analysing the liquor for Na, K, Mg, and Ca by Atomic Absorption Spectroscopy or ICP-MS (Semeniuk 2005).

Terminology

Because of some confusion and free substitution in the literature between the terms “sediment” and “soil”, Semeniuk & Semeniuk (2004) defined a range of terms in relation to wetland-filling materials. “Sediment” refers to

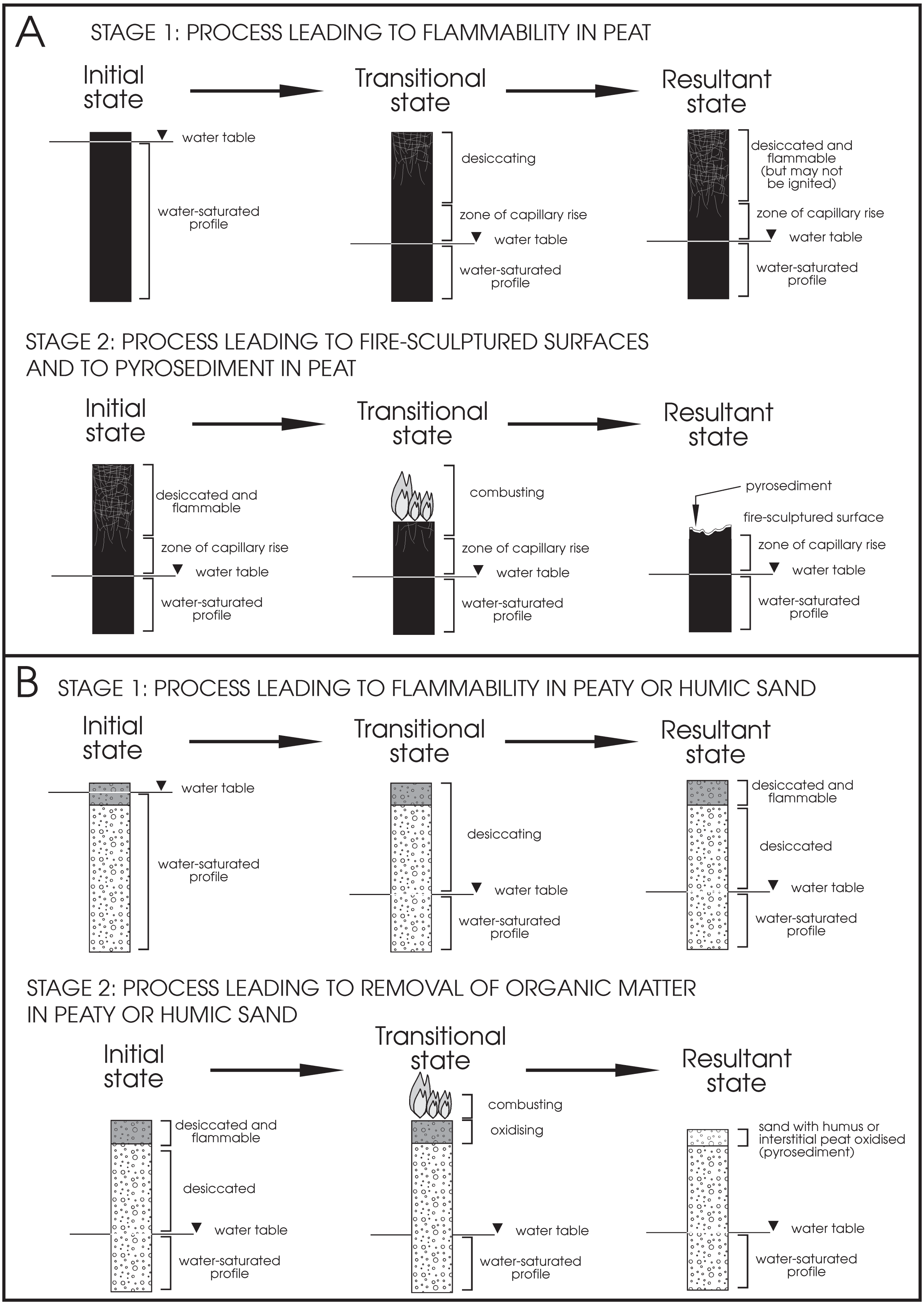


Figure 1. Processes leading to flammability of combustion-susceptible sediments and soils. In all these idealised stratigraphic columns, the depth of the profile is 2 m, and in general, the zone of capillary rise is up to 30 cm above the water table. A. Stage 1 involves falling water level and water table, leading to desiccation and a state of flammability (though not necessarily combustion). Stage 2 involves combustion of flammable material, leading to fire-sculpturing of the surface, and development of pyrosediments. B. Similar processes, but with a humus rich quartzose sand soil, or peaty sand.

accretionary and infiltrational material formed within the wetland (autochthonous, intrabasinal), or transported into the wetland (allochthonous, extrabasinal). Thus, peat and calcilutite as accretionary materials are types of wetland sediment, formed intrabasinally. "Sedimentary fill" refers to the total aggregate of sediments that have accumulated in a wetland basin upwards from the floor of the original ancestral basin. "Stratigraphic" and "stratigraphy" refer to the accumulated sequence of sediments. "Diagenetic" refers to the physical, biological, and chemical processes, acting alone or in concert, that overprint sediments after accumulation, and products resulting from these processes, *e.g.,* precipitation of pyrite and carbonate cementation. Processes of diagenesis can overlap with pedogenesis. "Soil" refers to the altered material near or at the surface of any pre-existing sediment or rock body that has been biologically, chemically, or physically (pedogenically) modified under extant conditions, *e.g.,* the weathering and humification of the surface layer of sand results in a surficial soil (Fig. 1 of Semeniuk & Semeniuk 2004). Soils that are buried, or that have formed under past climatic or hydrologic conditions, and therefore not extant, are palaeosols.

Wetland sediments are the primary (accretionary or infiltrational) accumulates within a wetland basin. Wetland soils are the surface and near-surface alteration either of these sedimentary materials, or of the parent "basement" material. Two examples are used to illustrate the principles that soils may be developed on wetland sediment or on basement materials. Whereas calcilutite fill within a wetland basin is accretionary intrabasinal sediment, the near-surface 10 cm thick grey calcilutite layer, with humified root-structured material, is the wetland soil. A wetland underlain only by basement quartz sand, *e.g.,* the Bassendean Sand (Playford & Low 1972), has no wetland sediment, thus any near-surface 10 cm thick grey sandy layer of humified root-structured sand is the wetland soil.

Pyrosediments, a term coined by Semeniuk & Semeniuk (2004), are secondary sediments, such as residues of diatomite, calcilutite, and quartz sand, formed as a result of the combustion of sedimentary materials. Various aspects of wetland pyrosediments and their diagnostic signatures of wetland sedimentary particles are described and discussed in Semeniuk & Semeniuk (2005a).

In this paper, following Semeniuk & Semeniuk (2004), the term "organic matter" is used to refer to the range of materials of various particle sizes that are derived mainly from plants. Organic matter ranges from relatively fresh plant material, to particles in various stages of decomposition (structural and biochemical breakdown, mediated by microbiological and fungal processes), to elemental carbon. The term "organic matter" is not used to refer to skeletal remains of invertebrate fauna, the calcareous products of disintegrated charophytes, or to the frustules of diatoms, though these particle types are produced by organic processes.

We separate three terms in the description of fire in wetland sediments, or the effect of fire on wetland soils: (1) *combustion*, a general term for the exothermic rapidly oxidising chemical reaction of materials which once ignited is self-sustaining and usually produces a flame; (2) *flammable*, referring to the property of materials that combust, often resulting in flames; and (3) in this paper, *rapid oxidation*, usually of soil materials, driven by the heat of fire in the overlying vegetation, and referring to the removal of soil carbon or organic matter as CO_2 without combustion or flammability of the material.

Regional setting and consanguineous wetland suites

The Swan Coastal Plain is the Quaternary surface of the Perth Basin (Playford *et al* 1976). The Plain comprises distinct large-scale landforms arranged subparallel to the Darling Scarp, or to the coast, except where they are associated with major rivers. These landforms correspond to the main sedimentary formations in the region (Woolnough 1920; McArthur & Bettenay 1960; Playford *et al* 1976; McArthur & Bartle 1980a,b; Semeniuk & Glassford 1987, 1989; Semeniuk 1988; Semeniuk *et al* 1989; Geological Survey 1990; Semeniuk 1995b). The units from east to west are (Fig. 2A):

- Pinjarra Plain: flat to gently undulating alluvial fans fronting the Darling Scarp and Darling Plateau (underlain by sand, laterite, and the Precambrian rocks), as well as floodplains and various sized channels; underlain by the Guildford Formation (clay, laterite, sand, muddy sand);
- Bassendean Dunes: undulating terrain of low degraded dunes (varying in relative relief from 20 m to almost flat), and interdune flats and basins; underlain by the Bassendean Sand (quartz sand) of Pleistocene age;
- Spearwood Dunes and Yalgorup Plain: large-scale, linear, near-continuous subparallel ridges (*c* 60m relief) and intervening narrow and steep-sided depressions, or of narrow plains; underlain by Pleistocene limestone (aeolianite and marine limestone) blanketed by quartz sand;
- Quindalup Dunes: Holocene coastal quartzo-calcareous sand dunes, beach ridge plains, tombolos and cuspate forelands.

A wide range of wetland types occurs on the Swan Coastal Plain, from basins (lakes, sumplands, and damplands) to flats (floodplains and palusplains) to channels (rivers and creeks), varying in size, shape, water characteristics, stratigraphy and vegetation (Semeniuk 1987, 1988; Semeniuk *et al* 1990). For instance, dependent on setting, wetland basins can range from large linear lakes to small round to irregular seasonally damp basins; from fresh water to hyposaline (brackish) to saline (Semeniuk 1987); from surface-water to groundwater recharged; their vegetation cover can vary from herbland to forest (Semeniuk *et al* 1990). All these attributes are influenced by regional features such as geology, geomorphology, soils, climate and hydrology, and local physical/chemical processes such as aeolian processes, groundwater flow, and karstification.

The variety of wetlands formed on the Swan Coastal Plain can be aggregated into natural groupings, *i.e.,* consanguineous suites (Semeniuk 1988), with each suite having its own variety of wetland types in terms of size, shape, water quality, substrates, and maintenance processes. Wetland suites are strongly related to

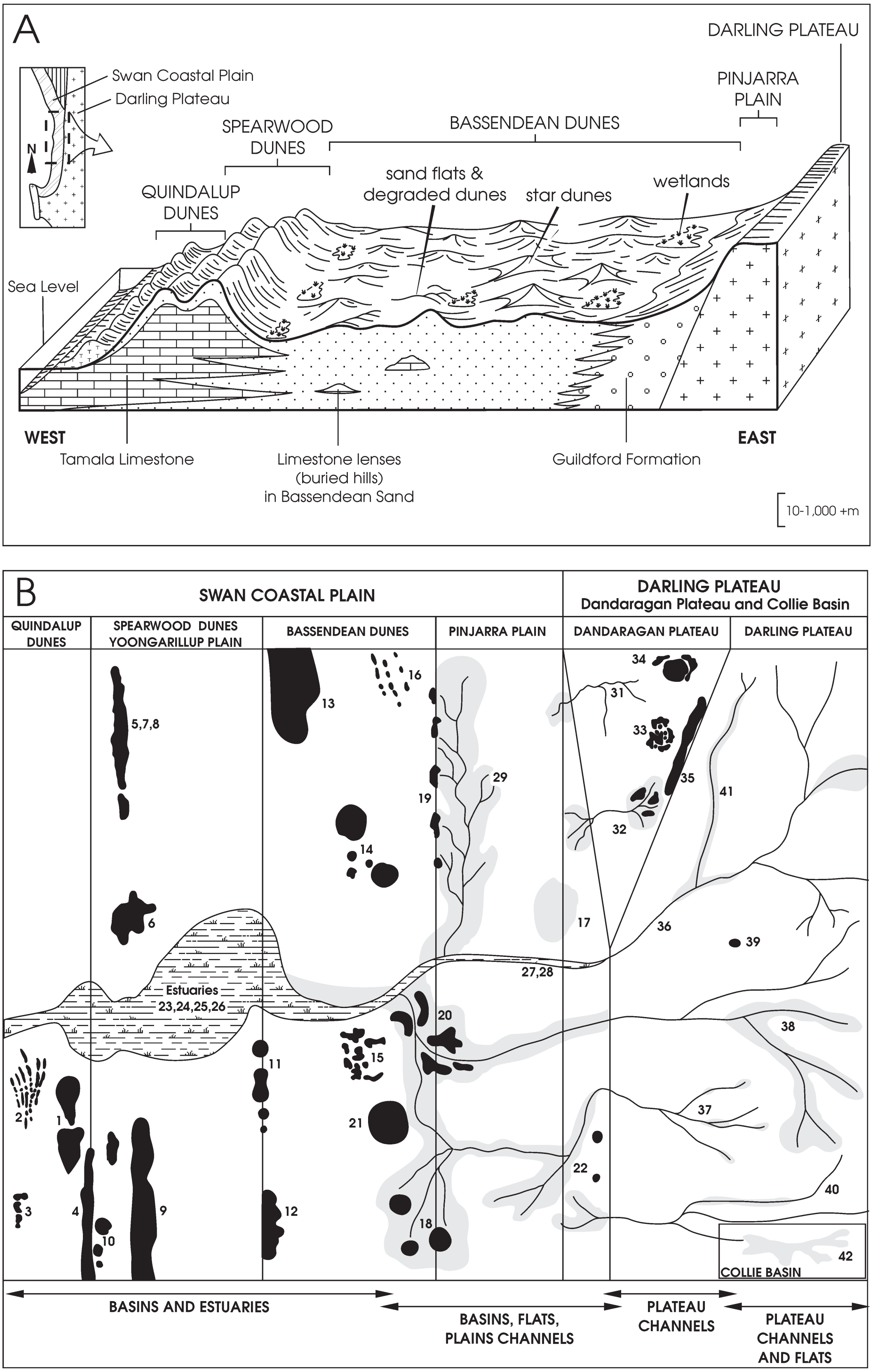


Figure 2. A: Idealised block diagram showing geomorphic units of the Swan Coastal Plain, their sub-parallelism to the Darling Scarp and the coast, their gross surface features, and their stratigraphy, with some details of landscape (after Semeniuk & Glassford 1989). B: Idealised map showing the variety and distribution of consanguineous wetlands (from Semeniuk 1988), *i.e.*, the natural wetland groupings or suites in the Darling Plateau and Swan Coastal Plain centred on the Moore River to Bunbury region. In this region there are 42 such groups each related to geomorphic setting, or interfaces between geomorphic units (for explanation of numbering of the consanguineous wetland suites, see Semeniuk 1988).

geomorphic setting, or to the interfaces between the main geomorphic units. An idealised diagram of the range of consanguineous suites across the central Swan Coastal Plain is shown in Figure 2B. Each individual or site-specific wetland, and wetland suite, is the culmination of broader Quaternary palaeoenvironmental as well as more modern processes such as geomorphic and sedimentologic processes, vegetation influences, and fire.

Wetland types and the origin of wetlands within a consanguineous suite tend to be similar because of the similarity of physical setting and causative factors, *i.e.*, geomorphology, geomorphic and sedimentologic processes and developmental history, climate, and hydrology. As such, for instance, within the Bassendean Dunes, wetlands set in geomorphically degraded dune terrain appear as a dappled pattern of irregular small wetland basins; within the beachridge setting of the Quindalup Dunes, there are linear patterns of small, oval to linear wetlands reflective of a setting in inter-beachridge swales; and along the interface between the Spearwood Dunes and Bassendean Dunes there are large, round wetlands set in a chain, reflecting the long term hydrological setting between these two geomorphic units (Semeniuk 1988). If concurrently there exists a pattern of wetland types, hydrology, hydrochemistry, and foundation materials, as related to geomorphic setting, similar suites of sedimentary fill also will be developed. Sedimentary fills within wetlands will therefore have a distinct geographic distribution. For example, wetlands residing in carbonate-enriched groundwaters will develop calcareous sediments, and those residing in carbonate-depauperate, silica-enriched groundwaters may have silica-enriched sediments. Thus geomorphic setting, hydrological and hydrochemical setting, expressed within a consanguineous suite will determine to a large extent the type of sediments and soils that will develop within a wetland (Semeniuk 1988).

Wetland sediments and soils, their general flammability, and products of combustion

Wetland sediments and soils

The particles that comprise wetland sediments and soils vary from mud-sized, to gravel-sized. Their composition may be organic matter, biogenic silica (diatoms, sponge spicules, and phytoliths), carbonate minerals, quartz, feldspar, mud-sized phyllosilicate minerals, or gypsum. Diagenetic products within wetland sediments include carbonate cements, silica cements, ferricrete, and the formation of sulphides (especially sulphides such as pyrites, marcasite, and arsenopyrites). Based on composition and texture, Semeniuk & Semeniuk (2004) recognised ten main end-member sediment types in wetlands of the Spearwood Dunes, Bassendean Dunes and Pinjarra Plain on the Swan Coastal Plain, focused only in the central Swan Coastal Plain mainly between Moore River and Bunbury; they are: 1. peat; 2. peat intraclast gravel and sand; 3. calcilutite; 4. carbonate skeletal gravel and sand; 5. carbonate intraclast gravel and sand; 6. diatomite; 7. diatomite intraclast gravel and sand; 8. kaolinitic mud; 9. quartz sand; and 10. quartz silt. However, for completeness of this paper, the full range of the wetland sediments of the Quindalup Dunes are included here (Semeniuk 1988, 2005). Basins in the Quindalup Dunes contain, as end-member sediments, calcilutite and peat (as above) and additionally quartzo-calcareous sand of aeolian origin and locally stromatolitic boundstone. In total therefore, while Semeniuk & Semeniuk (2004) list 10 end-member wetland sediment types for the central Swan Coastal Plain, for purposes of this paper, incorporating the geomorphic settings of Quindalup Dunes, Spearwood Dunes, Bassendean Dunes and Pinjarra Plain, there are 12 *end-member* wetland sediment types.

Mixtures of these end-member sediment types, contributions to peat and diatomite from sponge spicules and phytoliths, and mixtures between the primary sediments and quartz sand (that forms the basement or the margins to the wetland deposits) also occur (Semeniuk & Semeniuk 2004), resulting in spongolitic peat, diatomaceous peat, calcilutaceous peat, spongolitic diatomite, peaty sand, and muddy sand (calcilutaceous muddy sand, diatomaceous muddy sand, and kaolinitic muddy sand), amongst others. For purposes of this paper, a total of 21 common wetland sediments are described, *i.e.*, 12 end-member sediments and 9 sediment types formed by mixing of the end-member sediment types. These sediments, the mixtures between them, and their general flammability are described in Table 1. SEM photomicrographs of selected standard sediments are illustrated in Figure 3.

Organic, diatomaceous, and calcilutaceous fine-grained wetland sediments were classified by Semeniuk & Semeniuk (2004) using a ternary diagram (Fig. 4A). In this context, peat *sensu stricto* (*i.e.*, sediment with > 75% organic matter) is only a moderately common wetland sediment on the Swan Coastal Plain. Many of the dark grey sediments, high in organic matter (*i.e.*, 50–75% organic matter), superficially resembling peat *sensu stricto*, have significant content of diatoms or carbonate mud, and while belonging to the broad family of "peat" or "peaty" sediments, are termed "diatomaceous peat" and "calcilutaceous peat". Other fine grained dark grey sediments also superficially resembling peat, or appearing to be organic-enriched sediment, often have significant content of metal sulphides, particularly pyrite, that imparts a dark grey tone to the sediment. Thus, sediments that are organic-matter-rich, and not merely dark grey, and that are most susceptible to combustion, while belonging to the family of "peats" or "peaty sediments", are subdivided into peat (*sensu stricto*), diatomaceous peat and calcilutaceous peat.

Soils underlying wetlands are the organic-rich (humified) surface layer and root-structured zones most commonly developed on the primary wetland sediments listed above, but also are formed on basement quartz sand (Semeniuk & Semeniuk 2004). Where transformed to soil at the surface, depending on their content of organic matter, and particularly if they have concentrations of shallow root mats, all wetland sediment types and basement quartz sand may have some degree of flammability, or have the potential to lose their organic matter content through rapid oxidation under fire conditions (*e.g.*, humic quartz sand under damplands in the Bassendean Dunes may be oxidised to quartz sand under conditions of a very hot fire, and shallow horizons

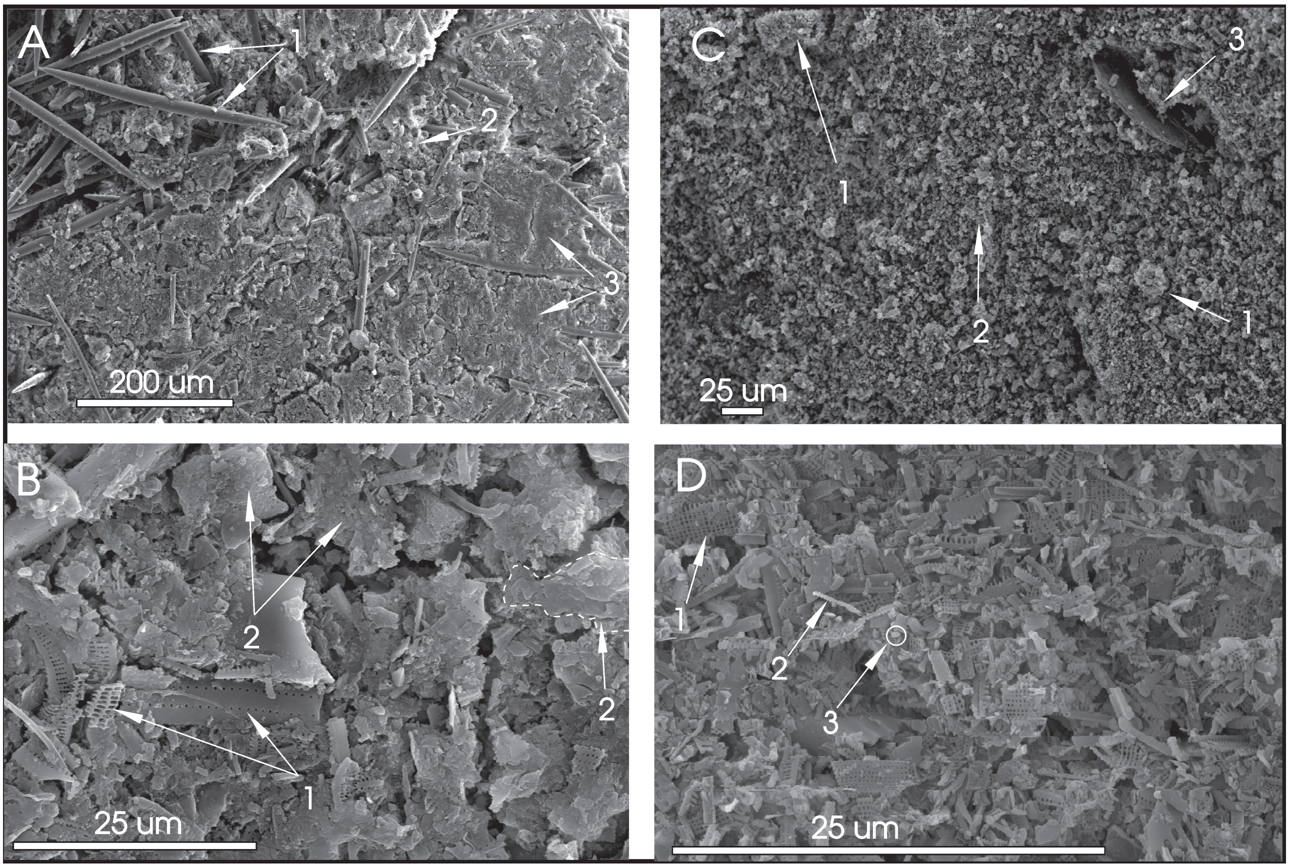


Figure 3. SEM photomicrographs of some wetland sediments. A. Diatomaceous peat showing abundance of whole and fragmented sponge spicules, 200–250 μm in size (arrow 1), scattered diatom fragments (arrow 2), and the fine-grained organic matter that dominates the sediment, here showing cracking by desiccation (arrow 3), as a result of carbon-coating under vacuum in the SEM process. B. Diatomaceous peat showing (1) typical fragments of diatom frustules, and (2) fine-grained plant detritus with layered internal structure. C. Calcilutite with carbonate grains showing progressive disintegration of *Chara*; larger fragments (1), 25–30 μm in size, disaggregated into smaller crystals (2), 1–4 μm in size; invertebrate skeletal fragments are scattered in the sediment (3). D. Diatomite showing progressive fragmentation of frustules from relatively large fragments (1), 5 μm in size, that exhibit wall structure, to nearly fully disaggregated frustules (2), to completely disaggregated frustules (3) < 1 μm in size.

of root mats may localise horizon-specific subsurface combustion zones).

Pyrogenic effects on wetland sediment/soils and particles

During the 30 years of monitoring and studying wetlands stratigraphically and sedimentologically, we have observed numerous wetlands that had been burnt during late summer, both on the Swan Coastal Plain and in other wetland regions of Western Australia. The response of the surface sediments and soils to these fires were noted, *i.e.*, whether or not they combusted. Forty seven of these wetlands fortuitously had been sampled for surface sediments and eight had been sampled for soils in advance of a given fire.

Three stratigraphic situations determined the response of the surface material to the fire (Fig. 5):

1. surface materials consisted of organic-matter-rich sediment such as peat or diatomaceous peat, and combustion consumed the flammable material to the level of the zone of capillary rise;
2. surface materials consisted of sediments that were non-flammable, *e.g.*, diatomite, but the shallow subsurface layer consisted of an organic-matter-rich root mat (derived, for instance, from *Kunzea ericifolia*, or from *Melaleuca* spp), which preferentially combusted, while underlying and overlying non-flammable layers of sediment, while not combusting, manifest structural, textural and compositional pyrogenic changes; often the root mat has developed because of the relatively impervious nature of the underlying fine grained wetland sediments; in this context, copses of shrubs and trees, therefore, would localise near-surface to subsurface combustion, depending on the depth of the root mat layer and its accessibility to the fire;
3. surface material is a soil with strong humic content or organic matter enriched zone developed on quartz sand, or calcilutite, both of which were not flammable; during a fire, while the quartz sand, or calcilutite remained non-flammable, the organic content of the soil was removed by rapid oxidation, locally resulting in a volume change in the material.

A ternary diagram classifying the fine-grained biogenic sediments based on their content of organic

Table 1

Description of wetland sediments (summarised from Semeniuk & Semeniuk 2004), ordered in terms of potential flammability

Sediment type	Description[1]	Origin	Potential flammability[2]
peat	black to grey, brown, homogeneous to root-structured to finely laminated, mainly fine-grained organic matter, with root fibres, plant detritus and scattered sand, and freshwater snails (or fragments); some peats with branches, twigs, and logs; often containing diatoms, phytoliths, and sponge spicules; organic matter content > 75%	derives from plant detritus, under acidic and anaerobic conditions in wetlands in all geomorphic systems; different types of peat are generated, in terms of their biochemical, geochemical, mineralogic, and sedimentary attributes, by different vegetation assemblages, *viz.*, *Typha* peat, *Baumea articulata* peat, *Melaleuca* peat, and their sedimentary setting	high
peat intraclast gravel and sand	black to grey, breccioid to conglomeratic, grading to sand-sized clasts of peat, or alternating layers of breccia, conglomerate, and sand-sized fragments of indurated peat; may be texturally layered, and root-structured	drying, cracking, heat induration, fragmentation and reworking of peat in wetlands of Bassendean Dunes	high
diatomaceous peat (and spongolitic diatomaceous peat)	peat as above, but with 50–75% organic matter content, and with significant diatom content, and often significant sponge spicule content	diatoms (and sponge spicules) mixed with plant detritus	high
peaty sand	quartz sand as above, but with fine-grained interstitial material with > 75% organic matter	organic mud mixed into sand at margins or at base of wetland	medium to low
calcilutaceous peat	peat as above, but with 50–75% organic matter content, and with significant carbonate mud content	charophytes and invertebrate skeletons comminuted to mud size, mixed with plant detritus	low to nil[3]
organic matter enriched calcilutite	grey to brown homogeneous calcilutite, as above, but with 25–50% content of organic matter	calcilutite as above, but mixed with organic matter derived from plant detritus	nil
organic matter enriched diatomite	grey to brown homogeneous diatomite, as above, but with 25–50% content of organic matter	diatomite as above, but mixed with organic matter derived from plant detritus	nil
calcilutite	cream to pink to grey homogeneous, laminated, burrow-mottled, root-structured, bioturbated, or colour mottled; consists dominantly of clay-sized carbonate particles; mainly calcite, with minor Mg-calcite, aragonite and dolomite, or locally dominantly dolomite; with freshwater snails or fragments	disintegrated charophytes in wetlands of the Quindalup Dunes and Spearwood Dunes; uncommon in the Bassendean Dunes	nil
carbonate skeletal gravel and sand	cream to grey, homogeneous to layered; very coarse to medium sand; consists of whole and fragmented skeletons of molluscs	commonly as layers in peat, deriving from local invertebrate fauna in wetlands of Quindalup Dunes and Spearwood Dunes	nil
carbonate intraclast gravel and sand	cream to grey, structurally homogeneous to layered, with local vesicular to fenestral structures; consists of medium, coarse to very coarse intraclasts of calcilutite or cemented aggregates of carbonate sand	cementation (induration), fragmentation and reworking of carbonate mud and sand in wetlands of Quindalup Dunes and Spearwood Dunes	nil
diatomite (and spongolitic diatomite)	light grey, locally dark grey in humus-rich upper layers, homogeneous to root-structured at the surface and laminated at depth; consists of silt-sized to clay-sized diatom tests and particles (and sponge spicules)	accumulation of diatoms (and sponge spicules) and their fragments in wetlands of Bassendean Dunes	nil
diatomite intraclast gravel and sand	light grey, rounded fine gravel- to sand-sized clasts of diatomite	drying/cracking, fragmentation, and reworking of diatomite along margins of wetlands	nil

Table 1 (cont.)

Sediment type	Description[1]	Origin	Potential flammability[2]
kaolinitic mud[4]	white, orange, dark brown, dark grey to black, homogeneous to root-structured, mostly mud-sized particles with scattered sand; kaolinitic mud is mainly kaolinite, but locally some montmorillonite and sericite; diatoms, sponge spicules and phytoliths are also present	fluvial or aeolian input into wetland, or translocated by groundwater movement in wetlands of Bassendean Dunes and Pinjarra Plain derives from wetland margins	nil
quartz sand[5]	white, light grey to dark grey sand, homogeneous to bioturbated to root-structured; locally with wispy lamination, or with vesicular structure; quartz, with minor feldspar	in wetlands of Bassendean Dunes and Spearwood Dunes	nil
quartzo-calcareous sand	white, light grey to dark grey sand, homogeneous to bioturbated to root-structured; consists of quartz, carbonate grains	derives from the wetland margins in wetlands of Quindalup Dunes	nil
quartz silt	cream to light grey, and structurally homogeneous to root-structured, silt-sized and some clay-sized silica particles, with scattered quartz sand; diatoms, sponge spicules and phytoliths are also present	derives from fluvial groundwater, and aeolian input into wetlands of Bassendean Dunes and Pinjarra Plain	nil
calcilutaceous muddy sand	quartz sand as above, but with interstitial carbonate mud	carbonate mud mixed into sand at margins or at base of wetland	nil
diatomaceous muddy sand	quartz sand as above, but with interstitial diatom mud	diatom mud mixed into sand at margins or at base of wetland	nil
kaolinitic muddy sand	quartz sand as above, but with interstitial mud-sized phyllosilicate mineral particles and quartz silt	mud-sized phyllosilicate mineral particles mixed into sand at margins or at base of wetland	nil
stromatolitic boundstone[6]	laminated, clotted, cemented columns and ellipsoids of cryptalgal (or microbialite[6] of Burne & Moore 1987) deposits composed of skeletal, pelletal and intraclast grainstone	trapping/binding of particles by algae and other biota, and inorganic to biomediated carbonate precipitation in some wetlands in the Quindalup Dunes under saline conditions	nil

[1] there also are a range of diagenetic products that form in wetland sediments (Semeniuk & Semeniuk 2004); these include carbonate cements and nodules, micro-etched surfaces (indicating dissolution) on biogenic silica, the bio-mediated precipitates of FeS_2 as framboidal pyrite, the sulphides of heavy metals and metalloids; these diagenetic products are not described in detail here.

[2] the assessment of potential flammability relates to whether or not sediments have been enriched enough in organic matter; clearly, the minerals calcite (the main constituent of calcilutite), biogenic silica, kaolinite, and quartz are not combustible (hence "nil" flammability); where the sediment has been humified or "organic matter enriched", the potential flammability is assessed as possible but "negligible"; assessment of flammability of the sediments in this Table also is based on the empirical evidence presented in Figure 4.

[3] though the field evidence suggests that calcilutaceous peat is not flammable, the data are limited, hence the sediment is assessed here as low to nil flammability to cover the possibility that some calcilutaceous peat, with coarse silt-sized carbonate particles rather than clay-sized or fine silt-sized carbonate particles, and with high content of organic matter, under an intense fire will combust.

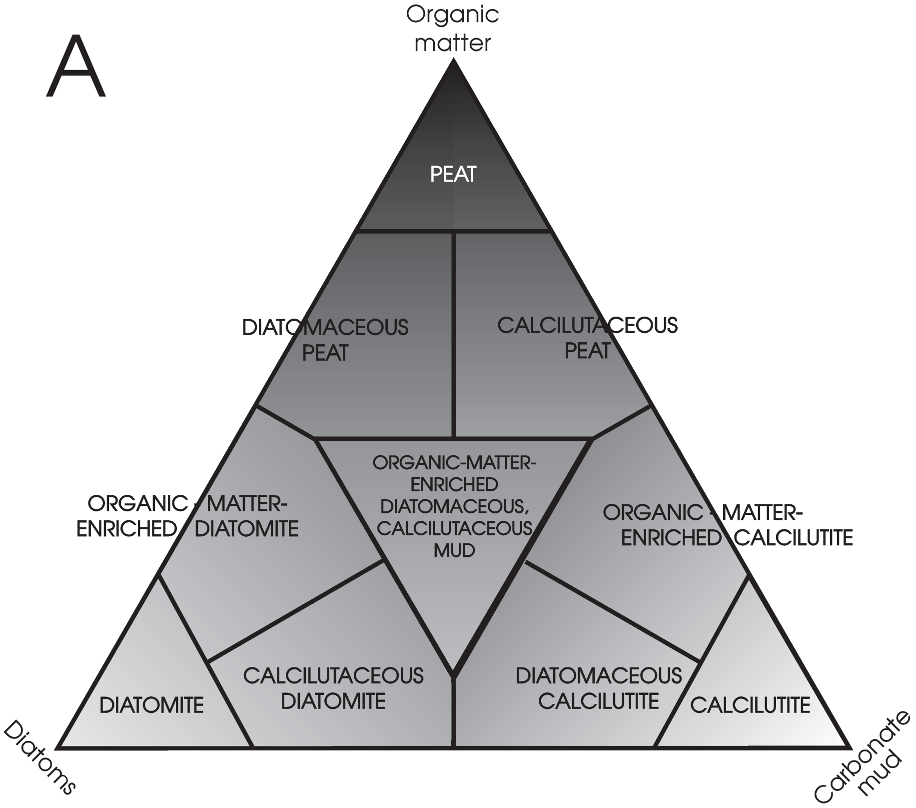
[4] the sediments formed as mixtures between kaolinitic mud and the biogenic muds of peat, diatomite, and calcilutite (Semeniuk & Semeniuk 2004) are not common sediments (the most common of this suite being organic matter-enriched kaolinitic mud, diatomaceous kaolinitic mud, and organic matter-enriched diatomaceous kaolinitic mud).

[5] quartz sand in this context is not the parent "basement" sand, but extrabasinal, transported *into* the wetland basin.

[6] the term "stromatolitic boundstone" is after Dunham (1962); "microbialite" is the term coined by Burne & Moore (1987) for a range of cemented emergent organo-sedimentary structures that include stromatolitic algal boundstone.

matter, diatoms and carbonate mud is provided by Semeniuk & Semeniuk (2004). As mentioned earlier, samples of surface sediments from 47 wetlands that had experienced fire had been analysed as to their particle composition as part of a regional study (Semeniuk & Semeniuk 2004) prior to the fires, and hence these data and the observations on the responses of the wetlands to the fire could be used to explore in a preliminary manner the relation between flammability and sediment type. The data on sediment composition and the observations on the flammability of the sediments underlying these wetlands are superimposed on the ternary classification diagram (Fig. 4B). The data provided insight into which sediment types were flammable, and with sampling after the fire event, what changes had been effected by the fire.

While organic-matter-enriched sediments clearly are flammable, the presence of $CaCO_3$ appears to raise the threshold at which flammability will occur. That is, while diatomaceous peat with content of organic matter > 60–65% is flammable, calcilutaceous peat needs to have organic matter > 75–80% to be flammable. $CaCO_3$ is



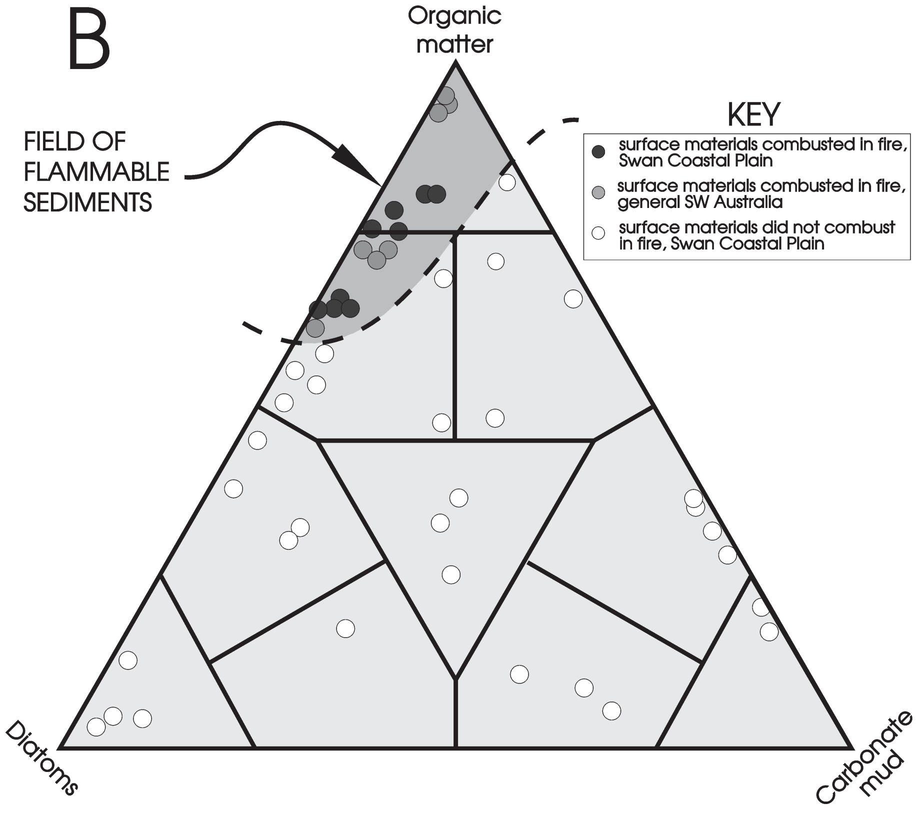


Figure 4. A. Ternary diagram illustrating the categories and nomenclature proposed by Semeniuk & Semeniuk (2004) for fine-grained sediment types that occur as end-members or as mixtures involving organic matter, diatoms, and carbonate mud. B. Superimposed on this ternary diagram are the data on sediment composition of the 47 wetlands that had been involved in bushfires, observations as to whether the sediments had combusted when they were dry at the end of summer, and the tentative boundary between flammable and non-flammable substrates.

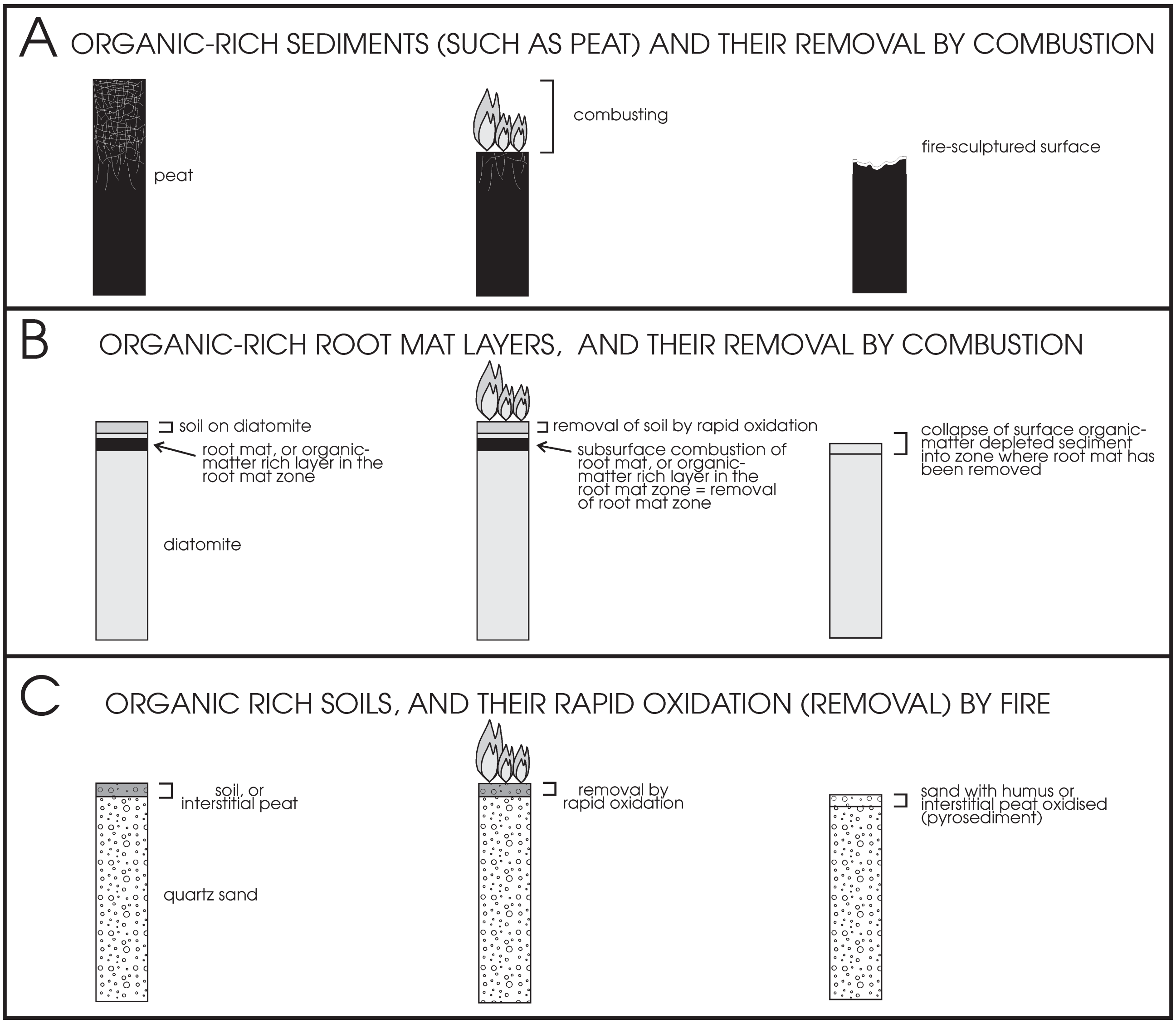


Figure 5. Three stratigraphic profiles that respond differently in their surface, near-surface, and shallow subsurface materials to fire. A. Peat, wholly flammable in its profile down to the zone of capillary rise. B. Subsurface or near-surface root mat zone with flammable root mat or flammable organic-rich layer. C. Humic soil (organic matter enriched quartz sand), not flammable but loses its organic matter through rapid oxidation during a fire.

known to be a fire retardant (Kroschwitz & Howe-Grant 1992), and the information in Figure 4B indicates that it also plays this role as fine-grained particles in organic-matter-rich sediments. The transformation of $CaCO_3$ into CaO and CO_2, is endothermic, and it would appear that fine-grained $CaCO_3$ in organic-rich sediments absorbs heat from any exothermic reactions triggered by fire, essentially arresting combustion (though not necessarily rapid oxidation) of the organic matter. Release of CO_2 by the chemical breakdown of $CaCO_3$, effectively smothering particle ignition, also may be occurring at fine particle scale, *i.e.*, particle-scale heterogeneity in calorific value of organic material, may result in temperatures sufficient to promote very local micron-scale breakdown of $CaCO_3$ to CaO.

Data on the organic matter content of root mat and organic-matter-enriched layers associated with root mats in three diatomite filled damplands and in one calcilutite-filled sumpland, and data on organic-matter-enriched soils developed on quartz sand underlying four damplands, were obtained prior to bushfires occurring in these wetlands. The root mats and the organic-matter-enriched layers associated with root mats were 5–10 cm thick, containing 22–90% organic matter. The soils generally are up to 10 cm thick, containing 2–3% organic matter. The root mat zones and the soils were resampled after the fires to determine the change in content of organic matter (if any). For two of the fires (in wetland A and wetland C in Melaleuca Park), the root mats were still smouldering in the subsurface several days after the main blaze had self-extinguished. After a fire, the content of organic matter in root mat zones was markedly reduced (Table 2). Also, with the removal of the organic matter, the fire significantly altered the substrate microtopography of root mat zones, *e.g.*, causing excavation of the surface, and/or collapse of the overlying layers into the zone where there had been removal of the flammable material or the material that had been rapidly

Table 2

Comparison between pre-fire and post-fire content of organic matter in root mats within diatomites, calcilutites, and in soils developed on quartz sand in damplands of the Bassendean Dunes

Occurrence of organic matter rich material	% organic matter in root mat or in soil prior to fire	% organic matter in root mat or in soil after fire
root mat zone in diatomite filled dampland A, Melaleuca Park	90.4 + 5.6	4.4 + 0.2
root mat zone in diatomite filled dampland B, Melaleuca Park	22.2 + 4.2	2.8 + 1.3
root mat zone in diatomite filled dampland C, Melaleuca Park	81.4	3.4 + 3.3
root mat zone in calcilutite-filled sumpland 163, Becher Point area	28.1 + 24.4	5.9 + 3.6
soil on sand-floored dampland (Gnangara wetland A)	29.6	7.0 + 3.1
soil on sand-floored dampland (Gnangara wetland B)	3.4 + 0.3	1.5 + 0.6
soil on sand-floored dampland (Gnangara wetland C)	1.6 + 0.4	1.6 + 0.1
soil on sand-floored dampland (Gnangara wetland D)	2.3	1.3 + 0.6

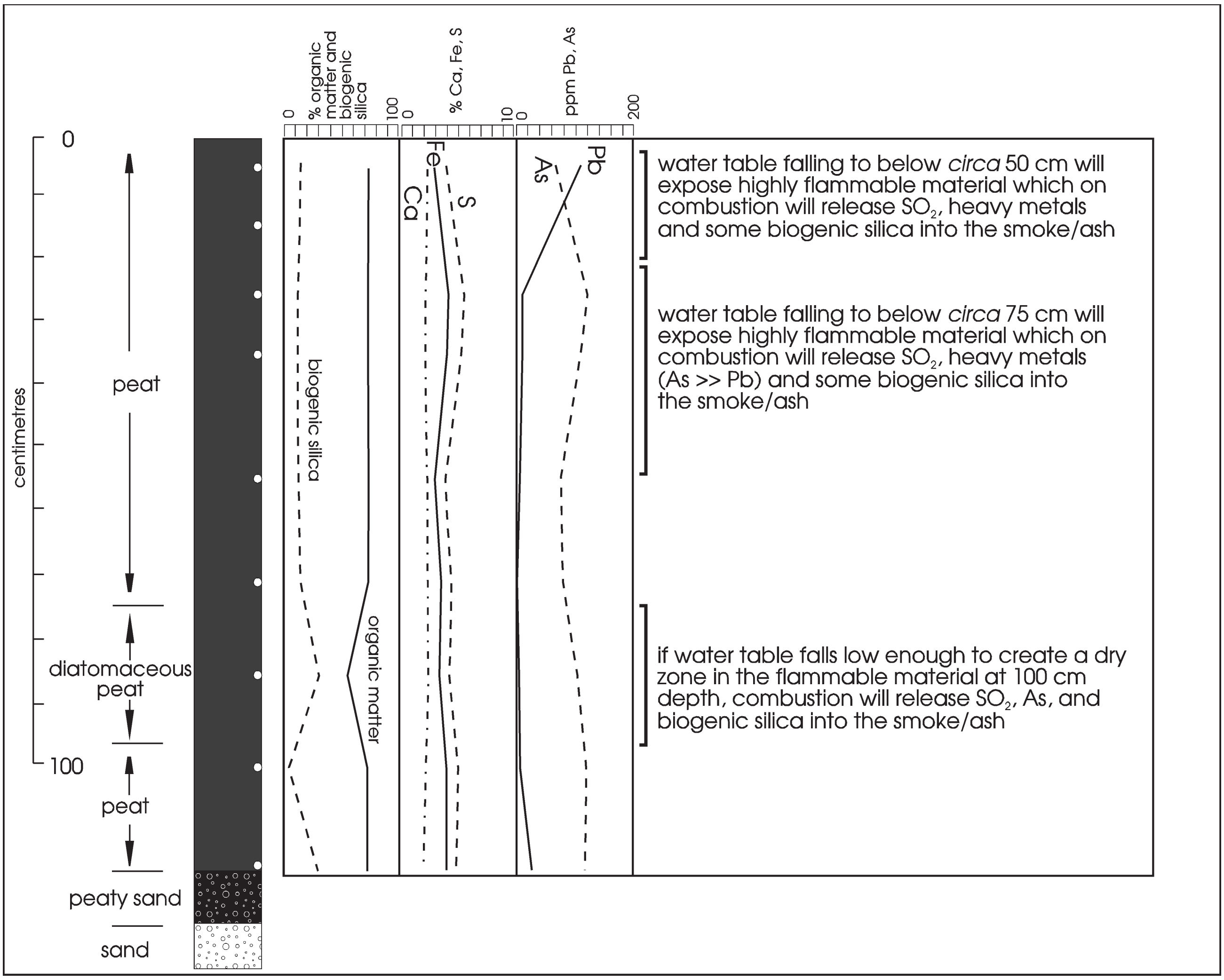
oxidised. For the soils developed on quartz sand, while fire did not alter substrate microtopography, the organic matter content of the soils was significantly reduced in three of the four wetlands (Table 2).

The information and discussion above is not meant to imply that the response of wetland sediments and soils to fires is simple. It is complex, and dependent on a range of factors. These include: the level of the water table in the wetland at the time of the fire, the extent of the capillary rise in relation to sediment type and its effect in moistening the surface materials, the type of vegetation inhabiting the wetland influencing the calorific value of the initial fuel (*e.g.*, fuel-rich and dense shrub and tall sedges *versus* fuel-poor herblands like *Centella asiatica* or low cover such as *Baumea juncea*), the recent fire history of the vegetation (*e.g.*, extent of dry fuel development on the wetland floor, and post-fire vegetation recovery and its physiognomy which also influences the calorific value of the fuel), the dryness of the vegetation in relation to season and to water stress, the biochemical nature of the organic-matter-rich wetland substrate, and the mineral nature of the sedimentary and diagenetic particles residing with the organic mater in the substrates. Nevertheless, Figure 4B and data for wetlands A and C in Melaleuca Park in Table 2 provide empirical information on materials that are flammable, and hence provide an indication of the composition of wetland materials that are likely to combust under dry conditions. In this context, it is the peat and diatomaceous peat that are flammable sediments, and root mat zones that are flammable soils.

Pyrosediments, formed as *residues* after combustion of diatomaceous peat, organic matter enriched calcilutite, peaty sand, or tree trunks with termite structures (see later) commonly are texturally and compositionally similar to the lithologically equivalent primary sediment described above, *viz.*, diatomite, calcilutite, and quartz sand. Some pyrosediments are new products of combustion, *e.g.*, fine-grained calcite crusts, anhydrite, alkaline metal carbonates, sulphates, and chlorides, goethite, and haematite. Pyrosediments also may manifest specific colouration, surfaces, structures, or geometry developed as a result of fire, *e.g.*, orange to red staining due to fire-induced oxidation of iron sulphides, fire-sculptured (irregular to scalloped) surfaces, heat-indurated surfaces, deep cracks (to be filled by later sediments, such as mud, or intraclast breccia), *in situ* breccioid structures, and millimetre-scale lensoid structures resembling flaser layering (Semeniuk & Semeniuk 2004).

The diverse sediments and soils that comprise wetland basin fills on the Swan Coastal Plain are composed of various autochthonous biogenic sedimentary (*i.e.*, formed within the wetland basin), allochthonous sedimentary (*i.e.*, delivered to the wetland basin from external sources), and diagenetic components. These sedimentary and diagenetic components respond to combustion in a number of ways. In the first instance, they may provide the basic fuel that drives the fires. In the second instance, they hold a reservoir of particle types (as biochemicals, plant matter, biogenic particles, and various mineral species) that upon combustion or intense heat release various elements and compounds into the environment: (1) as chemically transformed material remaining *in situ*; (2) as ash; and (3) as smoke and gases. These components are: organic matter, biogenic silica (diatoms, phytoliths, sponge spicules), quartz silt, metal and metalloid sulphides (*e.g.*, pyrite, arsenopyrite), and carbonates (calcite, Mg-calcite, and aragonite).

A core from a peat wetland on the Swan Coastal Plain is shown in Figure 6, illustrating the lithologic sequence, the content of selected elements (Ca, Fe, S, Pb, As, and S),



water table falling to below *circa* 50 cm will expose highly flammable material which on combustion will release SO_2, heavy metals and some biogenic silica into the smoke/ash

water table falling to below *circa* 75 cm will expose highly flammable material which on combustion will release SO_2, heavy metals (As >> Pb) and some biogenic silica into the smoke/ash

if water table falls low enough to create a dry zone in the flammable material at 100 cm depth, combustion will release SO_2, As, and biogenic silica into the smoke/ash

Figure 6. Annotated core from a peat wetland on the Swan Coastal Plain showing lithologic sequence, content of organic matter, % of biogenic silica, % Ca, Fe, and S, content of Pb and As in ppm, and pyrogenic implications of the geochemical and biochemical layering of the stratigraphy. The core represents continuous sampling and small circles on the stratigraphic column represent locations where samples were obtained for chemical analyses.

the percentage of organic matter and biogenic silica, and the implications of the geochemical and biochemical layering of the sediment in relation to pyrogenesis. The mineral content of peat determined by XRD is illustrated in Figure 7A & 7B, showing that in these particular peats biogenic silica, quartz, pyrite and arsenopyrite are the main mineral components – these will be the minerals that will be transformed by combustion (Table 3). In other peats, calcite and Mg-calcite may form minor additional mineral components.

Combustion of wood and sedges generates calcite ($CaCO_3$), anhydrite ($CaSO_4$), halite (NaCl), sylvite (KCl), syngenite ($K_2Ca(SO_4)_2.H_2O$), and other salts of the alkaline metals. After a fire, these minerals remain in the ash on the wetland floor, as a thin layer, or ribbons, or lenses, the latter two mirroring the local array of woody trunks, woody branches, multi-stemmed shrubs, or sedge tussocks (Fig. 8). Combustion of peat and root mats similarly generates calcite, anhydrite, halite, sylvite, and in addition, with the oxidation of metal/metalloid sulphides, depending on the temperature, goethite and haematite. Mineral components of plant- and peat-derived ash are mobilised later by meteoric or groundwaters (*viz*., halite, sylvite), or by wind (as dust), or remain as pyrosediment residues (*viz*., calcite) contributing to the stratigraphic accumulation (Semeniuk & Semeniuk 2005a).

Laboratory combustion of various sediment types (*e.g*., peat *sensu stricto*, and diatomaceous peat), and TEM and EDS analyses of smoke deriving from these materials indicate that different types of mineral species within smoke are generated from different types of sediments (Fig. 9). Specifically, Figure 9 shows that mineral components within the wetland sediment (such as biogenic silica) *are* mobilised into the smoke, that compounds generated by combustion from plant material and organic matter are also mobilised into the smoke (*e.g*., $CaSO_4$, NaCl, and silicates, amongst others), and that smoke can be source-specific, (*i.e*., biogenic-silica-rich peat will generate silica-bearing smoke).

Some of the morphological, mineralogic and textural changes effected on biogenic silica by experimental combustion are shown in Figures 7C, 7D and 10. Heating diatomite or sponge spicules in a combustion oven for 1

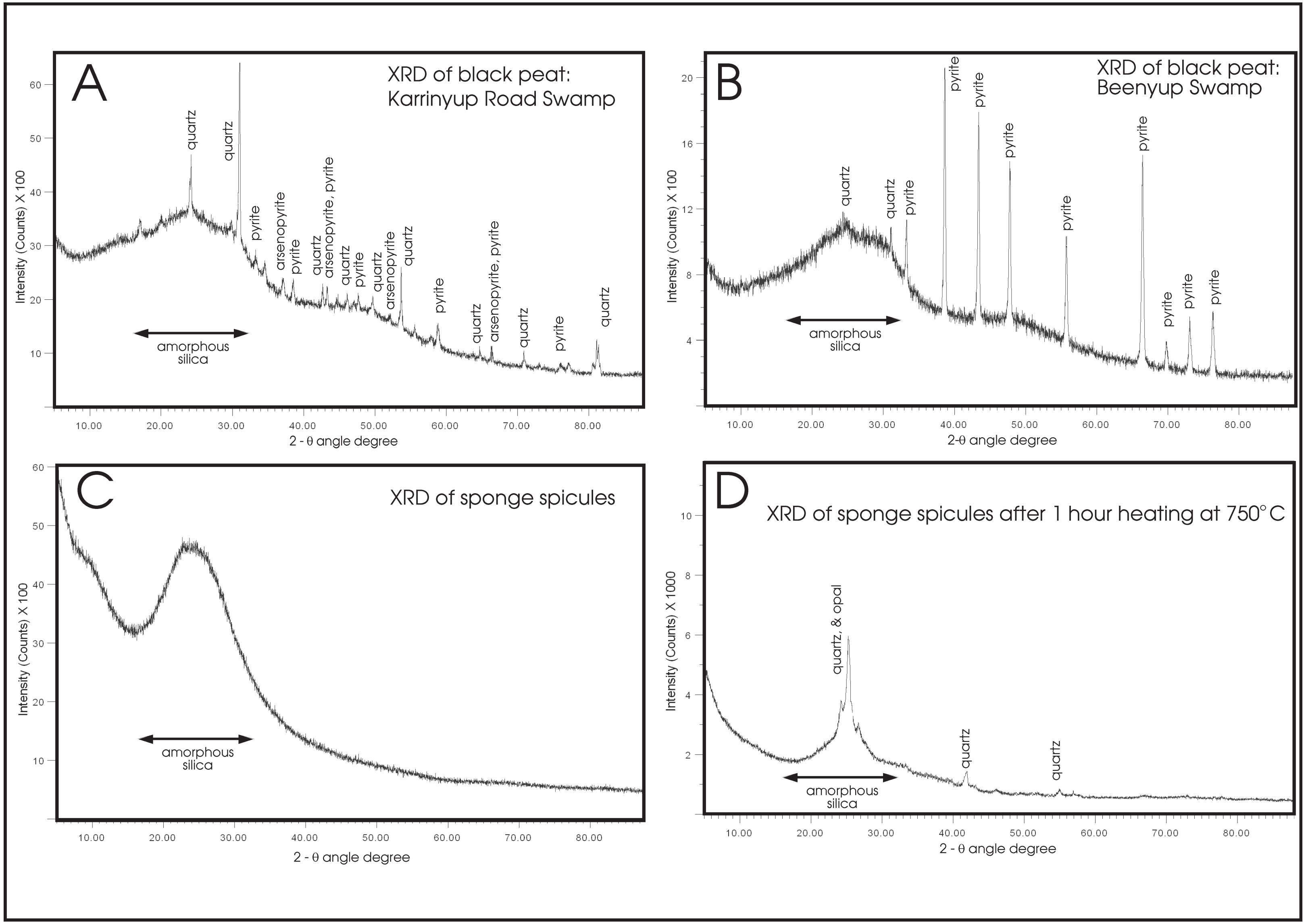


Figure 7. A–D. X-ray diffractometry of peat and sponge samples using Co Ka radiation. A & B. Occurrence of pyrite and arsenopyrites in peat. A. Black peat from Karrinyup Road Swamp showing biogenic amorphous silica, quartz silt, pyrite, and arsenopyrite. B. Black peat from Beenyup Swamp showing biogenic amorphous silica, pyrite, and minor amount of quartz silt. C & D. Crystalline silica developing from biogenic silica (note scale difference in y-axis between C & D). C. Diffractometry for spicules collected from a living sponge. D. Crystallisation of silica in the spicules from the same sponge as above after heating at 750° C for 1 hour.

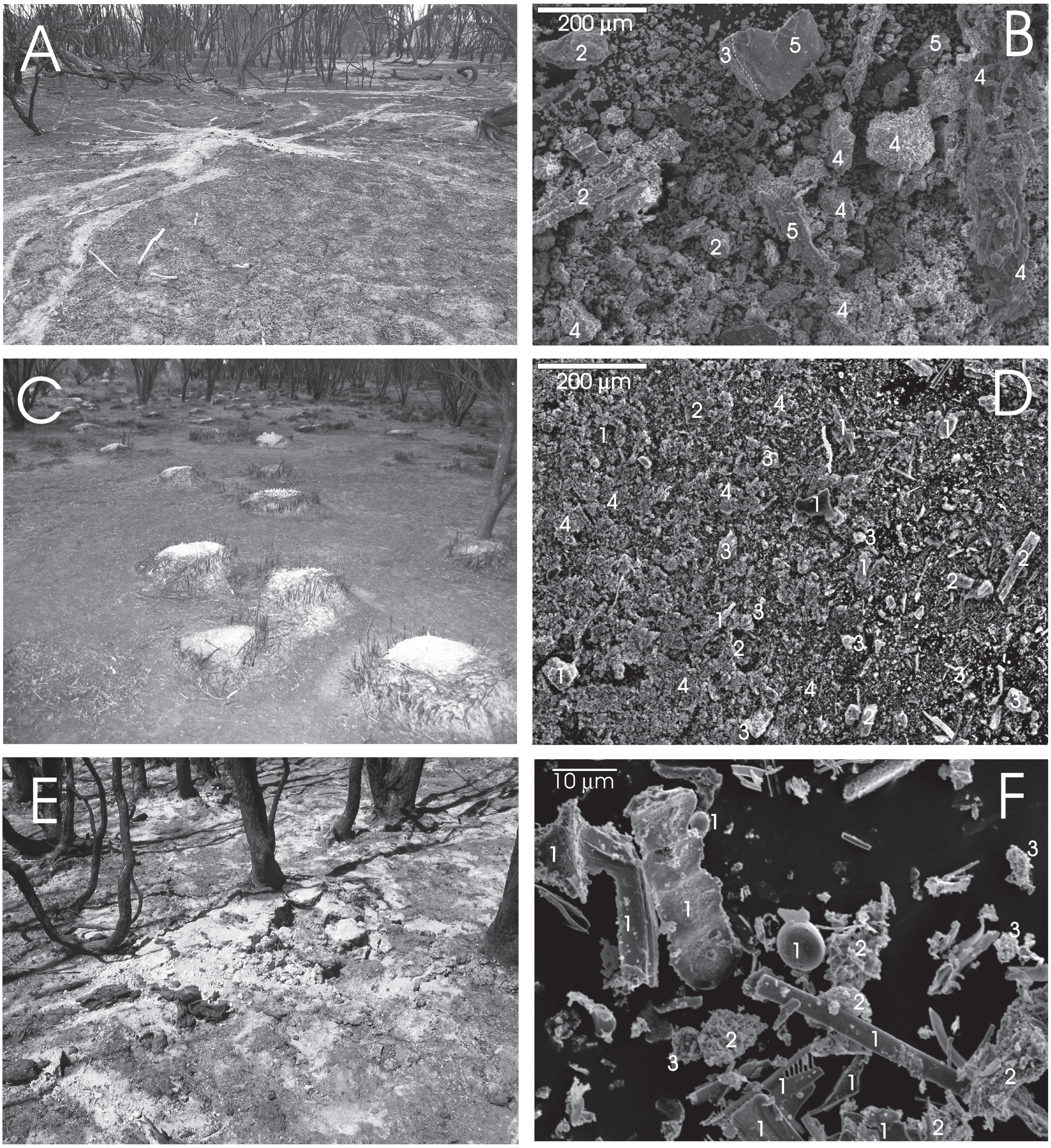


Figure 8. A–D Field and compositional aspects of ash. A. Ribbons of ash (composed of calcite, anhydrite, and other alkaline metal salts, as determined by XRD), *c* 2 mm thick, deriving from the combustion of wood, and mirroring the array of woody branches and trunks along the vegetated periphery of a wetland. B. SEM photomicrograph of the ash in (A) showing the fine grained material and aggregates; composition of particles determined by EDS, as annotated on the photomicrograph, are: 1. silica; 2. NaCl; 3. dominantly $CaSO_4$; 4. mixed $CaSO_4$, $CaCO_3$, NaCl and SiO_2; 5. dominantly NaCl, with $MgSO_4$ and $CaCO_3$. C. Lenses of ash (composed of phytoliths, calcite, anhydrite, and other alkaline metal salts, as determined by XRD), *c* 10 cm thick, left as residuals at the base of combusted tussocks of sedges. D. SEM photomicrograph of the ash in (C) showing the fine grained material and aggregates; the elongate particles are phytoliths, or phytoliths with adhering salts; composition of particles determined by EDS, as annotated on the photomicrograph, are: 1. biogenic silica (phytolith); 2: biogenic silica (phytolith), with adhering NaCl, KCl, $CaSO_4$; 3. mixed $CaSO_4$, $CaCO_3$, NaCl and SiO_2; 4. mixed NaCl, KCl, $CaSO_4$, $MgSO_4$, and $CaCO_3$. E. Crusts of diatomite collapsed around the base of burnt trees where root mats have been burnt away leaving ash. F. Annotated SEM photomicrograph of the ash in (E) showing the fine grained non-flammable residual biogenic material (diatom fragments, sponge spicules, phytoliths) and aggregates of salts derived from combusted organic matter; note spherical silica melt globule (or micro-droplet) in centre of photomicrograph field; composition of particles in the ash determined by EDS, as annotated on the photomicrograph, are: 1. biogenic silica (diatom fragments, sponge spicules, phytoliths, and spherical silica globules); 2. dominantly SiO_2 (as platelets = diatom fragments) and $CaCO_3$, with minor mixed NaCl, KCl, $CaSO_4$ and $MgSO_4$; and 3. dominantly NaCl. SEM and EDS work undertaken with assistance of Rick Hughes (CSIRO).

hour and for 2 hours at 250° C, 500° C, 750° C, and 1000° C results in the partial crystallisation of the X-ray amorphous silica to crystalline silica with increasing temperature (Fig. 7C & 7D). Petrographic microscopy shows that at higher temperatures 750–1000° C, the newly developed crystalline nature of sponge spicules becomes evident along the periphery of the spicules as birefringence (*i.e.,* optical anisotropy; Kerr 1959). This type of heating also results in the partial melting and change of morphology of the spicules, in their progressive fragmentation, and in the production of silica globules and micro-droplets (Fig. 10).

A brief description of the potential response of the various autochthonous sedimentary, allochthonous sedimentary, and diagenetic constituents of wetland sediments to combustion, based on the literature, field observations, and our laboratory combustion experiments, is presented in Table 3 below. Details of the various experimental procedures carried out in the laboratory and sampling following fires in wetlands in the field are provided in Semeniuk & Semeniuk (2005a).

Wetland stratigraphy

The term "wetland stratigraphy" refers to the sequence of sediments and soils that underlie wetlands, which on the Swan Coastal Plain are basins, channels or flats. The study of wetland stratigraphy involves investigation of sediment layering, the sequence of sediment types, the relationship of sediment fill to the base and margins of the wetlands, and the changes in sediment types (as facies) across a wetland. On the Swan Coastal Plain, the various types of sediments in wetlands described earlier may form stratal sequences composed entirely of the one sediment type, homogeneous mixtures of these sediment types, interlayered sequences of the sediments, or texture-mottled mixtures of the sediments. The mesoscale interlayering of various sediments within the wetland sequences (*i.e.,* interlayering in 50 cm or 100 cm units) is related to: 1. changes in climate through the Holocene, driving sedimentation, for example, from diatomite-dominated to peat-dominated, or calcilutite-dominated to sand-dominated; and 2. evolution of wetland hydrochemistry, driving sedimentation, for example, from calcilutite-dominated to peat-dominated (Semeniuk 2005), or diatomite-dominated to peat-dominated.

For basins, sediment fill in wetlands within the Swan Coastal Plain, as measured in the basin centre, varies in thickness from 0.1 m to 7 m (Semeniuk & Semeniuk 2005b), though most wetland sedimentary fill is 1–1.5 m thick. For peats, it ranges from 0.3 m to 7 m. For deposits of calcilutite, it ranges from 0.2 m to 5 m. For diatomites, the thickness ranges from 0.1 to 3 m. For kaolinitic mud deposits, the thickness ranges from 0.1 m to 1.5 m. The base of wetland fills tends to be gradational into the underlying Pleistocene materials, *e.g.,* peat, diatomite, or calcilutite overlying "basement" sand have a gradational zone of infiltrated or bioturbated wetland sediment resulting in development of peaty sand, diatomaceous sand and calcilutaceous sand, respectively (Fig. 11A). The margins of the wetland fills also may have an interfingering relationship with reworked deposits of the

Table 3

Response of the various autochthonous sedimentary, allochthonous sedimentary, and diagenetic constituents of wetland sediments to combustion.

Sedimentary and diagenetic particle types	**Response to combustion**
organic matter (fine-grained, as well as leaves, twigs, branches) and dry plant material	conversion mainly to CO_2, and various other complex hydrocarbon gases, SO_2 and NO_2; generation of smoke composed of varying carbonaceous particulate material; release of K, Na, Ca, and Mg, and their transformation into alkaline metal carbonates, sulphates, and chlorides, which may be mobilised into the smoke or may remain residual as ash; release of nutrients from the plant detritus
biogenic silica (*i.e.*, diatoms, phytoliths and sponge spicules, as micromorphologically diagnostic, X-ray amorphous silica)	when temperatures are high enough, fine-grained particles may be converted (in part) to crystalline silica, or may partially melt, developing deformed shapes, beaded tips, and melt micro-droplets; sponge spicules and diatoms fracture and fragment into finer particles; both fine-grained biogenic silica and any fire-generated crystalline silica, as well as melt micro-droplets may be mobilised into the smoke plume, and that which remains as ash may later be mobilised by wind
quartz silt	inert to combustion, but able to be mobilised into the smoke plume
metal and metalloid sulphides	oxidation of metal and metalloid sulphides to oxides (*e.g.*, pyrite to goethite and haematite), and SO_2, and their mobilisation into the smoke plume, or remaining as residua in the ash; the metal/metalloid oxide residues remaining in the wetland deposits later may be mobilised by wind or by meteoric and ground waters
calcite, Mg-calcite, aragonite	combustion temperatures usually not high enough to progress the wholesale transformation of $CaCO_3$ to CaO, but fine-grained carbonate grains can be mobilised into the smoke

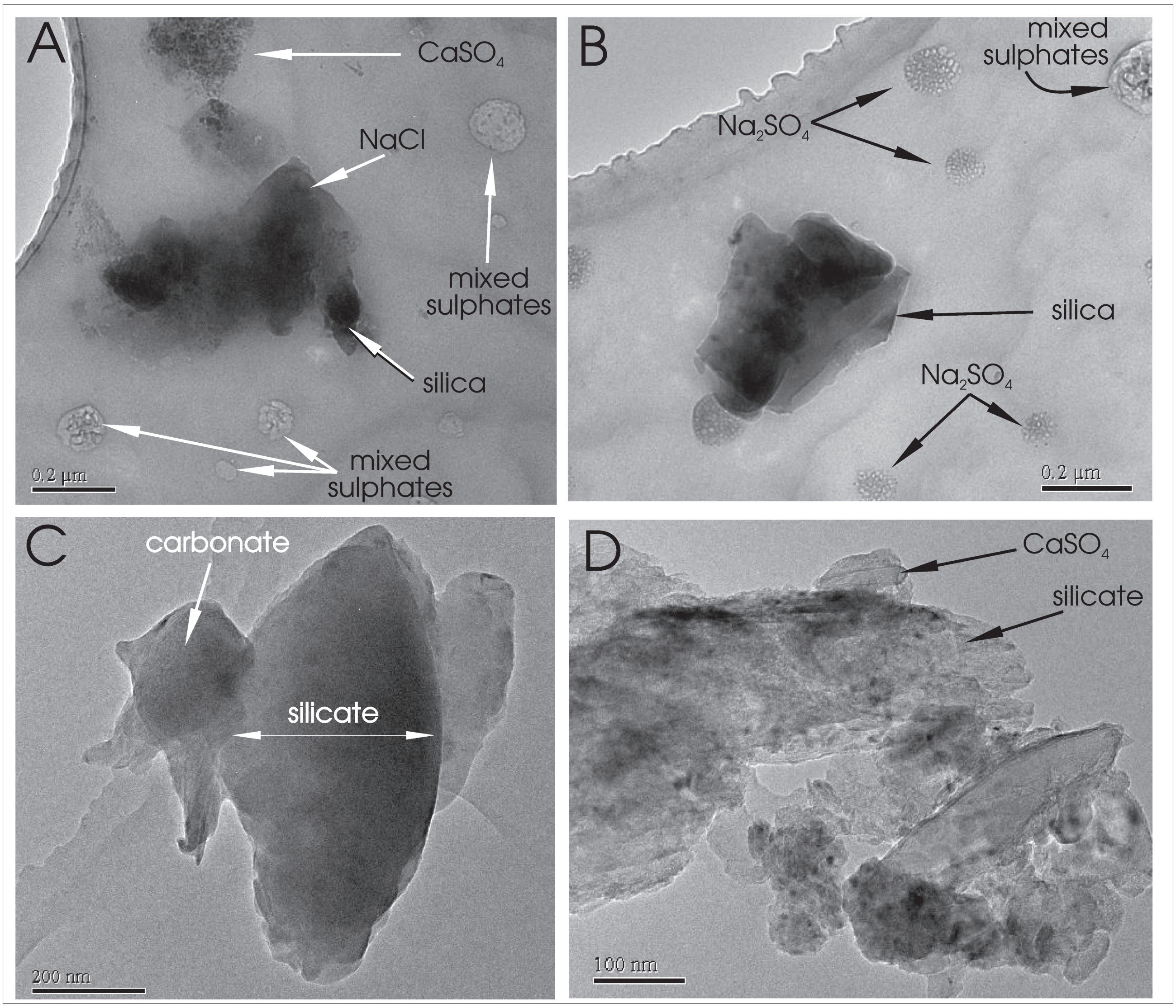


Figure 9. Images from transmission electronic microscopy (TEM) of smoke from a diatomaceous peat and from a peat, both experimentally combusted at 550° C. Collection grid was held above the burning material in the smoke of each for 20 sec to collect the samples. Images were taken by T A Semeniuk at ETH Zurich using bright field modes with a Phillips CM30 operated at 200 kv. Bright field images were supplemented by EDS to determine elemental composition. Mineral and particle phases are annotated to illustrate differences in smoke composition. A & B are from diatomaceous peat. C & D are from peat *sensu stricto*.

surrounding Pleistocene sediments (Fig. 11B). Thus, peat, diatomite, or calcilutite of central wetland basins may grade *via* peaty sand, diatomaceous sand, and calcilutaceous sand into the quartz sand of the Pleistocene margins, or sheets and tongues of quartz sand reworked from the margins may penetrate to a limited distance into the layers of the wetland fills.

Other factors contributing to wetland fill and variation in wetland stratigraphy include coastal aeolian influx (either as grainfall deposits *via* suspension in the air, or as grainflow deposits from migrating dunes), and fire, where interlayered peat and other sediment types are reduced to peat-free layers. In addition, through the process of groundwater fluctuations, wetland-fill and host materials in wetlands may be overprinted by bleaching and by development of ferricrete (Semeniuk & Semeniuk 2004).

Thirteen standard sequences are recognised in the sedimentary fill of wetlands by Semeniuk & Semeniuk (2005b) in the central Swan Coastal Plain in Bassendean Dunes and Spearwood Dunes and Pinjarra Plain; and two additional sequences are recognised in the Quindalup Dunes by Semeniuk (2005), giving a total of fifteen standard sequences. These standard sequences, with some variation in thickness of units therein, recur throughout the wetlands of the Swan Coastal Plain. The standard sequences and type locations (where best developed) are listed in Table 4.

In addition, there are wetlands, particularly damplands set in the Bassendean Dunes, that do not have sedimentary fill, but rather have humic soils or organic matter enriched soils developed on a seasonally-waterlogged "basement" of Bassendean Sand.

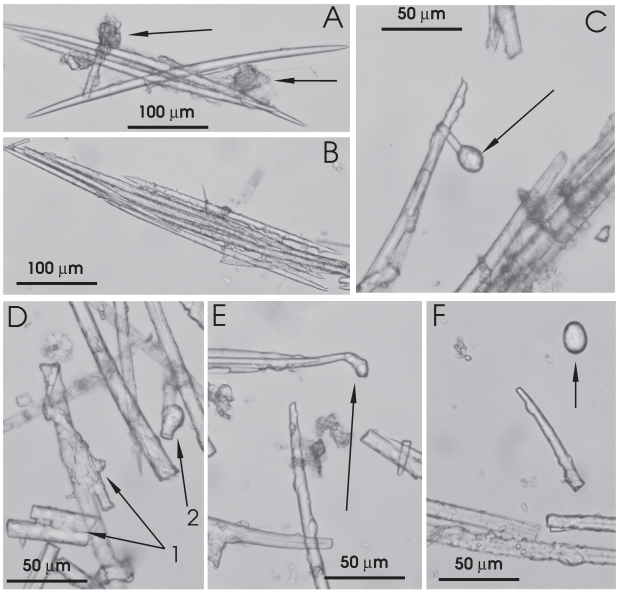


Figure 10 A–F. Photomicrographs of sponge spicules. A & B. Spicules from a living sponge showing smooth to slightly spiny external form of the spicules, the unfragmented (entire) nature of the spicules, and their distinct sharp tips; material connecting the spicules (arrowed) is dried sponge organic matter. C–F. Changes in the morphology of spicules after heating for 1 hour at 750° C. C. Normally sharp tip of spicule transformed by partial melting to form a globule (arrowed). D. Several spicules have fused through partial melting (arrow 1), a tip has melted to form a globule (arrowed 2), and there is a predominance of spicule fragments. E. Normally sharp tip of spicule distorted through partial melting (arrow). F. Spicules are predominantly fragmented, and a solidified micro-droplet of silica (arrow) is now isolated from the spicules.

Geographic distribution of stratigraphic types in wetlands

Knowledge of the distribution of the various types of wetland sediments and soils is a powerful tool in fire management because it allows for focus on critical areas where there is high potential for flammable sediments and soils to occur. On the Swan Coastal Plain, there is a pattern to the distribution of wetland sediments and soils and stratigraphic types geographically from east to west and from south to north. The east to west distribution is related to consanguineous suites (as related to geomorphic setting), and the south-north distribution is related to climate.

The stratigraphy of the wetland fills varies according to geomorphic and geologic setting, climate, and host water chemistry. The various consanguineous wetland suites, for example, reside in different geomorphic and geologic settings each with its own basement materials of white quartz sand, yellow quartz sand, limestone, quartzo-calcareous sand, and fluvial terrigenous sediments. In each setting, groundwater and surface water maintenance of the wetlands may vary, and hydrochemistry also will be affected by water source and geologic setting (*e.g.*, quartz sand, limestone, or quartzo-calcareous sand). Hence there occurs a variety of sedimentary fills in any east-west transect.

Channels and wetland flats (rivers, creeks, floodplains, and palusplains) associated with terrigenous sediments of river courses that occur on the Pinjarra Plain, or the Pinjarra Plain transition to Bassendean Dunes, along the eastern Swan Coastal Plain, tend to be underlain by extrabasinal sediments, such as sand and kaolinite-dominated mud and muddy sand, reflecting their delivery and sedimentation by fluvial processes, and basins within the Pinjarra Plain, or the Pinjarra Plain transition to Bassendean Dunes (*e.g.*, within the Mungala, Bennett Brook and Keysbrook Suites) are filled with peat, terrigenous muds or muddy sand.

Within the Bassendean Dunes, where the basin setting is a basement of quartz sand, the wetlands are lakes, sumplands, and damplands. The waters tend to be tannin-rich, acidic (to alkaline), and cation-poor, and the sedimentary fill is intrabasinal peat, diatomaceous peat, and diatomite (reflecting their hydrochemical setting), and extrabasinal kaolinitic mud, and quartz sand. These sediments may form sequences composed entirely of the one sediment type, or homogeneous mixtures, interlayered sequences, or texture-mottled mixtures of the sediments. Wetlands in the various consanguineous wetland suites in the Bassendean Dunes, depending on climate setting, may be peat-dominated (*e.g.*, Jandakot Suite and Riverdale Suite in southern Swan Coastal Plain areas), or peat-and-diatomite dominated (*e.g.*, Gnangara Suite and Jandakot Suite in central Swan Coastal Plain areas), or diatomite-dominated (*e.g.*, Jandakot Suite in northern Swan Coastal Plain areas).

Within Spearwood Dunes, where the basin setting is a basement of quartz sand and/or limestone, the wetlands are lakes and sumplands. The waters are more variable, ranging from tannin-rich to tannin-poor, alkaline (to acidic), and cation-enriched, and the sediment fills are intrabasinal peat, diatomaceous peat, or calcilutite, and extrabasinal quartz sand. Again, the sedimentary fills also may form sequences composed entirely of the one sediment type, or homogeneous mixtures, interlayered sequences, or texture-mottled mixtures of the sediments. Wetlands in the various consanguineous wetland suites within the Spearwood Dunes may be peat-dominated or with mixed peat-and-calcilutite (*e.g.*, Yanchep Suite), or peat-and-calcilutite dominated (*e.g.*, Stakehill Suite), or calcilutite-dominated (*e.g.*, Coogee Suite). The types of sedimentary fill in the basins reflect their hydrochemical setting in relation to local occurrence of quartz sand or limestone and their geomorphic setting in relation to reworking of quartz sand.

Within the Quindalup Dunes, where the basin setting is a basement of quartzo-calcareous sand, the wetlands are lakes, sumplands, and dampland. The groundwaters are of variable hydrochemistry, ranging from tannin-rich to tannin-poor, alkaline (to acidic), and cation-enriched, and the sedimentary fill is intrabasinal calcilutite (reflecting the hydrochemical setting), and some peat, and extrabasinal quartzo-calcareous sand. Wetlands in the various consanguineous wetland suites within the Quindalup Dunes are calcilutite-dominated (*e.g.*, Becher Suite and Cooloongup Suite), or humic sand and calcilutaceous muddy sand dominated (*e.g.*, Peelhurst Suite).

A summary of the east-west pattern of sedimentary

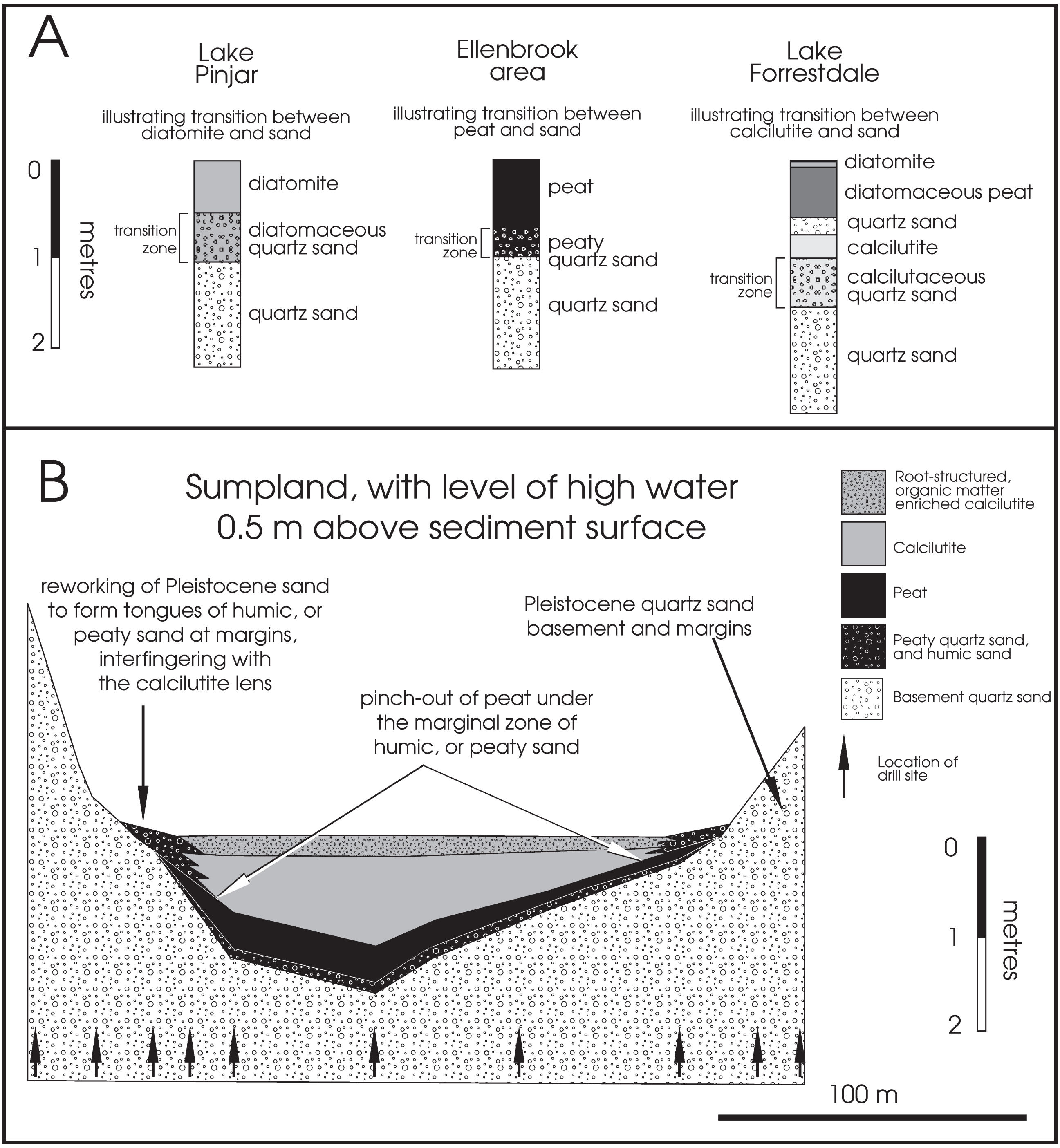


Figure 11. A. Examples from three sites showing typical transitions of fine-grained wetland sediment (diatomite, peat, and calcilutite) into underlying basement sand with the development of "muddy" sand. B. Stratigraphic profile of a sumpland (Little Carine Swamp). The basin is mainly filled by calcilutite, but with tongues of humic or peaty sand extending into the wetland from the margins. The peat at depth pinches out under the margins of the wetland, and a humic soil is developed on the calcilutite deposit.

fills in wetlands related to geomorphic settings on the Swan Coastal Plain is shown in Figure 12.

The Swan Coastal Plain, extending from Busselton to Dongara, traverses a climate from subhumid (annual rainfall *c* 1000 mm) to semi-arid (annual rainfall *c* 500 mm), with a concomitant increase in evaporation. In response to this climate gradient, from south to north, similar wetland basins change in their vegetation cover, hydrologic dynamics, hydrochemistry, and sedimentary fills. Wetlands within Bassendean Dunes provide an excellent example of climate-controlled patterns in sedimentary fill.

Throughout their longitudinal extent, the Bassendean Dunes exhibit a regionally similar template of basins and hills, inherited as desert dune landforms from the Pleistocene. The basins commonly intersect the regional

Table 4

Standard stratigraphic sequences within Swan Coastal Plain wetlands

Style of stratigraphy	Typical location[1]
Dominantly peat sequences	
thick peat	Karrinyup Road Swamp
thick peat and diatomaceous peat	Waluburnup Swamp
thin peat and diatomaceous peat	Melaleuca Park Swamp
Dominantly diatomite sequences	
thick diatomite	North Lake
thin diatomite and diatomaceous sand	Lake Pinjar
Dominantly calcilutite sequences	
thick calcilutite	Lake Manning
thin calcilutite	Cud Swamp
thin peat on thin calcilutite	Wawa Swamp
Terrigenous sequences	
kaolinitic mud	Lake Mungala
Mixed sequences	
peat, calcilutaceous peat, and diatomaceous peat	Stakehill Swamp
diatomite, calcilutite, and quartz sand	Lake Forrestdale
alternating peat and calcilutite	Leda Swamp
peat, calcilutite, quartz sand	Little Carine Swamp
peat, kaolinitic mud, quartz sand	Ellenbrook Swamp
diatomite, kaolinitic mud, quartz sand	Coonabidgee Swamp

[1] Stratigraphic types are described in Semeniuk & Semeniuk (2005b)

water table, resulting in a series of wetlands (Semeniuk 1988), and depending on the extent and depth that basins intersect the groundwater, the wetlands may be permanently inundated, seasonally inundated, or seasonally waterlogged. To the south, the basins have accumulated peat under sedges; they support mixed paperbark trees and sedges that cover the wetland. To the north, they have mostly accumulated diatomite, and support heath and paperbark trees, often confined to the basin margins. The transition from southern to northern types is gradational because of the mixed contribution of regional and local influences. It is largely the climatic setting that underpins the different vegetation associations and the different sedimentary fills across the latitudinal spread of these wetlands.

The same pattern exists for wetlands within Quindalup Dunes and Spearwood Dunes, *i.e.*, peat dominating southern areas, and calcilutite and diatomite in the north.

Water levels, water tables and climate

Management of fire-susceptible substrates is linked not only to their distribution, but also to the periods when such substrates are most susceptible to ignition and combustion. Clearly, substrates that are permanently inundated, or permanently waterlogged are not likely to ignite and combust, but an annual fluctuation of a water level or water table, however, can result in an annual drying out of potentially combustible substrates (Fig. 13). Figure 14 illustrates a range of annotated hydrographs from various wetlands on the Swan Coastal Plain showing the types of water level changes over the past decade, and their implications for substrate flammability. Further, if water levels or water tables exhibit progressively increasing annual fluctuations, or a progressive fall in mean low water level, the latter linked to a trend towards drier periods in medium and long-term climate patterns, then management of organic rich substrates will also have to address these changes.

Water levels and depth of water table are linked to annual rainfall, and variability in rainfall is related to climate variation. Notwithstanding that there is a current emphasis on correlating climate variation in southwestern Australia with the effects of mean sea level pressure and surface sea temperatures (Allan & Haylock 1993; Nicholls *et al* 1999; Smith *et al* 2000; Sadler 2002), tentatively linked by some authors to the phenomenon of El Nino – Southern Oscillation (also known as ENSO), we give emphasis to the fact that many of the natural climatic patterns of the Earth ultimately are underpinned by astronomical phenomena. The most obvious and well known is the annual progression of seasons driven by the orbit of the Earth and the tilt of the Earth's axis to the orbital plane. In the Perth region, this is expressed as the cool/cold, wet winters and the hot, dry summers. There are, of course, a range of other astronomical processes, orbits, and alignments that result in climatic expression on the Earth, and an understanding of these patterns helps to explain some climate dynamics (Fairbridge 1984), with the caveat that any astronomical effect on Earth climate may be accompanied by a time lag, so that direct correlation becomes blurred, particularly for the shorter term (decadal, or bi-decadal) cycles. Astronomical phenomena affect Earth climate through variable solar radiation, through tidal forcing of the atmosphere, by changing the heat capacity of the oceans through tidal perturbations, amongst other processes.

The main astronomical patterns that appear to be cyclic or periodic, and their relationship to the various climatic patterns, and in particular rainfall, are described in Table 5.

In regards to the effect on climate of the Lunar Nodal periodicity, there may be consensus that there is a *c* 20-year cycle in climate in relation to rainfall and drought (Currie & Fairbridge 1985; Tyson 1986; Semeniuk 1995a), which has been correlated with the 18.6-year Lunar Nodal periodicity, but some authors suggest that this climate pattern could also be related rather to the 19.9-year Saturn-Jupiter cycle, or to the 22-year double sunspot (or "Hale") cycle (*cf.* Camuffo 1999). Though proximal effects, such as Lunar tidal effects, probably have stronger influence on Earth climate than distal phenomena, we accept this caution.

While underpinned by solar radiation, the El Nino – Southern Oscillation phenomenon, with a return period of some 3–4 years, varying to 6–8 years, is not strictly periodic but is a quasi-periodic intra-planetary phenomenon.

Important features of cycles and periodicities in climate are that, firstly, they are predictable, secondly, they may affect the flammability of wetland sediments, and thirdly they may imprint on wetland sediments such that their products then provide a record that can be used to reconstruct past climates, and predict future climate

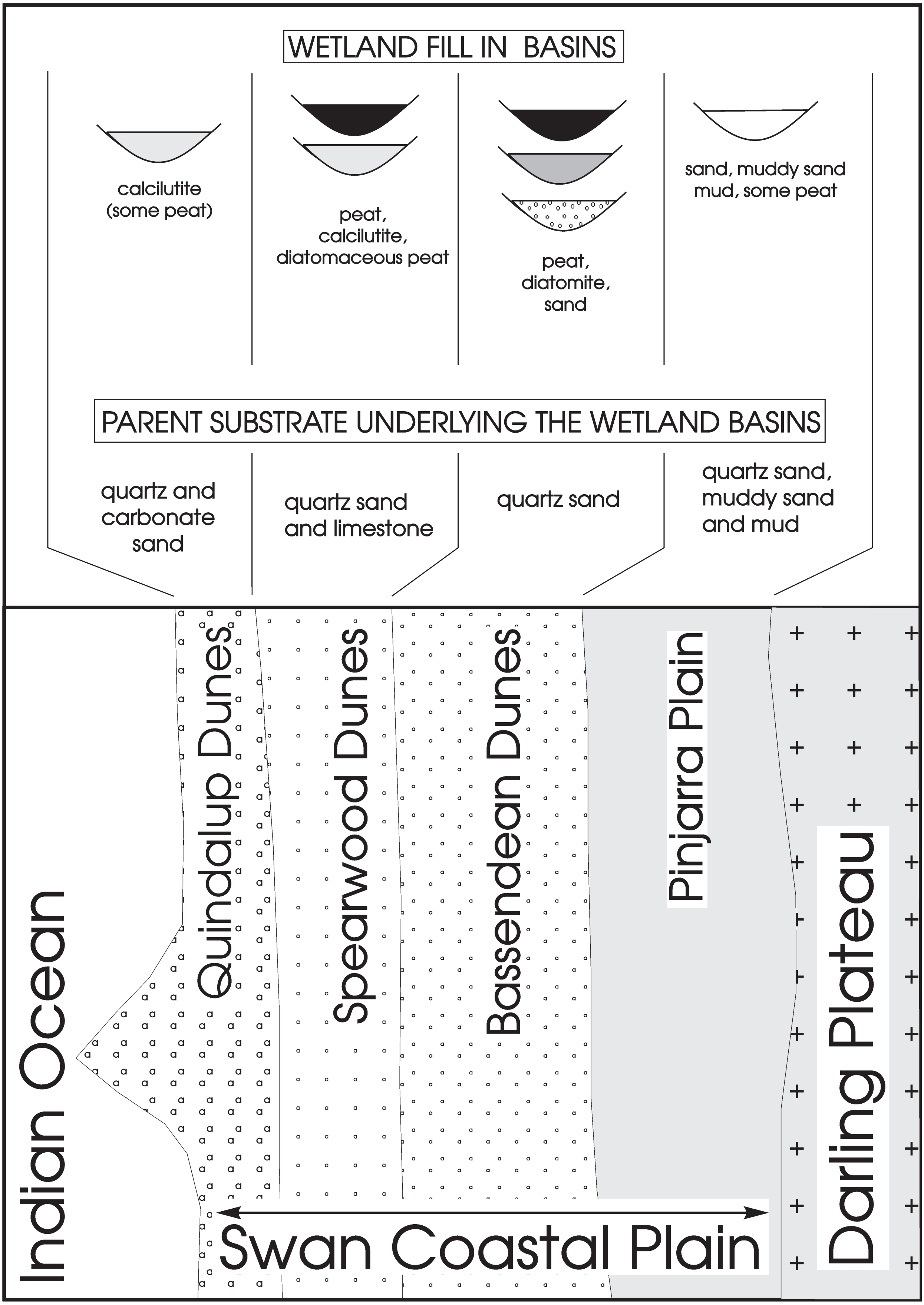


Figure 12. Idealised diagram summarising, with respect to geomorphic setting across the Swan Coastal Plain, the distribution of parent substrate types underlying wetland basins and the (simplified) wetland sediment types in basins.

trends. In these contexts, climate patterns are particularly important as tools in fire management.

While there may also be some influence from a human-induced greenhouse effect, we consider that the effects of the Lunar Nodal Periodicity (the *c* 20-year cycle), the 250-year cycle, and the Earth-axis precession on rainfall, water levels, and fluctuating water tables to be of particular interest for the management of wetlands, water levels, and the temporal occurrence of fire-susceptible substrates in that these phenomena carry with them some degree of predictability. Perth has a long-term rainfall record of *c* 120 years, and the patterns of *c* 20 year wet-and-dry intervals related to the Lunar Nodal Periodicity appear to be evident here (Semeniuk 2005) when the annual rainfall data are processed using a 10-year backward moving average (Fig.13). The effects of the 250-year cycle also may be partially evident in this record, if the relatively high rainfall period between 1920–1960 corresponds to the peak of rainfall within this cycle. Processing annual rainfall data using cumulative deviations from the mean rainfall (Yesertener 2005) shows a broadly similar pattern for the Perth rainfall record: a period of increased rainfall in the years 1920s–1970s is amplified using this procedure (*cf*. figure 2 of Yesertener 2005), and smaller amplitudes corresponding to increased and decreased rainfall on a *c* 20 year pattern are also evident. The effects of the Earth-axis precession on climate are not evident in the historic rainfall record but are partially evident in the Holocene stratigraphic record (Semeniuk 1995a) as a long-term trend towards a wetter climate.

From the perspective of the flammability of wetland sediments and soils, management of fire in wetlands should address the potential that there may be a short-term recurring pattern of drying out and wetting of wetland sediments on a *c* 20-year cycle, and a similar drying out and wetting on a longer term 250-year cycle because it is during those times of relatively dry climate phases that the greatest risk of combustion occurs. The *c* 20-year cycle of wet and dry years is a fairly regular event, and can readily explain the phases of wet years and dry years in the wetlands of the region. However, the question arises that if there is a 250-year cycle in rainfall in the southwest Australian region, where in this cycle does the current climate reside? If it is concluded that the period of maximum rainfall and elevated water levels that occurred during the 1920s–1970s coincided with the maximum rainfall within the 250-year cycle, then the trend thereafter has been towards the minimum dry phase, and it can be expected that there will be another 40–50 years of progressively drier periods, with shorter-term, superimposed lower amplitude 20-year cycles of wetter and drier phases. A summary of the patterns, and its implication to fire management is presented in Figure 13.

Anthropogenic use of water causing draw-down, drainage, waste water disposal, or silviculture such as pine plantations, can artificially affect water levels, and replicate, rival or exceed the effects of climate variability on water levels and water tables (Fig. 13). Thus, drying of wetland sediments, leading to increased risk of combustion, can be the result of water abstraction, draining, or silviculture, and is an issue that also must be addressed in fire management.

Observations and stratigraphic information on the effects of fire in wetlands

Mapping and monitoring wetlands for 30 years (Semeniuk & Semeniuk, 2005c) have provided opportunities to observe and document the effects of fire in wetlands in a number of locations on the Swan Coastal Plain in removing peat, altering lithology (*i.e.*, creating pyrosediments), creating distinctive stratigraphy, or fundamentally altering the wetland type and its vegetation associations. The information below presented from a range of wetlands exemplifies these effects. The wetlands selected are: Melaleuca Park (31° 40' 21" E, 115° 54' 15" S), Waluburnup Swamp (31° 47' 08" E, 115° 48' 14" S and 31° 47' 28" E, 115° 48' 25" S) and Beenyup Swamp (31° 47' 16" E, 115° 48' 00" S) of Yellagonga Regional Park, Bullrush Lake (31° 29' 29" E, 115° 39' 17" S), Yarkin Swamp (31° 47' 38" E, 115° 59' 43" S), and Ellenbrook (31° 45' 14" E, 115° 58' 18" S).

In the summer of 1976 in the Melaleuca Park area and during the 1980s in Beenyup Swamp, a series of fires swept through the peat-floored wetland basins. Some 20 cm of peat was removed by the combustions, similar to that described in peatlands by Horwitz *et al* (1999) in southern Western Australia, and the roots of *Melaleuca rhaphiophylla* trees within the wetlands were left standing above the sediment surface. The base of the burn-out in each case was the zone of capillary rise of the water table. This type of surface, developed by fire, often is irregular to hummocky, and is stained by oxidized iron. Such surfaces are recognisable in the stratigraphic record, and have been noted as buried surfaces in Little Carine Swamp and Lake Gwelup.

In 1985, while documenting wetland stratigraphy at Bullrush Lake, the effects of a fire that had been recently burning were observed. While there was a thin cooled crust on the surface, augering showed that there was still a furnace of burning peaty sediment for at least 30 cm in depth. During this fire, spongolitic diatomaceous peat was reduced to spongolitic diatomite (in this case, a pyrosediment) with the removal of organic matter. The iron sulphide of the peat was oxidized to iron oxide (haematite and goethite), imparting a red to orange coloration to the pyrosediment at the surface.

In May 1996, a fire swept through part of Waluburnup Swamp. While this fire consumed the vegetation, the monitoring bores emplaced by the V & C Semeniuk Research Group showed that the water table at the time was rising at the beginning of winter, and was only 10 cm below the sediment surface. The sediments were too waterlogged for combustion. Elsewhere, in this same wetland, where the water table was lower due to more rapid groundwater discharge, the fire consumed and removed the upper 5 cm of the peat profile; below this level, the peat was too waterlogged for combustion.

In 1992, fire swept through the margin of Yarkin Swamp, a peaty sumpland. The margin of this wetland was peaty sand overlying quartz sand at *c* 30 cm, and with vegetation cover of the Flooded Gum, *Eucalyptus rudis*. Termites constructed sand-structured termitaria within the trunks of the Flooded Gum, deriving the sand grains from under and within the peaty sand. Fire reduced the Flooded Gums to ashes, and the sand-structured termitaria, interior to the tree trunks, were

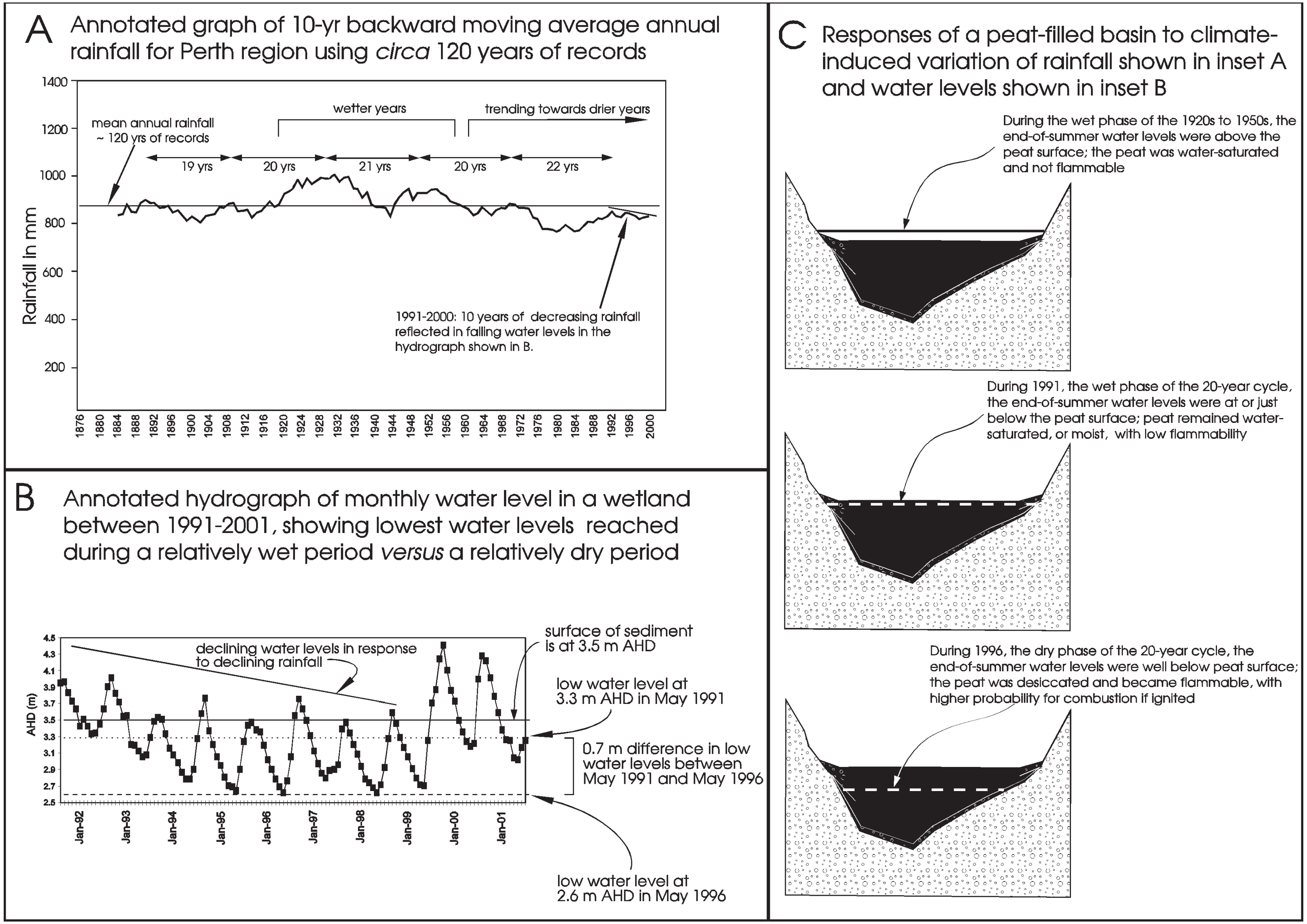


Figure 13. The relationship of climate variation (expressed in rainfall), water levels in wetlands, and potential flammability of fire-susceptible wetland sediments. A. Annotated graph showing medium term wet and dry phases, ranging from *c* 19–22 years, evident in the rainfall records of Perth over the past 120 years using the 10-year backward moving average (note that since the averaging procedure involves the previous 10 years of data, the wet and dry periods will be displaced along the time axis). B. Hydrograph showing details of 10 years of water level response to declining rainfall during the wet-to-dry transition within a "20-year" cycle, and the position of the wetland floor and water levels. C. Predicted response in regard to fire susceptibility of a peat-filled basin to the wet-and-dry climate phases depicted in inset A and B.

Table 5

Summary of astronomical cycles/periodicities and climate patterns (discussed for Western Australia by Glassford 1980 and Semeniuk 1995a)

Cycle/periodicity/pattern[1]	History and/or description	Climate effect
Milankovitch cycles (also known as the Croll-Milankovitch cycles[2])	formulated by Croll (1867a,b) and Milankovitch (1941) to explain the recurring glacial and interglacial periods, and other climatic changes, driven by variation of the Earth's orbit and rotation in terms of its eccentricity, tilt of rotational axis, and longitude of perihelion, with periods of return on a *c* 100,000 year, 41,000 year, and 23,000 year pattern; in this analysis, precession forms a component of astronomic events that drive glacial/interglacial periods	drives glacial/interglacial cycles, and hence the associated major arid to relatively humid climate changes over tens of millennia
Earth-axis precession	rotational precession of the Earth's axis, with a return period of *c* 19,000–23,000 years	drives the progressive migration of the calorific equator, and hence the gradual latitudinal shift in climate during the Holocene; for instance, will drive the long-term general increase in humidity in southwestern Australia over millennia
250-year pattern[3]	a high-frequency cycle of *c* 250-year period, empirically determined by Stocker & Mysak (1992) and Semeniuk (1995a) that at present appears to have no astronomical underpinning, though the temporally similar 245-year periodicity of Loutre *et al* (1992) has been related to Earth orbit parameters	evident in the larger beachridges at Rockingham that form every *c* 250 years (reflecting oceanic storminess and wind patterns), and for wetlands; will drive long-term wet and dry cycles in rainfall
Double-Hale cycle	solar phenomenon, where the sunspot activity varies on a 45-year cycle (Fairbridge & Hillaire-Marcel 1977)	evident in the smaller beachridges at Rockingham that form *c* every 50 years; not clearly reflected in rainfall variation
Solar sunspot 11-year cycle	solar phenomenon, where a pattern of increasing and decreasing sunspot varies on an 11-year pattern	generally, no clearly documented effect on climate, but Currie & Fairbridge (1985) link this phenomenon to cyclic 11-year induced droughts and floods
Lunar Nodal periodicity	the Lunar node rotates once every 18.6 years in the nodal cycle, and once every nine years the lunar node is oriented toward the Sun, causing syzygy to coincide with zero declination of the Moon; in this paper, the Lunar Nodal periodicity is informally termed the *c* 20-year pattern	reflected in relatively wetter and drier phases in rainfall on a *c* 20-year rainfall pattern (Currie & Fairbridge 1985), *e.g.*, in South Africa, North America, China, and southwestern Australia[4]

[1] terms and definitions for astronomical, celestial mechanics and geodesy are provided in Munk & Macdonald (1960), Vanicek & Kratiwsky (1982), and Matzner (2001);

[2] while commonly known in the literature as the Milankovitch Cycles, there has been a tendency in recent years to term this effect as the Croll-Milankovitch cycles, or Croll-Milankovitch Theory, in recognition of the important and early part that Croll played in the development of glacial theory and astronomic forcing (*cf*. Muller & MacDonald 1997)

[3] there appears to be a *c* 250-year climate pattern reflected in ice cores (Stocker & Mysak 1992), and in the repetitive construction of large beachridges on the Rockingham-Becher Plain (Semeniuk 1995a); Bradley (1999) reports the work of Loutre *et al* (1992) who calculated (from changes in precession, obliquity and eccentricity) various significant high-frequency periodicities, one of which was 245-year, and considers these high-frequency periodicities to be important in climate variability on the decadal to century timescale; while these calculations are for the northern hemisphere, and while Berger *et al* (1993) have shown there can be an asymmetry in climatic response across the latitudes and from northern hemisphere to southern hemisphere, the generalised insolation pattern for the northern hemisphere can be applied to the southern hemisphere;

[4] Borisenkov *et al* (1983), in calculating variation in terrestrial insolation resulting from perturbations in Earth's orbital parameters, report on a 18.6-year periodicity, which they ascribe to nutation of the pole, induced by lunar gravitational attraction and the inclination of the Moon's orbital plane to the plane of the ecliptic; *c* 20-year rainfall patterns are reported in South Africa by Tyson (1986) and Currie (1993), North America by Currie (1984) and Currie & Fairbridge (1986), China by Currie & Fairbridge (1985), and southwestern Australia by Semeniuk (1995a).

reduced to small conical piles of sand, which in time with rain wash became thin lenses of sand (a pyrosediment). Thus, fire can transform the stratigraphy of homogeneous peaty sand to one of peaty sand with scattered small, discrete thin lenses of sand.

In 1986, during a study of wetlands in the Ellenbrook region by V & C Semeniuk Research Group (Semeniuk & Semeniuk 2005c), a wetland basin was classified and described as a sumpland, underlain by 20 cm of a sequence of peaty sediments (peat, sandy peat and peaty sand), and vegetated by *Baumea articulata*. In the next ten years, following a general falling of the water table regionally, there was a drying out of the shallow sedimentary sequence. A fire swept through the wetland in the summer of 1993, and burned out the peaty sediments, exposing the underlying sand (noted in Figure 13B). After the fire, during the period 1993–2004, the wetland had become a sand-floored dampland, vegetated by *Melaleuca preissiana* and *Astartea fascicularis*. Thus, fire had removed the peaty substrates,

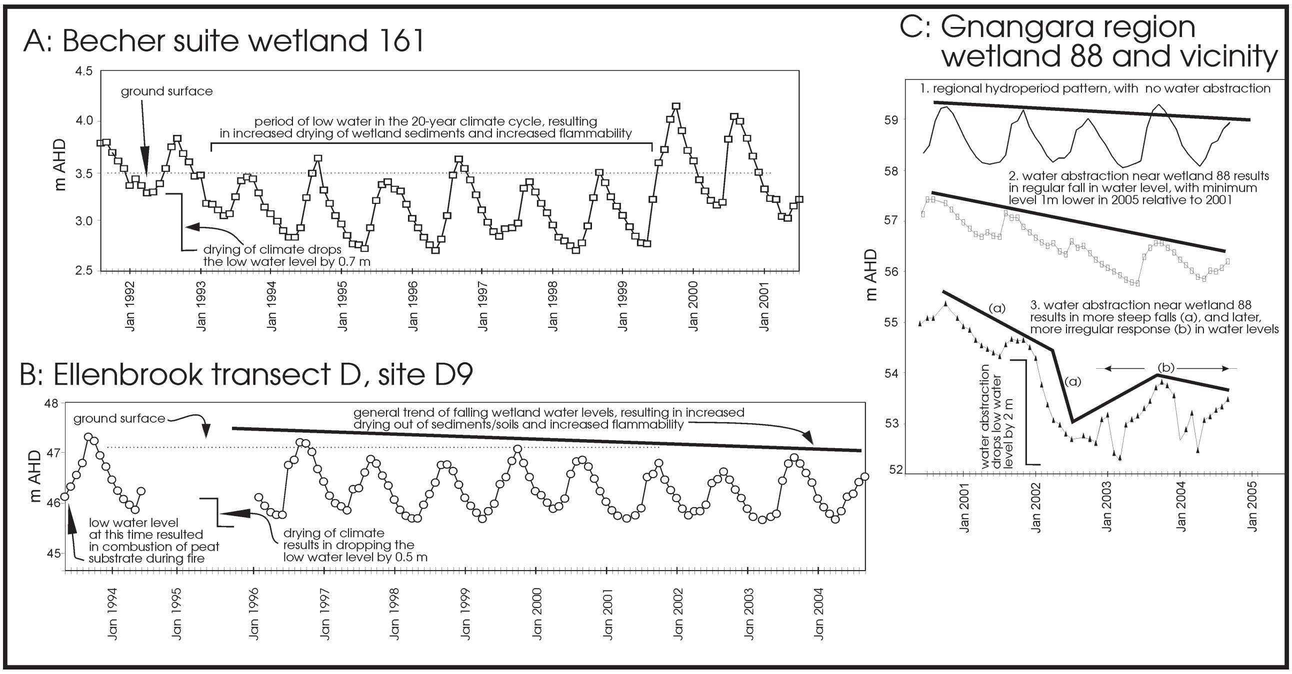


Figure 14. Annotated hydrographs from three wetlands on the Swan Coastal Plain from Semeniuk (2005) and Semeniuk & Semeniuk (2005c) showing: (1) hydroperiods and the natural and anthropogenically-induced trends in falling water tables (dark line), (2) location of ground-surface (stippled line) relative to the water level, and (3) the potential for flammability of the wetland sediment/soil. A. Becher Suite wetland 161 (Semeniuk 2005) exhibits falling, then rising water levels, and a period of increased flammability. B. Ellenbrook transect D shows falling wetland water levels in response to a drying climate, and the period when peat substrates combusted along this transect. C. Gnangara region wetland 88, and vicinity, showing wetland water level responses to water abstraction; hydroperiod (1) shows the hydroperiod pattern in the region, where there is no water abstraction, *i.e.*, a low decline in water levels; hydroperiod (2), a moderately steep decline in water levels as a result of water abstraction; hydroperiod (3) shows steep decline and irregular fluctuations in water level as a result of water abstraction; in this region, peat substrates in wetlands that exhibit hydroperiods (2) and (3) have increased potential for combustion. Note that the vertical scale in (A) is 2 x that of (B) and (C).

and in concert with a generally falling regional water table, the wetland was transformed from a peat-floored sumpland to a sand-floored dampland, with attendant changes in vegetation.

Discussion and conclusions

In Western Australia, to date, minimal use has been made of information on wetland sediments or wetland hydrologic patterns in formulating strategies and policies for fire management (Fire & Rescue Services of Western Australia 2000; SEMAC 2002; Auditor General W.A. 2004). Yet, as a result of accidental, poorly timed, or too frequent fire regimes, there have been varying pyrogenic effects on wetlands and their sedimentary fill, (depending of course on their lithological characteristics), varying responses in the combustion of wetland materials (*e.g.*, different types of fires, and different types of secondary effects deriving from these fires), and varying effects on the surrounding environment from the burning of wetlands.

Information on wetland sediments, wetland stratigraphy, and hydrologic patterns is important in the management of fire for many reasons:

1. the type of wetland sediment (*e.g.*, the composition of the peat) combined with the degree of moisture content, in relation to the depth of the water table at a given time of year, can determine the calorific value of the sediment and the intensity of the ensuing fire;
2. annual and longer term hydrologic patterns determine when wetland sediments become susceptible to burning;
3. in a stratigraphic context, regionally falling water tables over the long-term result in fires coming in contact with progressively deeper stratigraphic layers (with different sediment types, or different geochemistry), and consequently different combustion regimes and geochemical responses;
4. the heavy metal and metalloid content of the sediment, the type of parent plant material that originally formed the peat, the alkaline metal content of the decomposing plant material, the sulphide content of the peat, and the diatom, phytolith, and sponge spicule content of the burning substrate can result in various types of smoke, with implications for community health;
5. the oxidation and chemical perturbation of the wetland sediments during a fire and the development of a labile chemically complex ash result in a substantially different geochemical environment in the wetland, with implication that the post-fire situation can have a subtly altered wetland hydrochemistry;

6. the development of ash noted in (3) introduces various types of mineral species into the wetland, and this may be mobilised as dust by post-fire aeolian processes, with implications for community health;
7. burning of wetland sediments results in the destruction of wetland stratigraphic geoheritage.

These reasons clearly point to the necessity of accruing information on wetland sediments and having a framework for predicting the occurrence of the different types of wetland sediments and their stratigraphy. This information would then be coupled with historical data on water table levels in wetlands to be used for fire management purposes. Basic information on wetland sediments, water tables, and the stage of flammability of wetland sediments and soils, in connection with both the annual and longer term climatic patterns, would lead to the identification of wetlands at high risk to combustion, and the identification of high risk periods that may result from short or long-term low water tables and reduced saturation.

We suggest that fire management in wetlands requires design and implementation of pre-emptive strategies (*i.e.*, before fires are ignited) and operational strategies (to be undertaken during fire events), pertaining to sedimentological, stratigraphic, mineralogic, geochemical, and hydrologic properties of a wetland. The principles and information presented in this paper can assist with both. For instance, information on the distribution of wetland sediments in regard to landscape setting, climate, wetland type, and the temporal variation of material flammability, responding to fluctuating or declining water tables, provides a powerful tool in pre-emptive fire management. Knowledge of the stratigraphy of a wetland is an important tool in pre-emptive and operational fire management in that firstly stratigraphy provides information on the reservoir of flammable material available for combustion, and secondly, the stratigraphic array of flammable material along the wetland margins provides insight of how fire can access the surface and subsurface flammable material.

Drawing on information on sediment types and stratigraphy of wetlands from Semeniuk & Semeniuk (2004, 2005b), this paper provides a basic description of the variety of wetland sediments on the Swan Coastal Plain, broadly relating their occurrence and distribution to landscape setting east to west across the Coastal Plain, to the south to north climate gradient, and to hydrology. There is a strong relationship between composition of the wetland sedimentary fill, and landscape setting and wetland type, as well as between the sedimentary fill and geographic/climate setting, and this relationship provides a basis to broadly predict the occurrence and distribution of potentially flammable material in wetlands across the Swan Coastal Plain.

In a wetland, the basic materials that are susceptible to combustion pass through stages of high to low combustion potential, depending on the annual cycle of the falling and rising water table, and on the longer term climatic cycles. Hydrological data from wetlands at risk, incorporating annual water table fluctuations, and longer term regional trends, can be used to extrapolate material flammability.

From a chemical perspective, wetlands, comprising wetland vegetation and peat, are a reservoir of various mineralogic, geochemical and biochemical species that, after transformation during burning, can be mobilised into the atmosphere during the fire, by wind after the fire, and into the groundwater after the first rains following the fire. Setting aside the issue of wetland vegetation which is a source of fuel to a fire above the substrates of a wetland, stratigraphic sequences, surface sediment types, and soils underlying wetlands comprise the basic combustible material of fires in the substrates of wetlands, and data on these materials should thus form the first stage information base in the design of any pre-emptive fire management and operative fire management in wetlands, because their variability in terms of content of organic carbon, type of plant material contributing to the organic carbon, biogenic silica, quartz silt, alkaline metals, heavy metals and metalloids, and sulphide content can influence the type of fire and type of smoke generated, and influence post-fire environmental processes.

While wetland sediments have been described by Semeniuk & Semeniuk (2004) in terms of textures (*i.e.*, grain size fractions), mineralogic composition, the nature of their gravel, sand and mud-sized constituents, and the occurrence of fine-grained framboidal pyrite as microcrystalline FeS_2, the details of the heavy metal and metalloid content of wetland sediments, their stratigraphic occurrence, their mineralised geochemical setting, their hydrochemical setting, and the full implication of this variability in pyrodynamics are beyond the scope of this paper. However, in this paper attention is drawn to the fact that during an intense burn of wetland sediments and soils, in addition to the combustion and transformation of the organic matter in the wetland sediments, the other fine-grained constituents, either remaining as residues after combustion (*e.g.*, quartz silt), or geochemically or crystallographically transformed by the combustion (*e.g.*, sulphides, and biogenic silica), can be mobilised into the atmosphere with the smoke. Smoke is generally known to be a complex mixture of carbon, tars, liquids, particulate matter, and various gases that include carbon monoxide, aldehydes, nitrogen oxides, peroxides, acids, and products deriving from chlorine-bearing and nitrogen-bearing polymers (Ward & Hardy 1991; Andreae *et al* 1996), and studies elsewhere have highlighted the variability of emissions from biomass burning in terms of the biochemical and metal/metalloid species present in smoke, and their effects on human health (Allen & Miguel 1995; Yamasoe *et al* 2000; Andreae & Merlet 2001; Johnston *et al* 2002; Page *et al* 2002; Graetz & Skjemstad 2003; Lemieux 2004). However, while there has been an emphasis in the literature on the chemical composition of smoke, there has been less information on its mineralogy.

The matter of crystallographic transformation of biogenic silica during a fire and the mobilisation of this silica into the smoke is an important one in that crystalline silica (cristobalite) is a known carcinogen. Normally crystalline silica occurs as equant grains, but biogenic silica transformed partially to crystalline silica, albeit in low concentrations, retains its spicular or fibre form, and as such is toxic. Fubini (1998) considers biogenic silica converted to crystalline form to be one of the most fibrogenic forms of silica. Ash, left as a residual after a fire, also can be mobilised into the atmosphere later by wind. The material comprising these smoke and ash assemblages would include: the fine-grained particles of quartz silt and primary biogenic silica; biogenic silica transformed partly or wholly into crystalline silica by the heat during combustion; solidified micro-droplets of melted silica; the oxidised sulphides of heavy metals and metalloids (and other derivatives such as SO_2); and the carbonates, sulphates and chlorides of the alkaline metals. The issue is important to address because smoke and aeolian-mobilised ash deriving from burning and burnt wetlands may locally affect nearby communities, or affect specific susceptible members of the community. The potential health problems associated with generally inhaling smoke from biomass burning are discussed in Johnston *et al* (2002), Aditama (2000), Jalaludin (2000), and those associated with inhaling biogenic silica, and biogenic silica partially crystallised to cristobalite are discussed by Rabovsky (1995), Merget *et al* (2002), Stratta *et al* (2001), and Fubini (1998).

In summary, in relation to smoke and dust, chemically, with its cocktail of pyrogenic compounds, smoke is known to affect community health, but the matter of the pyrogenic mineral species in the smoke (and post-fire dust), and their effect on respiratory health has not been adequately addressed in the literature, and in many instances, not even recognised as a potential health issue. Knowledge of the range of sediment types in wetlands, as described in this paper, provides the first step in dealing with this matter, by indicating the wetland substrates that potentially pose, through combustion, some risk to community health. Stratigraphy and geomorphic setting are highlighted herein as the bases for predicting the nature of the *mineralogic and geochemical reservoir* that may contribute undesirable constituents to the smoke during the fire, to the atmosphere by aeolian mobilisation of ash, or later, through groundwater and meteoric water interactions with pyrogenic residues, to the groundwater.

The sediments that underlie wetlands can range from those with very low or nil susceptibility to combustion (*viz.*, diatomite, calcilutite, quartz sand, and kaolinite-dominated mud and muddy sand) to those that are highly or moderately susceptible to combustion (*viz.*, peat, diatomaceous peat, and spongolitic peat), with the flammability of the latter suite depending on the location of the water table, the vertical extent of the zone of capillary rise (the zone of wetting above the water table), the extent of drying out of the material underlying the wetlands, and the percentage of potentially combustible material. It should be noted, though, that all wetland basin sedimentary fills that have high content of organic matter in their soil (the upper 10 cm), or in their sediment profiles, or have dense root mats in the shallow subsurface, have some degree of flammability, or at least, potential for rapid oxidation in hot fires. Also, given the potential for variability of sediment types across a wetland, and the interlayering of buried organic-rich sediments along the wetland margins, the stratigraphy of wetlands needs to be addressed to determine the extent of flammable materials within a wetland. It particularly needs to be part of operational management where surface fires have already obviously occurred, and appear extinguished, but continue to burn, or smoulder in the subsurface. In this context, stratigraphy of wetlands should form a part of the information base needed to pre-emptively manage fire in wetlands, or to design on-site responses to a fire already underway.

At an ecosystem level, hydrogeological level, and hydrochemical level, the consequences of fire on water quality and aquatic ecosystems have been investigated by a number of authors: Johnson & Needham (1966), Humphreys & Craig (1981), Richter *et al* (1982), Helvey *et al* (1985), Belillas & Roda (1993) and Townsend & Douglas (2000) to determine what effects, if any, emanate from the burnt landscape, and reviewed for organic rich substrates in wetlands by Horwitz & Sommer (2005, this issue). Studies to date, however, have focused on dryland forests and heaths and the changes to soil nutrients and effects on waterway chemistry following a fire. The contributions to hydrochemical perturbations on waterways as a result of fires are manifold, including that induced by introducing ash into the environment, that resulting from increased soil erosion from the burned landscape, and that induced by changes in vegetation uptake. The effects of fires on hydrochemistry *within* wetlands, however, remain largely unexplored. Axiomatically, in wetland systems where vegetation, soils, nutrient storage and recycling, hydrology, and hydrochemistry are intimately linked (Semeniuk 2005), fires will have major effects, all with consequences for wetland hydrochemistry: reducing the store of elements within the vegetation and the substrate to ash, involving soluble labile and insoluble components; transforming minerals in the soil to their oxidised phases; removing elements and nutrients *via* smoke; and affecting aspects of wetland hydroperiod.

It is suggested that fire management strategies for wetlands be extended to the transitional zones around wetlands. In prescribed burning, it is probably advisable not to burn wetland buffer zones, or zones transitional between wetland and upland, where they are narrow, as they may not constitute a major fire risk, but where it is considered that wide buffer zones need to have a reduction in surface fuel, caution should be exercised with the timing of such an event, ensuring that wetland sediments are adequately saturated and therefore least combustible.

Thus, in summary, it is suggested that pre-emptive and operational management of fire in wetland sediments and soils should be based on knowledge of a number of factors: 1. their organic carbon content; 2. their mineralogic, geochemical and biochemical content; 3. the hydrology of a wetland; 4. the potential of wetland sediments to combust in relation to fluctuations of the water table in response to the seasons; 5. the potential of wetland sediments to combust in relation to longer term climatic patterns; 6. the areal extent of flammable material across a wetland; 7. the nature of any stratigraphic interlayering along the wetland margins; 8. the (predictive) distribution of sediment types in wetlands across the Swan Coastal Plain; and 9. the distribution of sediment types in wetlands along the climatic gradient of the length of the Swan Coastal Plain.

Whereas much emphasis in fire management to date has been placed on either the prevention or extinguishing of fires in wetlands because of the health, industrial, and property risks they pose, the importance of protecting wetland sediments and sedimentary records *per se* from fire has been largely overlooked. However, the Western Australian State Government objectives to conserve heritage features and promote sustainable ecology, as well as the mounting scientific evidence pertaining to the archival sedimentary records (Backhouse 1993; Pickett & Newsome 1993), require these aspects of wetland sedimentary fill to be addressed in fire management as part of geoheritage (Semeniuk & Semeniuk 2000). Fire can destroy the sedimentary record of wetlands (involving for example, pollen, diatoms, isotopic and other constituents, and fossil higher plant material) that provide geohistorical and biotic information of the evolution of the wetlands in terms of palaeoclimatology, palaeohydrochemistry, and palaeo-ecology (as discussed in Semeniuk & Semeniuk 2004). The protection of wetland sediments themselves also is integral to protecting wetland habitat and preserving the biodiversity resulting from the interplay between wetland sediment geochemistry and hydrogeology, *i.e.*, between wetland sediments/soils and water (*cf* Semeniuk 2005). Thus it is suggested that the preservation of both the information contained in complete, undisturbed stratigraphic sequences within wetlands and the sedimentary environment itself should be important goals in fire management, and organisations/groups responsible for fire management should endeavour to embrace them.

Recognition that wetland sedimentary fill is a mineralogic, geochemical and biochemical reservoir that potentially can produce hazardous smoke and dust during and after a fire should not be the basis of managing wetlands as a toxic management issue. Wetlands provide invaluable information in their stratigraphic sequences (Weiss *et al* 2002), and as discussed above, are sites of geoheritage and biodiversity significance. From the perspective of geoheritage and biodiversity, the complexity of wetland substrates should be the basis for their protection for inter-generational equity. In addition, the stratigraphic, mineralogic, geochemical and hydrochemical array in the wetland profile is interrelated, and as mentioned above, is the *foundation* of wetland biodiversity. We stress, therefore, that fire management should be focused on fire prevention, on education, and in sound town planning, and not on modifying and managing the wetlands.

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