Journal of the Royal Society of Western Australia, 87:139–186, 2004

Sedimentary fill of basin wetlands, central Swan Coastal Plain, southwestern Australia. Part 1: sediment particles, typical sediments, and classification of depositional systems

V Semeniuk & CA Semeniuk

V & C Semeniuk Research Group
21 Glenmere Road,
Warwick, W.A., 6024

(Manuscript received July 2004; accepted February 2005)

Abstract

The common sediments in wetland basins occurring in the Spearwood Dunes, Bassendean Dunes and Pinjarra Plain of the central Swan Coastal Plain, southwestern Australia are peat, diatomite, calcilutite (carbonate mud), their intermediates such as diatomaceous peat, organic enriched diatomite or calcilutite, and carbonate skeletal gravel and sand (all formed by biogenic processes), as well as quartz sand and kaolinite-dominated mud (as terrigenous sediments), and various types of muddy sand formed as mixtures between biogenic mud-sized sediments and quartz sand, or between kaolinitic mud and quartz sand. Synsedimentary processes and diagenesis result in local cementation, desiccation, and reworking of these deposits, particularly along the margins of wetland basins, and hence the development of carbonate intraclast gravel and sand, diatomite intraclast gravel and sand, and peat intraclast gravel and sand. A clear distinction is made between wetland sediments and wetland soils, and between primary wetland sediments and the products of diagenesis within and around wetlands. Gravel-sized particles in the wetland sediments include plant remains, invertebrate faunal skeletons, and intraclasts. Sand-sized particles include plant remains, quartz, invertebrate faunal skeletons, and intraclasts. Petrographic microscopy and scanning electron microscopy show the < 63 µm particles that comprise the sediments are plant remains, diatom frustules and fragments, sponge spicules and fragments, aggregates of calcite crystals derived from charophytes and the disintegrated clay-sized derivatives of these charophytic aggregates, comminuted invertebrate skeletons, quartz silt, and mud-sized phyllosilicate minerals.

Wetland sediments can be categorised as to origin, *i.e.*, biogenic *versus* terrigenous, as to whether they are end-member primary sediments, or derivatives, or mixtures, as to their location of formation relative to the basin, *i.e.*, intrabasinal, autochthonous *versus* extrabasinal, allochthonous, as to their infiltrational and accretionary nature in relation to the basement material, and as to their location within a basin, *viz.*, central basin *versus* marginal *versus* basal deposits.

Keywords: wetland sediments, peat, diatomite, calcilutite, Swan Coastal Plain wetlands

Introduction

Wetlands, as natural topographic depressions in the landscape, fill with sediment, and as a result, globally, they are known to be important reservoirs of information on geohistory, geochemical history, vegetational succession and palaeoclimate (Barber 1981; Druckman *et al.*, 1987, Gasse *et al.*, 1987; Talbot 1990; Baltzer 1991; Odgaard 1992; Leaney *et al.*, 1995; Wright and Platt 1995; Fritz *et al.*, 1999). The wetlands on the Swan Coastal Plain of the Perth Basin are prime examples of such archives as they contain vast and variable information in their sedimentary sequences. They have the potential to encode Holocene geologic, hydrologic, and hydrochemical history, vegetation changes, and climate changes, as preserved in their stratigraphic, diagenetic, isotopic, faunal, and floral records.

While there is mention and some description in the literature on the central Swan Coastal Plain of types of wetland sediments, their stratigraphic expression, and their local thickness (Simpson 1903; Teakle & Southern 1937; Allen 1979; Megirian 1982; Hall 1983; Muir 1983; Hall 1985; Semeniuk 1988; Newsome & Pickett 1993; Coshell & Rosen 1994; Pickett 1998), to date, these sediments have not been subject to a systematic or comprehensive description. This paper, the first in a series on wetland sediments of the Swan Coastal Plain, describes the particle types that comprise the wetland sediments in this region, describes the main sediment types, and provides an interpretation of their origin. It also provides a preliminary outline of wetland sediment diagenesis in order to clearly separate primary sediments from diagenetic products. The stratigraphy and the age structure of sedimentary fills in wetland basins will be the subject of later papers (Semeniuk & Semeniuk 2005 a). The scope of this paper is limited to those isolated wetland basins across the central Swan Coastal Plain, between Moore River and the Mandurah / Pinjarra region, mainly within the settings of the Spearwood Dunes, Bassendean Dunes and those local parts of the Pinjarra Plain that are not directly connected to fluvial systems

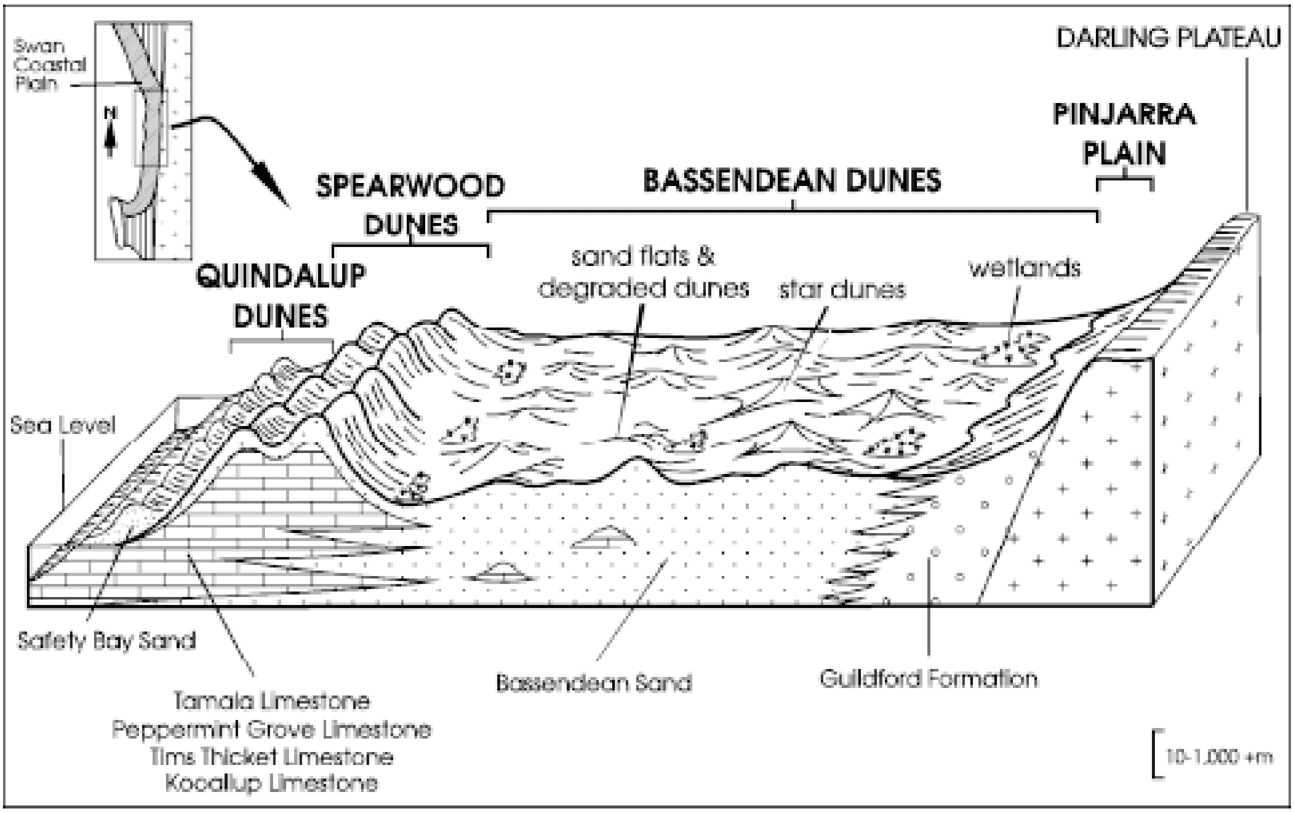


Figure 1. Idealised block diagram showing geomorphic units of the Swan Coastal Plain, their sub-parallelism to the Darling Scarp and the coast, their gross surface features, and their stratigraphy, with some details of landscape (after Semeniuk & Glassford 1989). The scope of this study involves only the Spearwood Dunes, Bassendean Dunes, and parts of the Pinjarra Plain.

(Fig. 1). The linear wetlands of the Yalgorup Plain (Semeniuk 1995) of the central to southern Swan Coastal Plain will be the subject of a separate study. Wetlands within the Becher Suite of the Quindalup Dunes of the central Swan Coastal Plain also are the subject of a separate study (Semeniuk 2005), though for completeness brief mention is made in this paper of some of their deposits in terms of the nomenclature used herein. Beachridges and lunettes that have formed along the margins of wetland basins, and that have become emergent above the high-water mark are not treated as part of the wetland fill deposits in this paper. The sediments of fluvial wetlands and related features (*i.e.*, channels and floodplains), whose landform surfaces range in age from Pleistocene to Holocene, as well as estuaries and linear lakes and lagoons formed leeward of marine-derived barriers also are not considered in this paper. Sedimentation in selected linear lagoons and estuaries marginal to the Swan Coastal Plain has already been described in Semeniuk & Semeniuk (1990), and Semeniuk (1996, 2000).

Classification and terminology

The wetland classification of Semeniuk (1987), developed for the central Swan Coastal Plain, is used in this paper. This classification uses the components of landform and hydrologic regime to develop wetland categories. As the emphasis in this paper is on basin wetlands, only the terms for these are noted here. Combining basin landform with hydrologic regime in the Swan Coastal Plain results in 3 categories of wetland: 1. permanently inundated basin = lake; 2. seasonally inundated basin = sumpland; and 3. seasonally waterlogged basin = dampland. Water and landform descriptors augment the primary categories.

In this paper, the term *intraclast* is extended from the usage of Folk (1962), who coined it for intraformational clasts in carbonate depositional regimes, to refer to any reworked clasts of cemented, indurated, or dried sedimentary materials that belong to the cycle of sedimentation in which they are embedded. Intraclasts may be gravel sized to sand sized. The term *intraformational* describes production of particles that form *within* a given sedimentary formation. For example, the cementation, reworking into clasts, and incorporation of these clasts into extant sediments are intraformational phenomena. The term *infiltrational* describes deposits that form by infiltration into another sedimentary formation. For example, the delivery by vadose processes resulting in the accumulation of fine-grained sediments interstitially *within* another sedimentary body, rather than superposed *on* that body, is an infiltrational phenomenon. The term *accretionary* describes deposits that accumulate vertically by superposition above another sedimentary formation. The term *synsedimentary* refers to processes that occur concurrently or penecontemporaneously with sedimentation. Burrowing by fauna, and root-structuring by vegetation, contemporaneous or penecontemporaneous with sedimentation are examples of synsedimentary phenomena. The term *synsedimentary* also is commonly applied to a particular stage of diagenesis in which there is alteration of sediment contemporaneously or penecontemporaneously with sedimentation (precipitation of sulphides and cementation by carbonate mineral are examples of synsedimentary diagenesis). The term *diagenesis* (and *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. Precipitation of carbonate within sediment to develop indurated layers, for instance, is a diagenetic phenomenon, and the precipitate may be referred to as "diagenetic carbonate", noting that diagenetic carbonate thus is distinct from any sedimentary carbonate material that has been derived from accumulating skeletons ("biogenic carbonate"), or that derived by chemical precipitation. Sediment fabric terms, such as grain-support, mud-support, grainstone and boundstone, are after Dunham (1962).

The term "organic matter" is used in the sediment descriptions in this paper to refer to the range of materials of various particle sizes that are derived from plants. Organic matter ranges from relatively fresh material, to particles in various stages of decomposition (structural and biochemical breakdown, mediated by microbiological and fungal processes) to elemental carbon.

Sediment *versus* soil

The approach in this paper is from a sedimentary perspective, *i.e.*, the materials accumulated in wetlands are sediments and are described from this sedimentary viewpoint. However, to avoid the confusion in the literature between the notions of "sediment" and "soil", a range of terms in relation to materials underlying wetlands are stipulatively defined below. "Sediment" refers to accumulated material that either has formed wholly within the wetland (autochthonous, intrabasinal sediment, *i.e.*, that formed inside the basin), or has been transported into the wetland (allochthonous, extrabasinal sediment, *i.e.*, that formed outside the basin). The term can be applied to individual sediment types or to inter-layered deposits. Thus, carbonate mud is a type of wetland sediment, and peat is a type of wetland sediment, since they both form as intrabasinal accumulative deposits. "Sedimentary" refers to any material accumulations that have formed as sediments. "Sedimentary fill" refers to the total aggregate of deposits filling a wetland basin. "Stratigraphic" and "stratigraphy" refer to the accumulated *sequence* of sediments.

"Soil" in this paper 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 modified under extant conditions (Buol *et al.*, 1973; Arnold 1983; Jackson 1997), *e.g.*, the weathering of the surface of the Bassendean Sand (Playford & Low 1972) on the Swan Coastal Plain, or the surface weathering of granite. Soils generally are not accretionary but degradational (Hunt 1972), though some authors place in the realm of soil the thin layer of fresh to decomposed organic matter accumulated *above* the mineral material (parent body), designated as the "O horizon", even if it has accreted to several centimetres in thickness (Buol *et al.*, 1973). Soils that have formed under past climatic or hydrologic conditions, and are not therefore extant, are *palaeosols*.

In this context, wetland sediments are the primary accumulates within a wetland basin, and not physical, chemical or biogenic alteration products of pre-existing material, and if soils are developed on them, the wetland soils will be near surface alteration of those primary materials (Fig. 2A). Thus, a wetland basin filled with white carbonate mud is filled with carbonate sediment, and the grey carbonate surface mud layer, say, 10 cm thick, of humified root-structured material at its surface is the wetland soil. Pre-existing Pleistocene quartz sand, *e.g.*, the Bassendean Sand underlying a wetland is the basement material (note: the term "basement" here refers to the floor of the wetland basin and is not to be confused with the notion of basement referring to Precambrian rocks). Where such quartz sand immediately underlies the wetland floor, and there is no development of wetland sediment, the surface grey sandy layer, say, 10 cm thick, of humified root-structured material developed on the sand is the wetland soil.

The term "soil" carries the implication that any layering developed within it (*e.g.*, the A, B and C horizons, or the A1, A2, and K horizons) has developed as a result of internal horizontal partitioning ("horizonation", *cf.* Buol *et al.*, 1973) as a result of leaching, export (removal), or redistribution of materials physically, chemically, and biogenically within the soil profile on a pre-existing parent material. As such, chromatic, compositional or textural "layering" in the soil profile is the result of pedogenic processes, *and the horizontal differentiation therein is interrelated.* Stratigraphic sequences, *e.g.*, interlayered accumulations of diatomaceous mud, biogenically derived organic matter and carbonate mud, are the result of the addition and accumulation of material generated within a basin and from the water column, and are not alterations or modifications of pre-existing materials. These horizontally-oriented differentiations are due to sedimentary accretion under differing regimes of water chemistry, or climate, or biotic assemblages, and are not internally interrelated. As such, the application of the term "soil" to stratigraphically layered material in a wetland accumulated from the intrabasinal processes is not correct.

In contrast to these definitions and concepts outlined above, practitioners in geomorphology, soil science, and wetlands tend to have a wider view of the term "soil", and would use it to refer to all the materials that underlie wetlands, and thus would apply the term to sediments, sedimentary-fill, stratigraphic sequences, and diagenetic products.

Commonly, in wetlands, there is addition of fine-grained wetland sediment (*e.g.*, organic matter, diatom mud, carbonate mud, or mud-sized phyllosilicate minerals) by infiltration or bioturbation *into* any underlying porous basement substrate, such as sand or gravel. This process may result in a "muddy" sand or gravel (Fig. 2B). The fine-grained material is interstitial to the sand or gravel grain-support framework (Dunham 1962), and not merely grain-coating, as is often the case

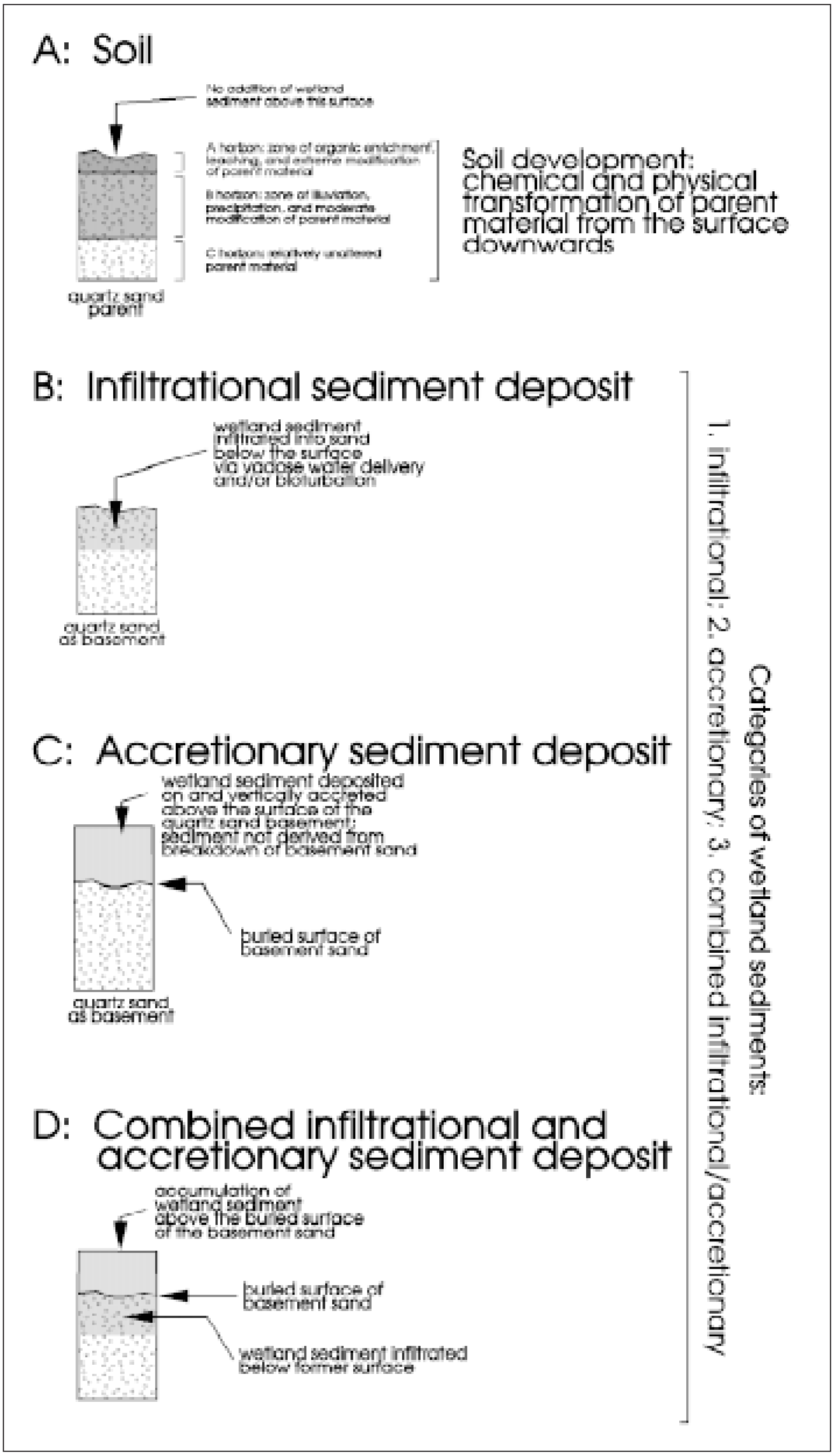


Figure 2. Concepts of soil *versus* sediment, as used in this study. A. Soil as a near surface alteration of parent material, using quartz sand as an example. B. Sediment autochthonously formed within a wetland and infiltrated into a porous basement substrate, in this case mud infiltrating the sand.; this type of deposit is *infiltrational* sedimentation. C. Sediment autochthonously formed within a wetland and vertically accreted above a basement substrate, in this case mud overlying sand; this type of deposit is *accretionary* sedimentation. D. Sediment autochthonously formed within a wetland and first infiltrated into a porous basement substrate, and then vertically accreted above a mud-clogged basement substrate.

for humus material in the A horizon of soils. The zone of "muddy" sediment may develop as a material in its own right, immediately underlying the floor of a wetland, or may be a unit that is transitional between any accreted wetland sediment and the basement substrate. The "muddy" material that has formed by infiltration of wetland sediment into underlying basement materials is the product of *infiltrational* sedimentation. Any material that accumulates above the surface of basement materials is the product of *accretionary* sedimentation (Fig. 2C). Both may be present in the one wetland (Fig. 2D). Infiltrational material, accretionary material, and combined infiltrational/accretionary material are treated in this paper as wetland sediment.

The processes leading to the development of wetland soils, and types of wetland sediments on the Swan Coastal Plain are summarised in Figure 3.

Materials and methods

A wide-ranging sediment sampling programme was undertaken at the surface of wetlands, in their stratigraphic sequence, 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 sediments. Samples were collected from hand cores and stratigraphic intervals in transects from some 143 wetlands (Appendix 1). Stratigraphy of wetlands was determined by examination of dewatered trenches and excavations (to 4 m) in 17 wetlands, and shallow augering (to 5 m) in 70 wetlands. Additionally, in 35 of the wetlands, reverse-air-circulation coring to 30 m was undertaken. The cliff faces provided by dewatered trenches and excavations allowed direct observation and description of stratigraphy, sedimentary and biogenic

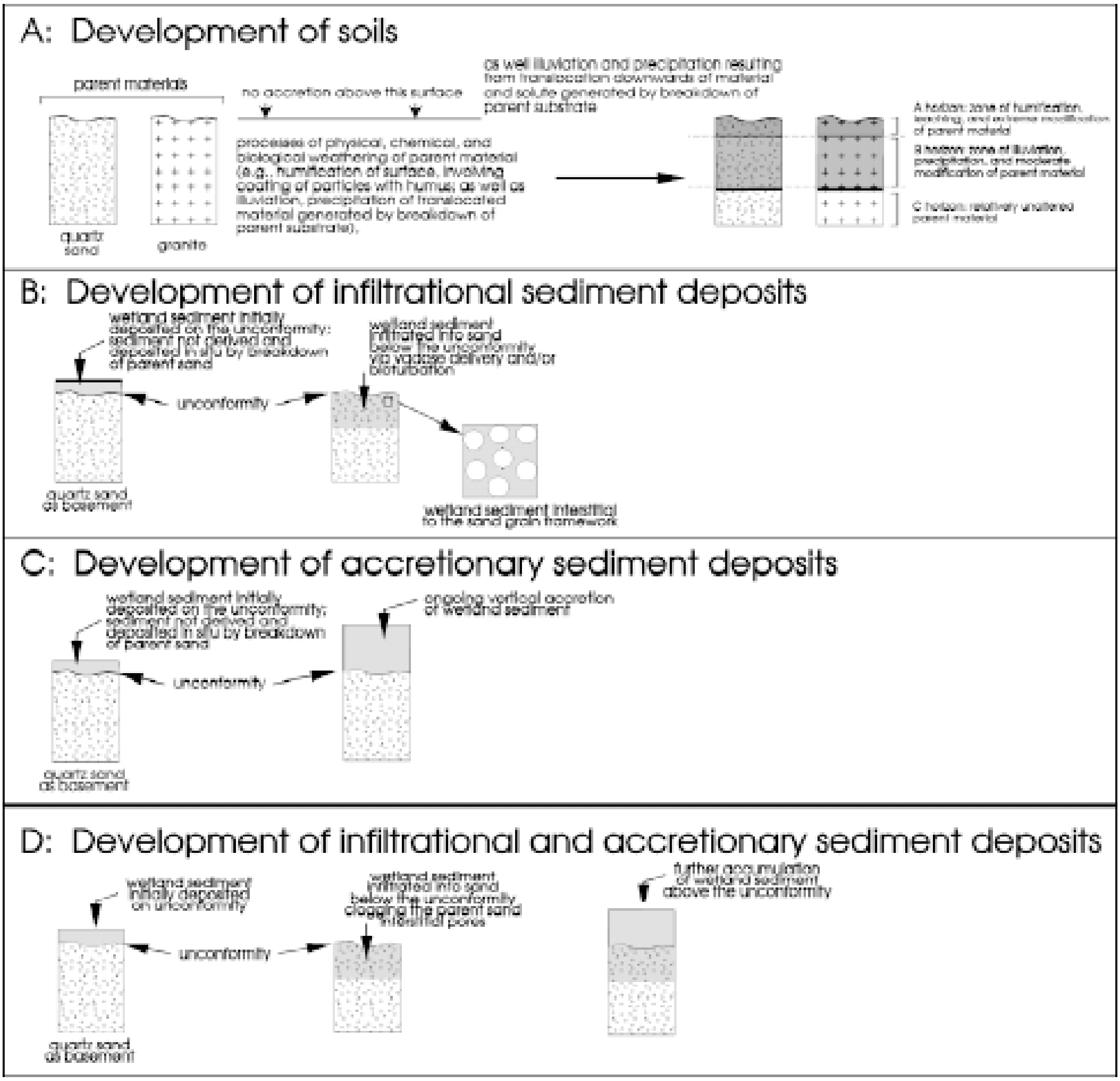


Figure 3. Processes operating to develop wetland soils and wetland sediment. In (A), quartz sand and granite are used as examples to illustrate the development soils.

structures, and sediment types under wetlands. Artificial exposures were described in 12 un-named wetland basins at Osborne Park, Bullcreek, and Forrestdale, as well as in excavation trenches in Lake Gwelup, Little Carine Swamp, Lake Pinjar, and Karrinyup Road Swamp. Sediments from trenches, excavations, and cores were described in the field in terms of colour, structure, fabric, texture, and composition.

Short cores of *in situ* sediment were obtained from a range of wetlands to study surface and near-surface sedimentary structures and micro-structures. These short cores were obtained by pushing 10 cm diameter PVC pipes, 10–30 cm long, into the substrate, retrieving them, and returning them to the laboratory. At some 30 sites, 75–100 cm long cores also were obtained. In the laboratory, the cores, generally in a water saturated state, or at least with pellicular water, were frozen for storage and ice-hardening. The cores later were longitudinally sliced while frozen to cleanly expose the stratigraphy and sedimentary structures. One half was returned to frozen storage as archive material; the other half was photographed, and used in further analyses.

In the laboratory, the samples of sediment were described and analysed using five progressive levels of detail to provide a comprehensive view of the variety of sediment types.

Firstly, the large range of surface sediments, stratigraphic samples, and hand cores from all the wetland sites, involving several hundred samples, were examined and described as to colour, texture, and composition, and categorised according to their sand and mud content (*i.e.*, clean sand, muddy sand, sandy mud and mud) following the grain-support *versus* mud-support concept of Dunham (1962). With the aid of a stereomicroscope and a light transmitting microscope the presence of carbonate in sand and mud was determined (with dilute HCl), carbonate intraclasts, carbonate skeletal tests and their fragments, plant material (stems, roots, fibres, leaves), quartz sand, quartz silt, lithoclast sand, carbonate mud, invertebrate skeletal debris, and sponge spicules (as monaxons), and mud-sized phyllosilicate minerals were identified, and sediment was assigned to size fraction categories of gravel, or coarse, medium, fine or very fine sand, muddy sand, or mud.

Secondly, examination of sand grain mounts and mud particle mounts, where sand and mud-sized fractions, respectively, are dispersed in a fluid medium on a glass slide (Swift 1971), and thin sections, under a polarising petrographic microscope was undertaken on a selective basis for *c.* 200 samples. Under a petrographic microscope with high power for resolving mud-sized particles, grains in the sand and mud particle mounts were categorised in types based on their size and shape, and their crystallinity and mineralogy determined on their colour, refractive index, cleavage, and birefringence (Kerr 1959). With this method, very fine-grained plant remains, diatoms and their fragments, various types of siliceous monaxon sponge spicules (megascleres, microscleres, and gemmoscleres; *cf.* Williams 1980), siliceous phytoliths (Meunier & Fabrice 2001), and various invertebrate skeletons (*cf.* Williams 1980), in addition to the grains noted above, were identified. Thin section study of epoxy-impregnated sediments, and of any hard layers in the wetlands was undertaken under a petrographic microscope for about 100 selected samples.

Thirdly, the content of organic matter and calcium carbonate in a range of black, dark grey, and brown sediments was determined in some 100 samples using a variety of peats, peaty sediments, and dark grey fine-grained sediments – the problem of determining organic matter content was not an issue for carbonate-mud-dominated sediments or diatomite-dominated-sediments. The samples were divided in three sets of subsamples. One set was processed by combustion at 550° C and then at 1100° C. Another set was prepared as mud particle mounts for examination under a petrographic microscope. The third set was processed by acid digestion (using dilute HCl) to estimate the content of $CaCO_3$. Since loss of weight on ignition at 550° C can be due to loss of organic carbon, loss of sulphur liberated as SO_2 from sulphides (if sulphide was present in the sediment), and other volatiles liberated from the combusting organic matter, it may not be a direct measure of the content of organic carbon or even organic matter. Additionally, the loss of weight on ignition at 1100° C may not be a direct measure of primary $CaCO_3$ content since some $CaCO_3$ could have been generated from organic matter rich sediments during their combustion at 550° C. Hence, some independent calibration of sediment composition was undertaken for organic-matter rich sediments and dark grey sediments. This involved the point counting procedure, and chemical analyses, mentioned above. Mud particle mounts were point-counted under a petrographic microscope to estimate their content of organic matter, carbonate, quartz silt, diatoms, sponge spicules, and phytoliths, and the data compared to the results from the combustions to assess within the sample the amount of organic matter, biogenic silica, and carbonate mud. After combustion, opportunity also was taken to examine the ash as grain mounts and mud particle mounts under a petrographic microscope as these residues commonly are comprised of the concentrated remains of biogenic silica. Fifty selected pre-combustion samples and their combustion residues were analysed by mass spectrometry (using ICP-MS) and XRD to determine their elemental nature (Na, K, Ca, Mg, Fe, As, Cd, Pb, S and Si) and mineralogy (carbonate minerals, quartz, biogenic silica, pyrite, marcasite, arsenopyrites, goethite, haematite), respectively, as a record of wetland sediment geochemistry. The results of the content of Fe and S, and their correlation, also provided another internal assessment of the contribution of sulphide minerals to loss on ignition at 550° C.

Fourthly, more detailed systematic analyses were undertaken for some 32 selected samples obtained from various locations and depths for the purpose of typifying a range of muddy sediment types, and particularly muds, sandy muds, and muddy sands. In this paper, these samples are referred to as the "wetland sediment standards". These analyses involved all the procedures outlined above as well as sieving to quantitatively determine sand *versus* mud content, acid digestion and furnace combustion to determine the content of carbonate and organic matter, respectively, of the mud and sand fractions, X-ray diffractometry (XRD) to determine mud fraction mineralogy, and routine photography and description of sand and mud fractions under a stereoscopic binocular microscope and petrographic microscope.

Fifthly, scanning electron microscopy (SEM), and associated analyses, were undertaken for a subset of the 32 wetland sediment standards and 30 other sediments to determine the crystal form and characteristics of the fine-grained constituents to ascertain their ultrastructure and hence their origin, and to confirm the nature of the silt-sized and clay-sized opaline silica and amorphous silica from their X-ray diffractometry patterns. During the SEM, images of fields of view 100–200 µm in size were obtained using back-scattered electron emissions (BSE) in order firstly to map the distribution of average atomic number, which was used as a surrogate to determine the consistency of element distribution, and hence consistency of the distribution of particle types, and also to map the distribution of selected elements (specifically C, Ca, Mg, Al, and Si as indicators of organic matter, calcite / aragonite, Mg-calcite, phyllosilicate minerals, quartz, and diatoms, respectively). This provided a method for evaluating the homogeneity, for instance, of the carbon content of peat, or the diatom content of diatom-bearing peat. Additionally, routine spot analyses of 5 to 6 particles within each SEM field of view, some 100–200 µm across, with particle selection based on the heterogeneity of the SEM image, or heterogeneity of the BSE field, or on particle shape, were undertaken using Energy Dispersive Spectroscopy (EDS), which allowed for determination of relative element content of individual particles. With this method, elemental content of particles, combined with information on their shape, allowed identification of diatoms, very fine and ultrafine-grained diatom fragments, sponge spicules, invertebrate skeletons / tests and their fragments, quartz silt, mud-sized phyllosilicate minerals, organic carbon, plant detritus, calcite, and framboidal pyrite.

To assist with identification of particle sizes < 63 mm in size under SEM, standards of several mollusc species, ostracods, and *Chara* species and other carbonate-impregnated filamentous algal species were prepared for XRD and SEM analyses. The XRD analyses provided data on the range of mineralogic types that comprise skeletal grains, information particularly useful in interpreting the origin of mud-sized carbonate particles. The SEM and associated EDS analyses of known skeletal grains provided micromorphologic, microstructural, and ultrastructural standards for comparisons with wetland sediment particles, and provided information for the various mollusc species, crustaceans, and *Chara* on the range of their composition in terms of calcite and aragonite content, their Mg content in low Mg calcite and high Mg calcite, and in terms of Mg, Sr and Pb content in aragonite cements.

In the field, during appropriate seasons, various large-scale and small-scale physical and biological processes, instrumental in developing sediment types, were observed within and adjacent to wetlands. These processes, such as wave action, sheet wash, bioturbation by fauna, and desiccation, provided information on some of the mechanisms of sediment particle generation, and the development of sedimentary structures and sediment types.

Regional geologic and geomorphic setting

The Swan Coastal Plain is the Quaternary surface of the Perth Basin (Playford *et al.*, 1976). The Plain comprises distinct large-scale landforms which are either arranged subparallel to the Darling Scarp or the coast, or 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; C A Semeniuk 1988; Semeniuk *et al.*, 1989; Geological Survey of Western Australia 1990; Semeniuk 1995):

- 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 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.

The units relevant to this paper are the Bassendean Dunes, which are ergs formed during glacial periods, the Spearwood Dunes, which were composite ergs, *i.e.*, quartz sand desert ergs formed during glacial periods, and calcareous coastal ergs formed during interglacial periods (Semeniuk & Glassford 1988; Glassford & Semeniuk 1990), and the Pinjarra Plain. In these settings, there are two main lithologic / stratigraphic units that either adjoin or underlie wetlands: 1. Pleistocene quartz sand, and 2. Pleistocene limestones.

Pleistocene quartz sand is typically yellow, but varies from white to orange to locally red. Yellow sand forms thick formations landward of Pleistocene limestones on the coastal plain, but extends as sheets covering these limestones, along unconformities within the limestone, and underlies the coastal limestones (Allen 1981). The yellow sand is mostly homogeneous, but locally there is large-scale, aeolian cross-layering (Glassford & Semeniuk 1990). Towards the contact with Pleistocene aeolian limestones to the west, the yellow sand contains scattered limestone lenses (Semeniuk & Glassford 1988). Yellow sand is typically composed of quartz, with moderate to trace amounts of feldspar, and minor kaolin, goethite, and heavy minerals (Prider 1948; Glassford & Killigrew 1976; Glassford 1980). Yellow quartz sand grains have a thin coating of kaolinite clay and quartz silt impregnated with goethite (yellow) and / or haematite (red) (Glassford 1980). Goethite-pigmented kaolinite and quartz also comprise the < 90 µm fine-grained interstitial material to yellow sand (Glassford 1980).

Pleistocene limestones in near-surface sections mostly are composed of an overlapping series of aeolianites, with local lenses, wedges and thin sheets of intercalated marine units. These limestones have been referred to the Tamala Limestone, the Tims Thicket Limestone, the Kooallup Limestone, and the Peppermint Grove Limestone (Playford *et al.*, 1976; Semeniuk & Johnson, 1982, 1985; Searle & Semeniuk, 1985; Semeniuk 1995). The aeolianites are large-scale cross-layered, mainly medium sand-sized quartz, skeletal lithoclastic grainstone, cemented by sparry calcite and micritic calcite (locally forming calcrete). Limestone surfaces are mantled by yellow quartz sand, penetrated by pipes filled with yellow sand, and dissected by karst features.

Wetlands on the Swan Coastal Plain

A wide range of basin wetland types occur on the Swan Coastal Plain, varying in size, shape, water characteristics, stratigraphy and vegetation (Semeniuk 1988; Semeniuk *et al.*, 1990). Dependent on setting, wetlands can range from large linear lakes to small, round or irregular, seasonally damp wetland basins; from fresh water to hyposaline (brackish) to saline; from basins which perch surface water to those which are recharged by groundwater; with vegetation cover which can vary from herbland to forest. These attributes are determined by regional features such as geology, geomorphology, soils, climate and hydrology, and local physical/ chemical processes such as groundwater flow and karstification. While there is a large variety of wetland types across the Swan Coastal Plain, using criteria of size, shape, patterns of clustering, water quality, substrates, and maintenance processes, they can be aggregated into natural groupings that are termed consanguineous suites (Semeniuk 1988).

In this paper, the wetlands for sediment study have been drawn from the following consanguineous suites: 1. Yanchep Suite, 2. Balcatta Suite, 3. Coogee Suite, 4. Stakehill Suite, 5. Bibra Suite, 6. Jandakot Suite, 7. Riverdale Suite, 8. Gnangara Suite, 9. Mungala Suite, and 10. Bennett Brook Suite (Semeniuk 1988). Site descriptions of these settings and a description of the wetlands from which the 32 sediments were studied in more detail are provided in Appendix 2.

Types of sediment fills

Sedimentary particles

A variety of particles comprise wetland sediments, ranging from those that are biogenic, siliciclastic, to abiotic intraformationally-generated. Biogenic particles include whole shells, frustules, tests, and skeletons (*e.g.*, molluscs, diatoms), disintegrated remains of biota (*e.g.*, diatoms, charophytes), to decayed plant remains and detritus. There is a large range of organisms that inhabit wetlands of the Swan Coastal Plain (Hembree & George 1978; John 1981, 1993; Balla & Davis 1993; Davis *et al.*, 1993; Helleren & John 1994; Maly *et al.*, 1997; Chessman *et al.*, 2002), and in the arena of invertebrates and microscopic plants, many make conspicuous and/or significant contributions to the wetland sediments as skeletal remains (*e.g.*, the calcareous remains of molluscs and ostracods, the siliceous remains of freshwater sponges, the siliceous remains of diatoms, and siliceous phytoliths). There also are other organic particles that contribute mainly to the surface sediments of wetlands; *e.g.*, the chitonous tests of insects. However, while some of these latter biogenic particles can occur in the shallow stratigraphic sequences, many of the exoskeletons of invertebrate fauna, such as chitonous tests, do not survive synsedimentary diagenesis or shallow burial diagenesis. Only particles that are preserved in the sedimentary record have been described here.

XRD and EDS of shelly biota and *Chara* and carbonate-impregnated filamentous algae show the following: molluscs, depending on species, may be wholly calcitic, or Mg-calcitic, or interlayered aragonitic and calcitic (similar to the mineralogy of marine molluscs; *cf* Bathurst 1971); ostacods are calcitic, or aragonitic and calcitic; *Chara* may be calcitic, Mg-calcitic, or aragonitic; and that carbonate-impregnated filamentous algae have mediated precipitation of calcite or Mg-calcite as crusts on their cell walls. The implications are that carbonate sediments composed of, or derived from these biota will have a similar range in mineralogy.

Grains of pollen, spores, phytoliths, and microcharcoal (Clarke 1988; Faegri *et al.*, 1989; Odgaard 1992; Meunier & Colin 2001) also occur in wetland sediments, and are important in the analyses of sediments and stratigraphic sequences for palaeo-environmental studies and palaeoclimatic reconstructions. However, while their occurrence is noted, they do not contribute enough material to the sediments to be recognised as distinct wetland sediment types.

A note is made here on the use of the terms “clay mineral”, “phyllosilicate”, and “phyllosilicate clay” for particles that comprise the fine-grained component of many wetland sediments. The term “clay” has two meanings in the Earth Sciences (Jackson 1997). One has a grainsize connotation denoting particles < 4 µm. The other is as a rather imprecise mineralogical term, *viz.*, “clay mineral”, intended to cover categories of layered silicates (hence “phyllosilicate clay”) such as kaolinite, smectite, illite, halloysite, and montmorillonite (Kerr, 1959; Sinkankas 1964; FitzPatrick 1983), based on an assumption that it is finely crystalline layered silicates that dominantly comprise “clay-sized” minerals. However, as described later, calcite, quartz, goethite, and feldspar can occur as clay-sized particles, but they are not viewed traditionally as “clay minerals”, and hence the term “clay mineral” is not appropriate for use in this paper. The range in grainsize of kaolinite further complicates the use of the term “clay mineral” because in the wetland sediments of this study kaolinite manifests a variety of grainsizes: it can be very fine (< 1 µm), and hence conforming with the notion of being a “clay-sized” mineral, but can range up to medium silt size. Additionally, some micas, such as muscovite, can be comminuted to silt or clay-sized and hence occur in the < 63 µm fraction. Given these problems, the term “clay mineral” is not used in this paper, and while the term “phyllosilicate” is used to refer to the mineral group of layered silicates, it is not used in association with “clay” as it is often traditionally used. Kaolinite, white mica (muscovite), hydrobiotite, and montmorillonite, occurring in wetlands sediments, are referred to as

Table 1

Particle types in wetland sediments

mud-size particles (< 63 µm in size)
organic mud-sized particles < 63 µm, and mostly < 4 µm in size;
microcharcoal < 63 µm in size;
carbonate mud particles (calcite, Mg-calcite, aragonite, dolomite), < 63 µm in size, mostly < 4 µm in size, as comminuted shell, intraclasts, and charophytes, single crystals, and undifferentiated types;
quartz silt particles, < 63 µm in size;
phytoliths as silt-sized and clay-sized siliceous particles, < 63 µm in size;
diatom as silt-sized and clay-sized particles, < 63 µm in size;
sponge spicule fragments, < 63 µm in size;
phyllosilicate mineral particles (kaolin, montmorillonite, white mica), < 63 µm in size, mostly < 4 µm in size;
goethite mud, < 4 µm in size;
feldspar silt, < 63 µm in size;
heavy minerals (*e.g.*, haematite, rutile), < 63 µm in size (mainly silt).
sand-size particles (63 µm – 2000 µm in size)
quartz sand, mostly 125 µm to 1000 µm in size;
carbonate intraclast sand, mostly 125 µm to 2000 µm in size;
sponge spicules, mostly 100 µm to 300 µm in size;
diatom intraclast sand, mostly 125 µm to 2000 µm in size;
peat clast sand, mostly 125 µm to 2000 µm in size;
microcharcoal and charcoal 63 µm to 2000 µm in size;
carbonate shell-fragment sand, mostly 125 µm to 2000 µm in size;
heavy minerals (*e.g.*, haematite, rutile), mostly 63–125 µm in size;
gypsum crystals as single crystals and rosettes, mostly 63–250 µm in size.
gravel-sized particles (> 2000 µm in size)
carbonate intraclast gravel particles, > 2000 µm in size;
carbonate shell (gastropod) gravel, > 2000 µm in size;
diatom intraclast gravel, > 2000 µm in size;
peat intraclast gravel, > 2000 µm in size;
charcoal > 2000 µm in size.
Vegetation material
plant fibres, detritus, leaves, flowers, fruit, twigs, branches and trunks

"mud-sized phyllosilicate minerals" or as "mud-sized phyllosilicate mineral particles" to circumvent the issue that these "clay minerals" can range from clay-sized to silt-sized. Sediments composed dominantly of kaolinite are termed "kaolinitic mud" since there will be clay-sized and silt-sized kaolinite therein.

The main sedimentary particles and sedimentary components that constitute wetland sedimentary fill are shown in Table 1. The methods of identifying these sedimentary constituents in wetland sediments in this study are summarised in Table 2.

Current terms for wetland sediment types formed from the common particles

In the literature, there are a number of terms that apply to deposits formed in wetlands that are relevant to the particle types encountered in this study, *viz.*, those composed of organic (plant) matter, diatom remains, sponge material, fine-grained carbonate mud, or water saturated sand. Sediments composed of organic matter, mostly as decayed plant material, have been termed organic mud or organic ooze, sapropel to saprocol, and peat. The terms "organic mud", "organic ooze", "muck", or "gyttja" could be applied generally to deposits that are mud-sized and composed of organic carbon and decayed plant remains, but are more relevant to the immediate surface layers of organic deposits in wetlands where sediments have a degree of thixotrophy than to the more consolidated deposits at shallow to moderate depths. "Sapropel" is a term for unconsolidated jelly-like ooze or sludge composed of plant remains macerating and putrefying on the shallow bottoms of lakes and seas, and "saprocol" refers to an indurated sapropel (Jackson 1997). The terms are part of a sapropelitic series that reflect increasing consolidation into coal (*viz.*, sapropel, as organic ooze, saprocol, as indurated sapropel, and saprodil, as sapropelitic coal of Tertiary age, saprodite, and so on). In the soil literature, materials composed of accumulated organic matter (or peat) are referred to as "histosols", an order of soils (USDA 1975; FitzPatrick 1983), with further subdivision into suborders based either on the degree of decomposition, *e.g.*, "fibrist" (the least decomposed), "hemist" and "saprist" (the most decomposed), with the extent of decomposition assessed by the content of plant fibre (Soil Survey Staff 1998), or on moisture content. In the Earth Sciences, unconsolidated deposits of semi-carbonized plant remains in a water-saturated environment are referred to

Table 2

Method of identification of particle types

Mud-size particles (< 63 µm in size)	**Method of identification**
organic mud-sized particles carbonate mud particles quartz silt particles sponge spicule fragments phytoliths diatom silt and clay particles phyllosilicate mineral particles goethite mud feldspar silt microcharcoal	dealing only with the < 63 µm size class separated by sieving: combustion for organic matter; SEM and EDS; acid-digestion, and XRD, SEM and EDS for carbonate particles; SEM and EDS and light microscopy for diatoms and types of carbonate mud particles; XRD and EDS for phyllosilicate mineral particles, goethite mud and feldspar silt; high resolution petrographic microscopy for plant remains, quartz, phyllosilicate mineral particles, diatoms, phytoliths, carbonate particles, and sponge spicules.
Sand-size particles (63 µm – 2000 µm in size)	
quartz sand sponge spicules carbonate intraclast sand peat intraclast sand carbonate shell-fragment sand microcharcoal and charcoal gypsum crystals	binocular microscopy and petrographic microscopy for the quartz sand and gypsum, sponge spicules, and carbonate sand types; binocular microscopy for the peat clasts.
Gravel-sized particles (> 2000 µm in size)	
carbonate intraclast gravel carbonate shell (gastropod) gravel diatom intraclast gravel peat intraclast gravel charcoal	binocular microscopy for the peat, diatomite, and carbonate clasts; light microscopy for diatoms within clasts.
Vegetation material	
plant fibres, detritus, leaves, flowers, fruit, roots, rhizomes, culms, twigs, branches and trunks	visual inspection on excavation faces, and sieve residues, and binocular microscopy.

as "peat" (Jackson 1997). Teakle & Southern (1937) use two terms to refer to deposits (or "soils") of organic material: peat, and muck. Following Dachnowski (1920), Teakle & Southern (1937) recognised three main groups of peaty material: sedimentary or pulpy peat, fibrous peat, and woody peat. For purposes of this paper, the single term "peat" will be used for surface and subsurface sedimentary deposits composed of plant debris, plant detritus, and organic matter, in that it is a term that encompasses organic deposits that range from "ooze" to semi-consolidated material in the sense of Clymo (1983), and with varying structure, fabric and texture (from structureless, laminated, root-structured, to bioturbated, and from fibrous to massive).

Sediments composed mainly of diatoms and their fragments are "diatomite", which is synonymous with the term "diatomaceous earth" (Jackson 1997). The term "diatomaceous earth" carries with it a connotation of the sediment being porous (the result of interstitial porosity developed by platey diatom grains in randomised array in a grain-support framework, as well as intrafrustule porosity), and having low bulk density. It is this interstitial and intrafrustule porosity within "diatomaceous earth" that renders it useful as a filter for industrial and domestic purposes. However, as will be described later, diatoms comprising wetland sediments range from whole to totally fragmented frustules, and as a result, diatomaceous sediments can vary from those with properties close to "diatomaceous earth," to those composed of closely packed fine-grained silica fragments (giving broad XRD peaks typical of diatoms) with the sediment having the properties and bulk density of quartz silt. Given this range of sediment particle possibilities, the term preferred in this paper is "diatomite".

Sediments composed mainly of sponge spicules and fragments are "spongolites" (Jackson 1997). Spongolitic is used herein to refer to wetland sediments with moderate amounts of sponge spicules. There is no current term for sediments composed dominantly of phytoliths, and in this study phytoliths were not of sufficient abundance to warrant coining a lithologic term to cover this category. Phytolithic is used herein to refer to wetland sediments with moderate amounts of phytoliths and fragments.

Sediments composed of fine-grained mud-sized calcium carbonate particles have been termed "carbonate mud", or "calcilutite" (the Latin equivalent for "calcium carbonate mud"). The term "calcilutite" has had a complex and varied history. Originally introduced by Grabau (1903) to refer to limestone composed of mud-sized calcite, the meaning of the term has since expanded to encompass fine-grained limestones, consolidated calcareous mud, and unconsolidated calcareous mud (Bathurst 1971; Jackson 1997), and from an original concept involving only calcitic mud, the term now also has broadened in meaning to include aragonitic mud (Bathurst 1971). In Western Australia, the term "calcilutite" has been used to refer to formations (*e.g.*, the Bridport Calcilutite of Semeniuk & Searle 1987) as well as consolidated earlier Holocene carbonate deposits (Backhouse 1993). In this paper, conforming with the now broadened usage, addressing the issue that carbonate mud in wetlands of the Swan Coastal Plain can grade mineralogically from calcite-dominated to aragonite-dominated, and in recognition that the majority of mud deposits are calcitic or low Mg calcitic, the term "calcilutite" is used to refer to all carbonate deposits, whether consolidated, semi-consolidated, or unconsolidated, and whether the mud-sized particles comprising the calcilutite are wholly calcitic, or dominantly aragonitic, or mixtures of calcite and aragonite.

In the literature, water-saturated sand has been referred to as "gley", or "gleysol", a term in soil science referring to any water-saturated unconsolidated material (FitzPatrick 1983; FAO UNESCO 1974; USDA 1975; Jackson 1997), particularly if it is anoxic. The original term "gley" was a Russian local name for a "mucky soil mass", to connote water-saturated conditions, but has since been redefined in the Soil Sciences to denote sand or soils that are water saturated, in the reduced state (ferrous ion) and grey-green, but with ferric mottles, and within a zone of fluctuating water table (Hunt 1972, Etherington 1983, Mitsch & Gosselink 1986, Sprecher 2001). However, within the Soil Sciences, there is no connotation as to whether the water-saturated sand is a transported sediment or *in situ* soil, as the term can be applied to both settings. The term "gley" is not used in this paper to denote water-saturated sands because of this imprecision, and because the amount of water saturation of wetland sedimentary fill is not relevant to defining and describing wetland sedimentary material. Where quartz sand comprises sedimentary fill as an accretionary sedimentary deposit, it is referred to as "quartz sand". Where quartz sand comprises the Pleistocene basement substrate under the wetland fill sequence, it is referred to as quartz sand basement.

Sediment types, this paper

Ten main end-member sediment types occur in wetlands on the Swan Coastal Plain; they are: 1. peat, 2. peat intraclast gravel and sand, 3. calcilutite (carbonate mud), 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. Mixtures of these end-member sediment types also occur, as will be described later. While sponge spicules are a common component of wetland sediments, occurring within peat and diatomites, generally they do not form "spongolites". Usually, where they occur, sponge spicules and fragments may constitute up to 10% of a wetland sediment, and in this context, the term "spongolitic" `is used as a descriptor to the main wetland sediment name. The main sediments that are spicule-bearing are peats and diatomites, hence there are "spongolitic peat" and

Table 3

Description of the various types of sedimentary structures

Structure	Description/definition
layered	sediment with conspicuous layering evident on > 1 cm scale; often sediment is lithologically interlayered
laminated	sediment with conspicuous lamination evident on < 1 cm, and usually < 1 mm scale; lamination can vary from regular and even, to wavey and uneven
wispy laminated	sediment with discontinuous lamination, with individual laminae occurring as thin wisps; often the lamination is accentuated by compositional differences
homogeneous or structureless	sediment shows no structure and appears texturally and compositionally massive
fibrous	prominent structure imparted by random orientation to vertical orientation of plant fibres, roots, and (decayed) stems
root-structured	prominent structure imparted by ramifying roots
burrow-structured	prominent structure imparted by vertical burrows, where individual burrows are discernible
burrow-mottled	prominent structure imparted by burrows, where individual burrows, though overlapping, are still discernible and impart a colour or texture mottled appearance to the sediment
bioturbated	where abundant, and overprinting earlier phases of biological imprints, root-structuring, or burrowing has proceeded to the extent that individual root-structures and burrow-structures are not discernible, or only vaguely discernible, and there is an overall mottled appearance in the sediment
texture-mottled	where mottling is distinguished by textural differences, *e.g.*, sand mottles in mud
colour-mottled	where mottling is distinguished by colour differences
fenestral	small flattened cavities, usually parallel to layering, and developed in cemented carbonate intraclast sediment; fenestrae are *c.* 1 mm up to 1 cm in size (*cf.* Tebbutt *et al.*, 1965; Jackson 1997)
vesicular	small open structures produced by bubbles of air or other gases; usually a few millimetres up to 1 cm in size
brecciated	sediment exhibiting a fragmented structure, formed by desiccation and cracking at centimetre to metre scale

Figure 4. Sediments and sedimentary features from various wetlands. A. Desiccation of calcilutite forming mud crack polygons at the surface of the wetland margin during a dry phase in the hydrological cycle. B. Desiccation of diatomite forming mud crack polygons at the surface of the wetland margin during a dry phase in the hydrological cycle. Some examples of diatom mud-coated vegetation debris (twigs) are arrowed. C. Development of intraclast gravel of diatomite along a wetland margin by break-up of desiccated diatomite; older bleached diatomite intraclasts are arrowed. D. Surface layer of sediment showing several cycles of diatomite intraclasts (medium grey to bleached) incorporated into the sediment. E. Small thin lens of intraclast gravel of diatomite (arrowed) concentrated by wave action during high water. F. Concentration of diatomite intraclast gravel in a polygonal desiccation crack (outlined). G. Diatomite intraclasts (arrow 3) incorporated into the white sand apron (arrow 2) along the edge of a wetland; in this example, the thin sand deposit rests on grey diatomite (arrow 1). H. Thin veneers of white sand (arrow 2) transported into the margin of a wetland by sheet wash, forming an apron, in this example resting on dark grey diatomite (arrow 1).

"spongolitic diatomite". Similarly, peat may contain a significant proportion of diatoms and their fragments, and these sediments are termed "diatomaceous peat". Mixtures of peat, sponge spicules and diatoms are referred to as spongolitic diatomaceous peat.

To complete the picture of the variability and occurrence of wetland sediments of the central Swan Coastal Plain, it is worthwhile to note that within the Quindalup Dunes calcilutite, peat, carbonate muddy sand (to be discussed later), and quartzo-calcareous sand occur as sediment types in the Becher Suite (Semeniuk 2005), calcilutite, peat, carbonate muddy sand, intraclast gravel and sand, and stromatolitic boundstone occur at Lake Walyungup, Lake Cooloongup and Lake Richmond of the Cooloongup Suite, and calcilutite, peat, carbonate muddy sand, and quartzo-carbonate sand occur in the Peelhurst Suite (Semeniuk 1988).

The wetland sediments are described below in terms of: colour; structure (layered, laminated, wispy laminated, homogeneous or structureless, root-structured, burrow-structured, bioturbated, texture-mottled, colour-mottled, fenestral, bubble-structured or vesicular, brecciated; see Table 3); fabric (grain-support, mud-support; *cf.* Dunham 1962); texture (grainsizes of gravel, grades of sand, and mud); and composition (quartz sand, kaolinitic clay, iron oxides, carbonate mud or sand, skeletons, and opaline silica and X-ray amorphous siliceous frustules and skeletons). Some of the field settings of wetland sediments are shown and described in Figure 4. Annotated selected cores of sediments showing overall lithologic appearance and structure are shown in Figure 5. Selected photomicrographs of sediment dispersed on slides, and of SEM images are presented and described in Figures 6–11. The geographic, geomorphic and consanguineous setting of the 32 wetland sediment standards, and the results of detailed microscopy and analyses of these sediments, in terms of sand *versus* mud content, organic carbon content and carbonate content of the mud fraction, and the mineral composition of the mud determined by XRD, are provided in Appendices 2 & 3.

Peat

Peat is a black to grey, and in certain horizons, brown sediment. It is mainly homogeneous to root-structured, and in upper near-surface layers weakly laminated to compositionally layered, to fibrous; some layers at depth in peat profiles also are laminated. Texturally, peat consists of fine-grained organic matter < 63 µm in size, and larger root fibres, stem fibres, plant detritus particles and scattered (< 5%) quartz sand and quartz silt. Local deposits may contain minor amounts of freshwater snails, or their comminuted fragments. There is also a presence of fine-grained iron sulphide (evident as pyrite framboids in SEM, and detected as pyrite and marcasite in XRD), and occurrence locally of arsenopyrites. Cores through peat show an upper layer of partly decomposed leaves, stems, twigs, and roots that grades down within 30 cm, and locally within 100 cm, into fine-grained to fibrous organic material that has scattered plant material, and non-fibrous organic matter. In some peats, at depth, branches, twigs, and logs are still preserved in the fine-grained organic accumulation. Near the surface, root holes and burrows may have oxidation haloes surrounding them. The surface of peats that dry out are polygonally cracked, with desiccation cracks descending locally down to 20 cm into the peat.

In the upper parts of peat, within 10–30 cm of the surface, where the plant material is not wholly decayed, various types of vegetation contributing to the deposit can be recognised, *e.g.*, the leaves of *Melaleuca rhaphiophylla* and *M. cuticularis*, and the leaves, stems and rhizomes of *Baumea articulata* and *Typha* spp (Fig. 5A–C). Roots and plant fibres are also common in these upper layers. Grain-mount microscopy and SEM show peat to be composed of plant detritus in various stages of fungal and bacterially induced structural breakdown (Fig. 8). For instance, large particles are riddled with fungal hyphae.

SEM and petrographic microscopy of many homogeneous or structureless, fine-grained, black to dark grey peat-like materials show them also to have a significant component of diatoms and/or sponge spicules, and siliceous phytoliths. Where diatoms and sponge spicules are abundant, the peats become diatomaceous or spongolitic peat. Sponge spicules and diatoms in peat range from complete spicules and frustules to largely fragmented particles.

Since peat can grade into organic matter rich diatomite and organic matter rich calcilutite, the lithological boundary of peat is set at > 75% content of organic matter (as dry weight), and sediments containing 74%–50% organic matter mixed with diatoms, or calcilutite, are termed diatomaceous peat and calcilutaceous peat respectively (see later). The content of organic matter as dry weight in some typical peats is presented in Table 4.

Multiple values of organic matter content reflect variablity of peat composition spatially, where samples have been collected at a number of sites within a large wetland, or from several proximally located small wetlands within the same consanguineous suite, or collected stratigraphically at the one site.

Peat intraclast gravel and sand

Peat intraclast gravel and sand are a black to grey coarse-grained suite of sediments, ranging from breccias,

Table 4

Content of organic matter in some typical peats on the Swan Coastal Plain (for co-ordinates of locations see Appendix 1)

Location of sample (ordered south to north)	% organic matter
Australind wetlands	94, 75
Riverdale wetlands	80, 90
Lake Mealup	96
Wawa Swamp	75
Forrestdale Road Swamp	78, 88, 77
Leda Swamp	95
Karrinyup Road Swamp	90, 75, 90
Lake Gwelup	78, 83, 84, 83, 89, 95,
Lake Goolelal	90
Beenyup Swamp central	78, 79
Beenyup Swamp south	79, 80, 81, 80, 81, 80, 95
Waluburnup Swamp	89
Ellenbrook Swamp	89, 83
Melaleuca Park	90, 75

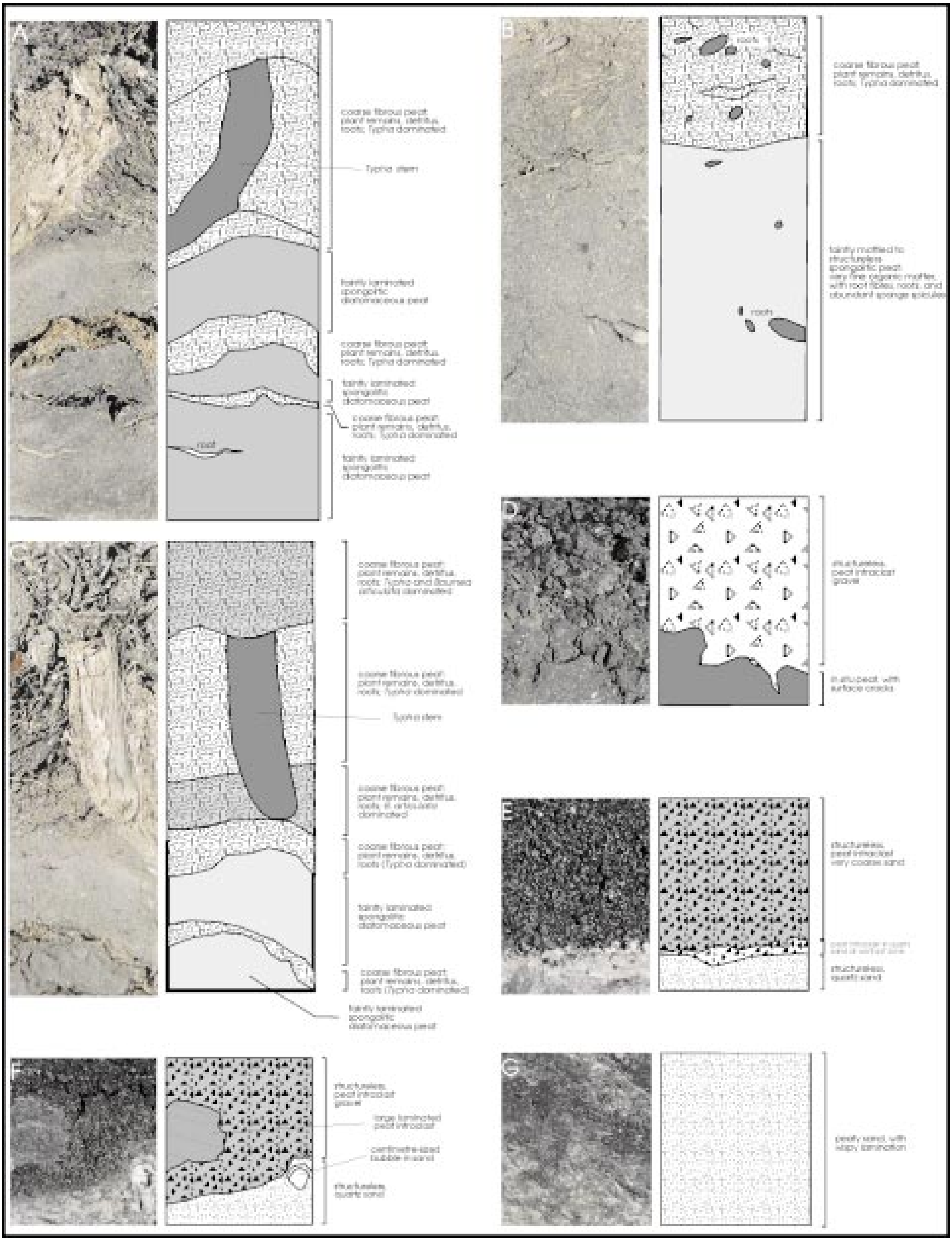
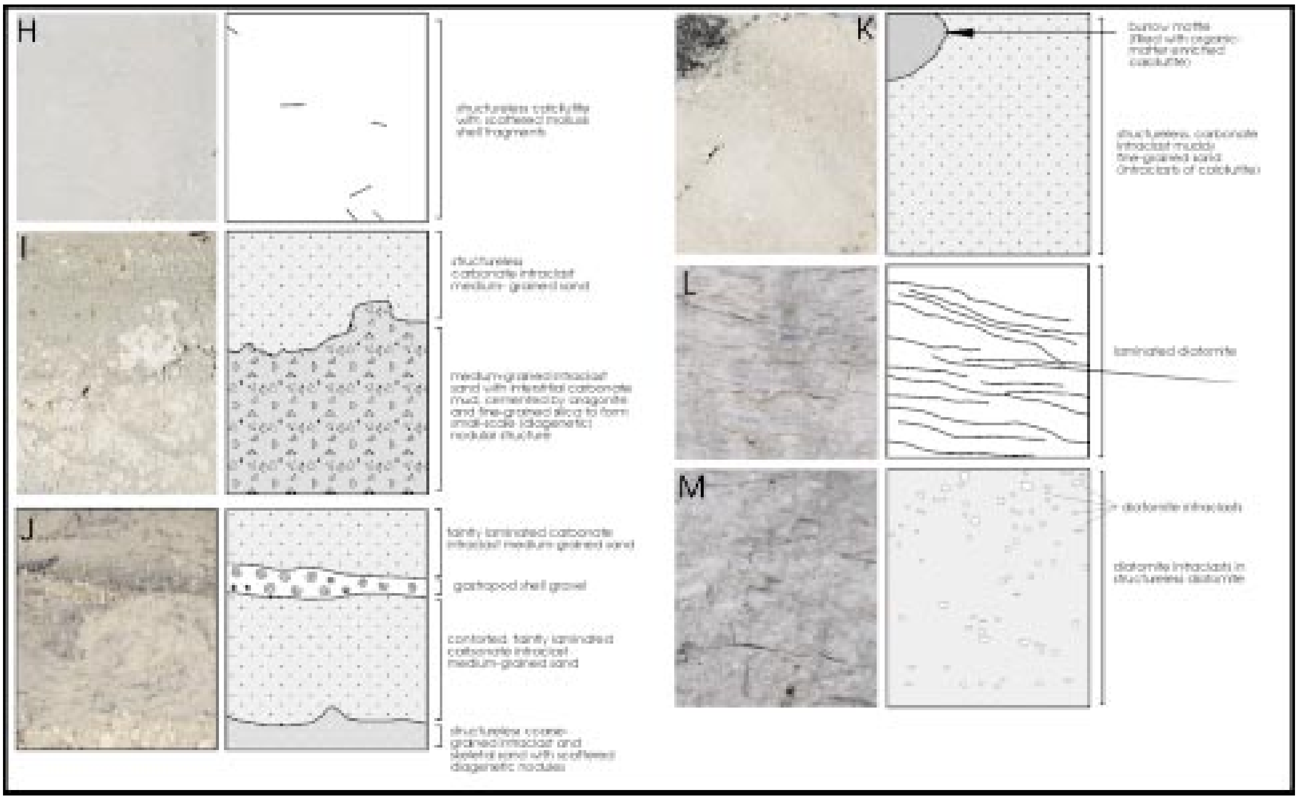


Figure 5. Annotated cores of selected sediments (width of all cores is 10 cm). A–C. Cores of peat. D–G. Cores of peat intraclast gravel and sand, quartz sand, and peaty sand. G–K. Cores of calcilutite, and carbonate intraclast gravel and sand. L–M. Cores of diatomite, and diatomite intraclast gravel.



with fragments *c.* 1 cm (gravel-sized angular fragments of peat), down to sand size (Fig. 5D–F). Chemically, and in terms of the texture of the fine-grained organic matter that comprise the breccia clasts and sand, they are similar to the peat deposits described above. Structurally and granulometrically, however, the sediments are homogeneous, brecciated to conglomeratic, grading to sand-sized clasts of peat, or are layered with alternating grain size (pebble-sized, very coarse sand-sized, to coarse sand-sized fragments of indurated peat) of breccia and conglomerate, and locally root-structured. Texturally, these deposits consist of gravel to sand-sized angular to rounded clasts of peat set in a fine-grained organic matter < 63 µm in size, with root fibres, plant detritus particles and scattered quartz sand. Cores through peat intraclast gravel and sand show alternating grainsize-differentiated layers of peat clasts, and locally, vesicular structure.

Calcilutite

Calcilutite is cream, pink, or grey fine-grained carbonate sediment (Fig. 5H). The sediment is homogeneous, laminated, burrow-mottled, root-structured, bioturbated, or colour mottled. Texturally, the calcilutite consists of mixtures of silt-sized and clay-sized carbonate particles 63 µm to < 1 µm in size, ranging down to sediments composed dominantly of carbonate clay-sized particles, generally < 4 µm. Compositionally it is mainly calcite, with lesser amounts of organic carbon. In some wetlands, there is admixed Mg-calcite, aragonite and dolomite, and in some the muds are dominantly aragonitic. The sediment may contain freshwater snails and/or pelecypods, and ostracods, as gravel or sand-sized components, or their comminuted fragments, in layers, or scattered in random orientation throughout the sediment in low abundance (< 5%). The gradation of gravel and sand-sized particles through to clay-sized particles with consistent microstructure and ultrastructure throughout, together with the elemental composition determined by EDS, indicate that the < 63 µm fraction of carbonate particles is the accumulation of disintegrated (highly comminuted) mud-sized remains of charophytes and calcareous fauna such as molluscs and crustaceans. Reflecting the various biotic sources, calcilutite particle mineralogy may be calcite, low Mg calcite (Mg content 1–4%), high Mg calcite (Mg content 4–10%), and aragonite, with the particles deriving from calcitic shell, or disintegrated charophytes of calcitic or Mg-calcite mineralogy, or Mg-calcite shell, or aragonitic mollusc shell, respectively). The mineralogy of the mud also depends on the range of diagenetic precipitates that may occur within the sediment (*e.g.*, aragonite crystal sprays, or dolomite).

Using a modern species of *Chara* as an example, Figure 9 A,B,C illustrates the progression from 10–50 micron-sized aggregates (internally composed of units of micron-sized carbonate crystals), embedded in the walls of *Chara*, through to particulate carbonate sediment of micron-sized crystals. Calcilutite composed of fine-grained particles derived from invertebrate skeletons is shown in Figures 9 E & F. Similar transitions can be documented for the disintegration of carbonate-impregnated filamentous algae to calcitic and Mg-calcitic mud.

Carbonate skeletal gravel and sand

Carbonate skeletal gravel and sand are a cream or grey medium to coarse grained suite of sediments.

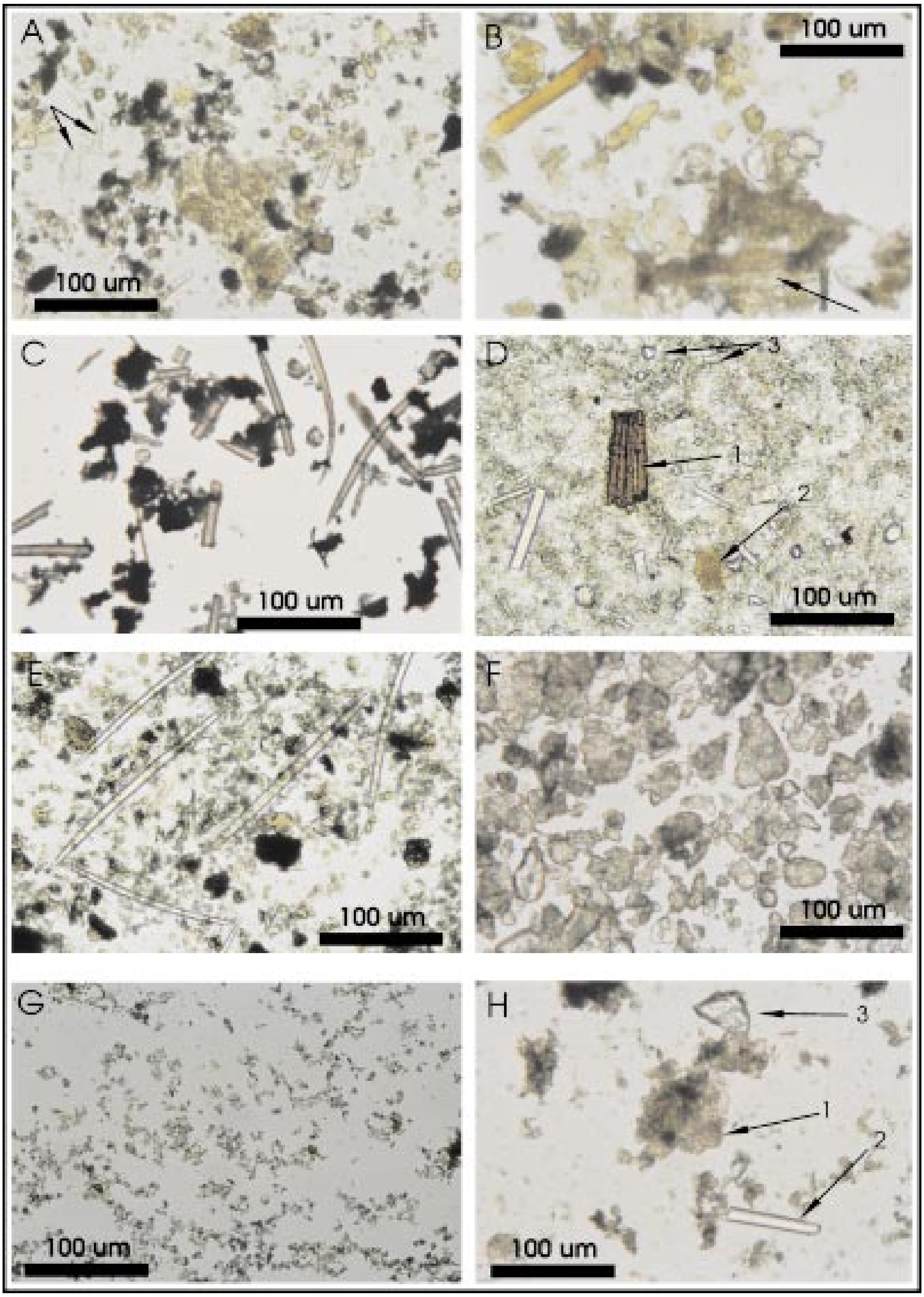


Figure 6. Annotated photomicrographs of standard particles in the fine-grained fraction of wetland sediments. Scale bar on all photomicrographs is 100 µm. Photomicrographs of the sand fraction is with reflected light through a stereoscopic microscope using a black background to the slide. All photomicrographs of the fine-grained fractions are using plane polarised transmitted light, except for (G), in which the light is partly cross-polarised. A. Organic matter (honey brown) in peat from Karrinyup Road Swamp, with scattered diatom debris (arrowed). B. Organic matter (brown and light honey brown) in peat from Karrinyup Road Swamp, with vestiges of cellular structure (arrowed) in the plant matter. C. Organic matter (dark particles) and sponge spicules and their fragments in peat from the shore of Lake Joondalup. D. Cellular plant material (arrow 1), homogenous plant material (arrow 2), quartz silt (arrow 3), and fragments of sponge spicules in a matrix of diatom silt; sample is the interstitial material from a diatomaceous peaty quartz sand. E. Sponge spicules in a diatom silt; sample of diatomite from wetland basin within Bassendean Dunes area east of Yanchep. F. Interstitial material from a kaolinitic muddy sand; the dominant mineral is kaolinite, with scattered quartz silt. G. Fine-grained calcite particles from a calcilutite, Lake Coogee. H. Carbonate intraclast (arrow 1), broken sponge spicule (arrow 2), and quartz silt (arrow 3) from a carbonate intraclastic sediment from Lake Coogee.

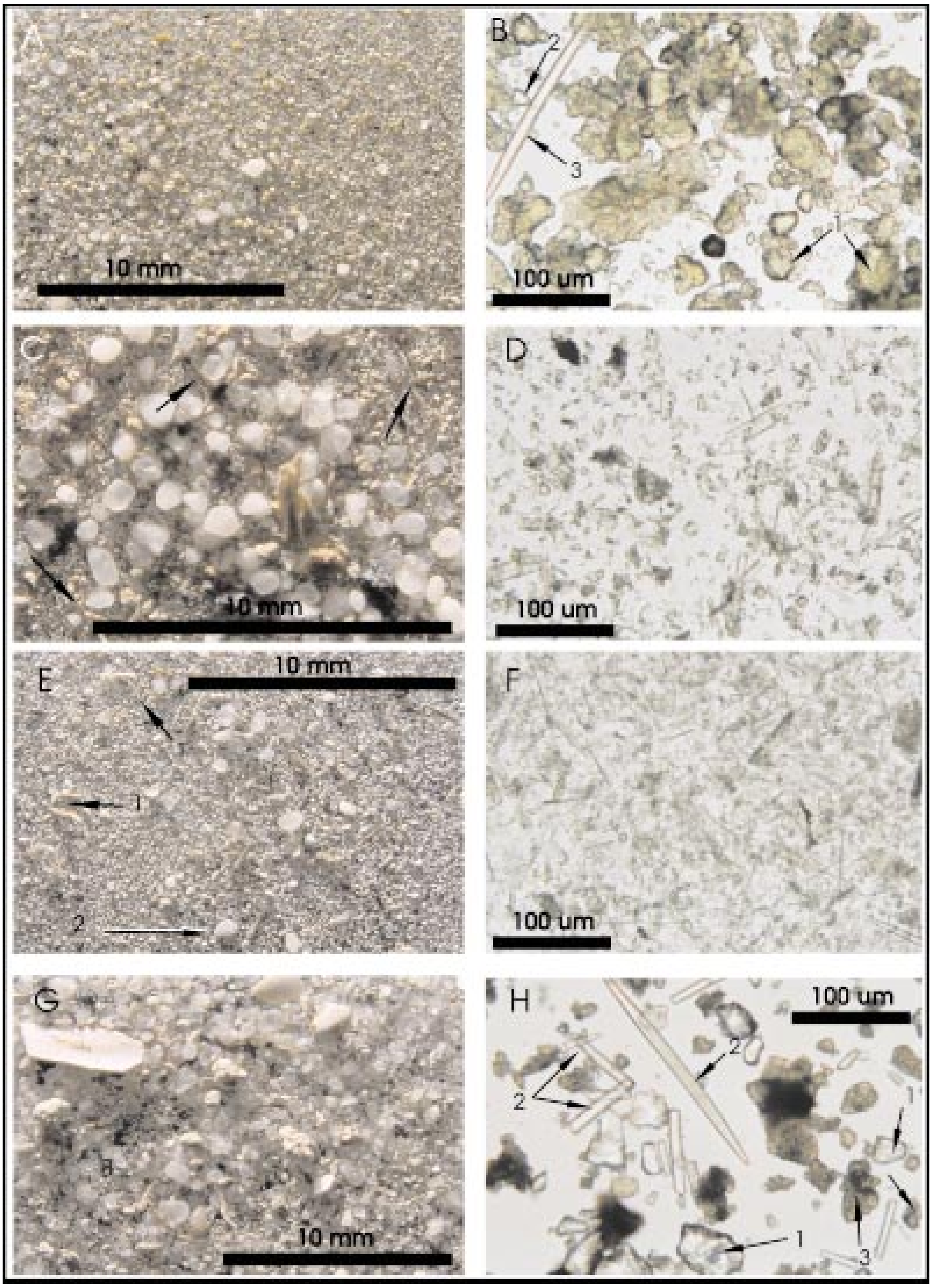


Figure 7. Paired annotated photomicrographs of grain mounts and mud particle mounts of the gravel-sized, sand-sized, and the fine-grained fractions of wetland sediments to illustrate their characteristics. For correlation of these photomicrographs with the description of the wetland setting and the wetland sediments, see Appendices 2 & 3. Scale bar on all photomicrographs of the sand fraction is 10 mm. Scale bar on all photomicrographs of fine-grained sediment is 100 µm. A & B: Sample No. 15 from Lake Mungala. A. Sand fraction of wetland sediment showing bleached and orange quartz sand grains. B. Mud-sized phyllosilicate minerals (arrow 1), quartz silt (arrow 2), and sponge spicule (arrow 3) comprising the fine-grained fraction of the sediment. C & D: Sample No. 18 from Melaleuca Park. C. Sand fraction of wetland sediment showing bleached quartz sand grains, and vegetation (root) fibres (arrowed). D. Hash of diatom frustule fragments and plant matter (dark grains) comprising the fine-grained fraction of the sediment. E & F: Sample No. 20 from Casuarina Swamp. E. Sand fraction of wetland sediment showing bleached quartz sand grains, fine sand-sized diatomite intraclasts, vegetation (root) fibres (arrow 1), and a rounded intraclast of diatomite (arrow 2). F. Hash of diatom frustule fragments comprising the fine-grained fraction of the sediment. G & H: Sample No. 32 from Bollard Bullrush Swamp. G. Sand and gravel fraction of wetland sediment showing bleached quartz sand grains, and mollusc gravel-sized and sand-sized skeletons. H. Quartz silt (arrow 1), sponge spicule and spicule fragments (arrow 2), and mud-sized phyllosilicate minerals (arrow 3) comprising the fine-grained fraction of the sediment.

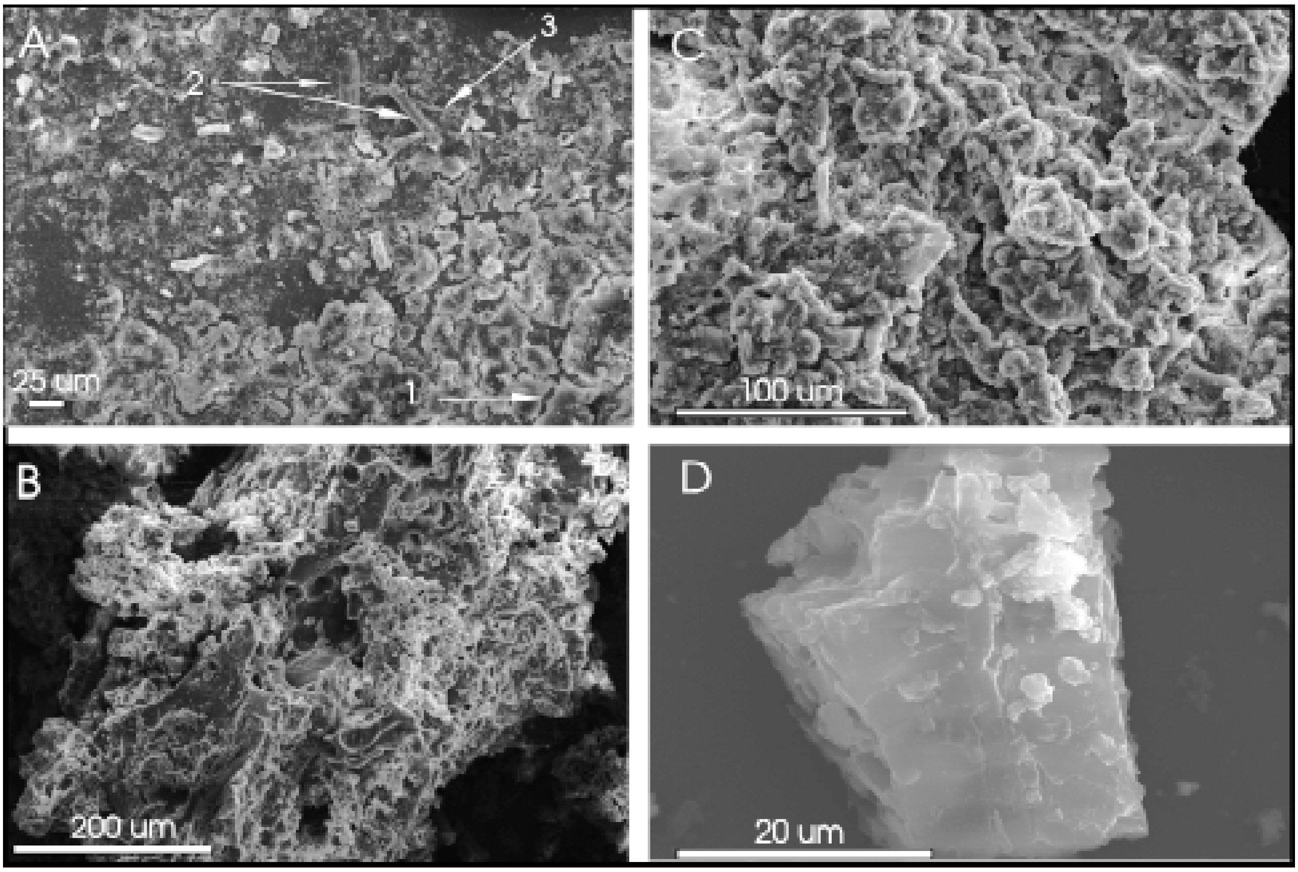


Figure 8. SEM photomicrographs showing features of peat. A. Overview of sample from Willie Pool showing general fine-grained nature of the peat (arrow 1; desiccation in the SEM photograph is due to the vacuum process), phytoliths (arrow 2), and root fibres (arrow 3). B. Plant detritus comprising the peat at Leda Swamp, showing material riddled with fungal hyphae and cavities produced by bacterial activity. C. Relict structures of plant detritus, here riddled with fungal hyphae and cavities produced by bacterial activity. D. Close-up of plant detritus from peat at Leda Swamp.

Structurally, the sediments are homogeneous to layered. Where sand-sized, the sediments grade from very coarse to medium sand. Compositionally, the sediments consist of whole and fragmented skeletons of molluscs, gastropods and/or pelecypods, and locally ostracods. The sediments commonly form layers in carbonate mud or peat deposits (Fig. 5J).

Carbonate intraclast gravel and sand

Carbonate intraclast gravel and sand are a cream or grey medium grained to coarse grained suite of sediments. They have homogeneous to layered structure, and local vesicular to fenestral structures (Fig. 5I–K). Texturally, where sand-sized, the grade is medium, coarse to very coarse grained. Compositionally, four types of intraclast are recognised: 1. clasts of calcilutite that essentially were dried, fragmented and reworked into intraclast sand; 2. clasts of carbonate cemented calcilutite, reworked into intraclast gravel and sand; 3. clasts of carbonate cemented intraclast sand (polycyclic intraclasts), reworked into intraclast gravel and sand; and 4. clasts of carbonate cemented skeletal sand, reworked into intraclast gravel and sand. Carbonate intraclast gravel and sand has formed within wetland basins, and particularly along their margins, where desiccation has cracked and fragmented calcilutite deposits, and high water wave conditions have reworked and rounded them to form thin shoreline deposits (Fig. 4A).

Diatomite

Diatomite is light grey fine-grained sediment, though locally dark grey to brown in organic-rich layers. It is homogeneous to root-structured at the surface, and laminated to structureless at depth (Fig. 5L). Grey to dark grey to brown diatomite has disseminated organic matter and/or fine-grained pyrite. Diatomite consists of silt-sized to clay-sized diatom skeletons and particles (Fig. 10). It may have scattered (< 5%) quartz sand and quartz silt. Diatomite ranges from porous sediment with low bulk density (composed of whole and fragmented diatom tests) to a compacted, dense sediment with relatively higher density (composed largely of wholly fragmented tests). This latter sediment, as mentioned earlier, has the bulk properties of a quartz siltstone or silt deposit (*i.e.*, not porous, but compact, and with a moderate bulk density unlike traditional "diatomaceous earth").

Diatomite intraclast gravel and sand

Diatomite intraclast gravel and sand are a light grey medium to coarse-grained suite of sediments, composed of rounded fine gravel to sand-sized sized clasts of diatomite (Fig. 5M). Diatomite intraclast gravel and sand form within wetland basins, and particularly along their margins, where desiccation has cracked and fragmented diatomite deposits and high water wave conditions have reworked and rounded them to form thin shoreline

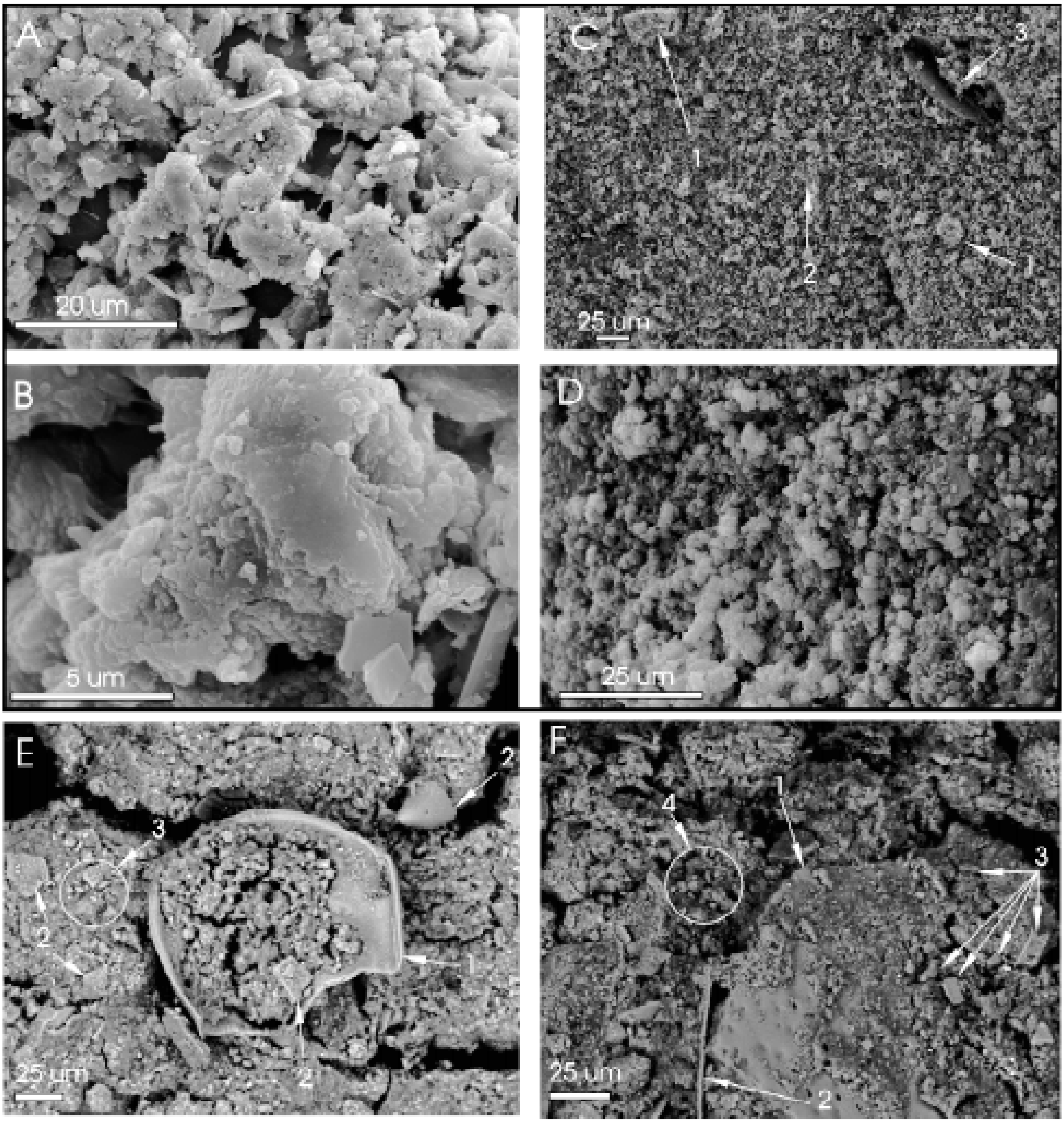


Figure 9. SEM photomicrographs showing nature of calcite impregnation of living *Chara*, and fine-grained constituents of calcilutite A. Overview of *Chara* exterior showing calcite crystals forming aggregates or clusters 10–20 µm in size. B. Close-up showing calcite aggregates in *Chara* with crystal components within aggregate from 5 to < 1 µm in size. Disintegration of these calcite aggregates will result in polycrystalline particles *c* 5 µm in size down to single unit crystal particles *c* 1 µm in size. C. Calcilutite from Lake Coogee showing various aggregates and sizes of carbonate grains, and their progressive disintegration from larger fragments of *Chara*, 25–30 µm in size (arrow 1), to smaller crystals, 1–4 µm in size (arrow 2); invertebrate skeletal fragments are scattered in the sediment (arrow 3). D. Close-up of calcilutite from Lake Forrestdale showing general fine-grained nature of the carbonate crystals 1–2 µm in size to < 1 µm in size, similar to crystal size and morphology of calcite crystals shown in *Chara* in (B) above. E. Close-up of calcilutite showing progressive comminution of calcareous invertebrate skeletons to form silt and clay sized carbonate particles: sand-sized skeletal particle (arrow 1); skeletal fragments *c* 25 µm in size (arrows 2); circled area (arrow 3) where there is a range of skeletal particle sizes from 10 µm to 1 µm in size. F. Close-up of calcilutite showing progressive comminution of calcareous invertebrate skeletons to form silt and clay sized carbonate particles: sand-sized skeletal particle (arrow 1) with perforated wall structure; coarse silt-sized skeletal fragment *c* 50 µm in size (arrow 2); a range of skeletal particles decreasing in size from 5–10 µm to 1 µm in size (arrows 3); circled area (arrow 4) where there is a range of skeletal particle sizes from 5 µm to 1 µm in size.

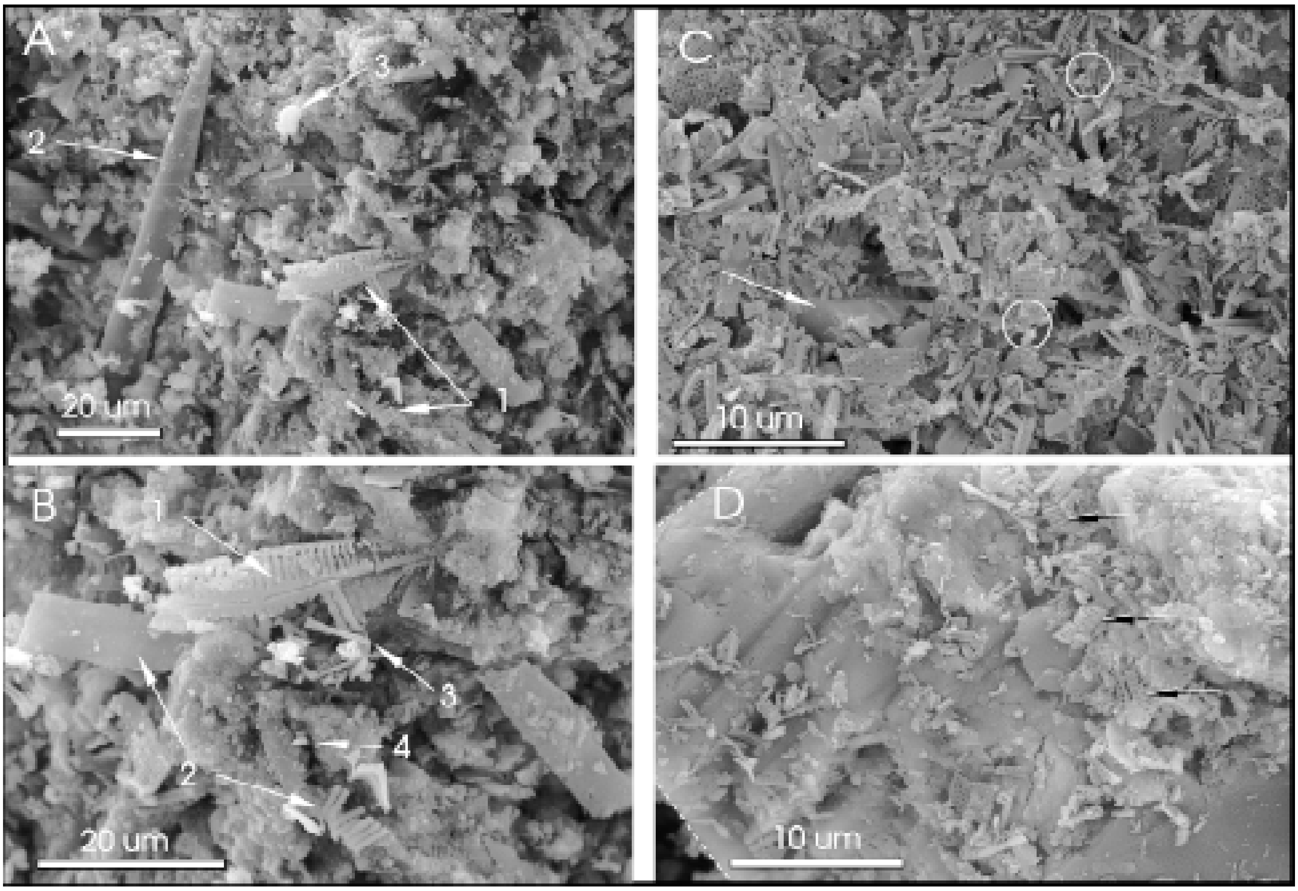


Figure 10. SEM photomicrographs of diatomite. A. Diatomite from a wetland basin in the Bassendean Dunes, east of Yanchep, showing typical view of diatom frustules in various stages of fragmentation (arrow 1), sponge spicule (arrow 2), and scattered kaolinite particles (arrow 3). B. Close-up showing the stages of fragmentation of diatom frustules: semi-complete diatom valve (arrow 1), 30 µm in size, fragmented valves (arrow 2) and (arrow 3), 15 µm in size, and 3–5 µm in size, respectively, leading finally to small fragments (arrow 4), < 1 µm in size. C. Close-up of diatomite from Lake Gnangara, showing diatoms in generally fragmented state; fragments show clear wall features such as sieve structure; particle sizes are mainly 1–5 µm; examples of diatom fragments < 1 µm in size are circled; the sample contains scattered quartz silt (arrow). D. Close-up of diatomite from Lake Gnangara showing diatom frustules in various stages of fragmentation from 3 µm in size, and showing wall structure (arrows), to 1–2 µm in size, and showing remnants of wall structure, to < 1 µm in size and structureless; the particles in this SEM view are adhering to a quartz silt particle (partial margin outlined).

deposits (Fig. 4B–G). Commonly, the intraclasts are embedded in a fine-grained diatomite matrix.

Kaolinitic mud

Kaolinitic mud deposits vary from white, orange, dark brown, and dark grey to black, and are homogeneous to root-structured. Locally, the mud beds exhibit polygonal cracks. Texturally, the mud deposits are composed of mostly clay-sized and silt-sized particles with scattered (< 5%) quartz sand. In sumpland and former sumpland basins, there also is occurrence within the kaolinitic mud of fragmented diatoms, sponge spicules and phytoliths. Compositionally, while these deposits are mainly kaolinite, locally, there may be some montmorillonite and fine-grained white micas such as muscovite or paragonite. Admixed with kaolinitic mud deposits also are small amounts of quartz and feldspar silt.

Quartz sand

Quartz sand is white, or light to dark grey deposit that is structurally homogeneous, bioturbated or root-structured, locally wispy laminated, and locally vesicular (Fig. 5E–F). In some areas, where freshwater crustacea are common, the sand is burrow-structured, with vertical burrows, up to several centimetres in diameter. Texturally, quartz sand is mostly well sorted, medium-grained and well rounded, though it may vary to poorly-sorted, mixed coarse, medium and fine in grainsize. Its composition is dominantly quartz, with minor feldspar, and minor amounts of heavy minerals.

Quartz silt

Quartz silt is cream to light grey, and structurally homogeneous to root-structured. It consists of silt-sized and some clay-sized silica particles, with scattered (< 5%) quartz sand. In sumpland and former sumpland basins, there is occurrence of fragmented diatoms, sponge spicules and phytoliths in the sediment. Deposits of quartz silt form only thin units in isolated wetlands.

Mixtures of sediments

While the sediments described above occur as end-member types, many wetland deposits are mixtures of these. The most important gradational series are between

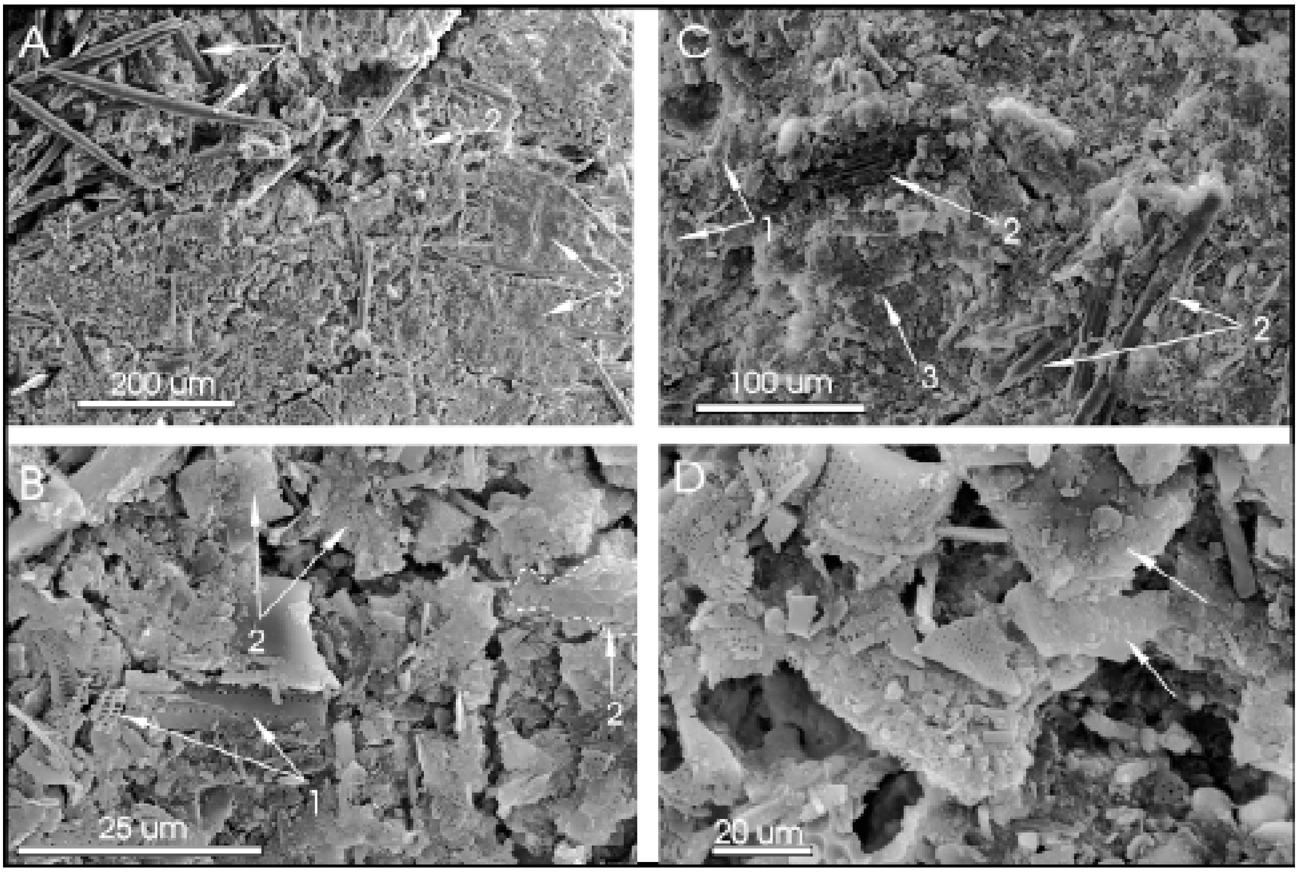


Figure 11. SEM photomicrographs of diatomaceous peat. A. Overview showing abundance of whole and fragmented sponge spicules, 200–250 µm in size (arrow 1), scattered diatom fragments (arrow 2), and the fine-grained organic matter that dominates the sediment, here showing cracking by desiccation (arrow 3), as a result of carbon-coating under vacuum in the SEM process. B. Close-up of typical fragments of diatom frustules, 5–20 µm in size (arrow 1), in various stages of disaggregation, and fine-grained plant detritus with layered internal structure (arrow 2). C. Overview of interstitial sediment of peaty sand from a wetland basin in the Ellenbrook area showing diatom fragments (arrow 1), plant remains and fibres (arrow 2), and phytoliths (arrow 3). D. Close-up showing diatoms in various stages of fragmentation from 20 µm in size to < 1 µm in size, and plant detritus (arrows).

the biogenic mud-sized sediments (*i.e.*, peat, diatomite and calcilutite), and between quartz sand and mud-sized components.

In the sediments dominated by biogenic mud-sized components, there may be a gradational series of sediment types between peat, diatomite, and calcilutite, *i.e.*, organic matter, diatoms and carbonate mud are mixed together to form a variety of mud-dominated sediments. Sponge spicules generally are not abundant enough in the wetland sediments to form spongolites, and hence in this paper are not considered to be an end-member biogenic sediment type. In this study they were most abundant in a thin layer of peaty sediment at Lake Gwelup, contributing *c.* 50% of particles to the sediment; in this context, the sediment is a spongolitic peat. A simplified classification and nomenclature of the three end-member biogenic fine-grained sediment classes and the sediments produced as mixtures of organic matter, diatoms and carbonate mud is presented in Figure 12A. The sediment types formed in this manner are: diatomaceous peat, calcilutaceous peat, organic matter enriched diatomite, organic matter enriched calcilutite, organic matter enriched diatomaceous calcilutite, diatomaceous calcilutite, and calcilutaceous diatomite (rare). The classification presented in Figure 12A involves only mixtures of biogenic mud-sized components and not mixtures of mud-sized and sand-sized components. Analyses from some 100 fine-grained wetland sediments are superimposed on the ternary diagram in Figure 13A to illustrate the variability in composition of these types of wetland sediments.

Generally, kaolinitic mud does not form significant mixtures with the biogenic muds. However, if there is admixed organic matter, carbonate mud, diatoms and kaolinite mud, the following nomenclature is proposed. With > 75% kaolinite, the sediment is kaolinitic mud. With 50–75% kaolinite, and diatoms or organic matter comprising the remaining 25–50% of the sediment, the sediment is termed diatomaceous kaolinitic mud, organic-matter enriched kaolinitic mud, or organic-matter enriched diatomaceous kaolinitic mud. With 25–50% kaolinite mud, the term “kaolinitic” becomes an adjectival descriptor to be added to one of the various mud sediment terms illustrated in Figure 12A, *e.g.*, kaolinitic organic matter enriched diatomite, or kaolinitic diatomaceous peat. Where the mud component is not kaolinite, the term “phyllosilicic mud” replaces “kaolinitic mud”.

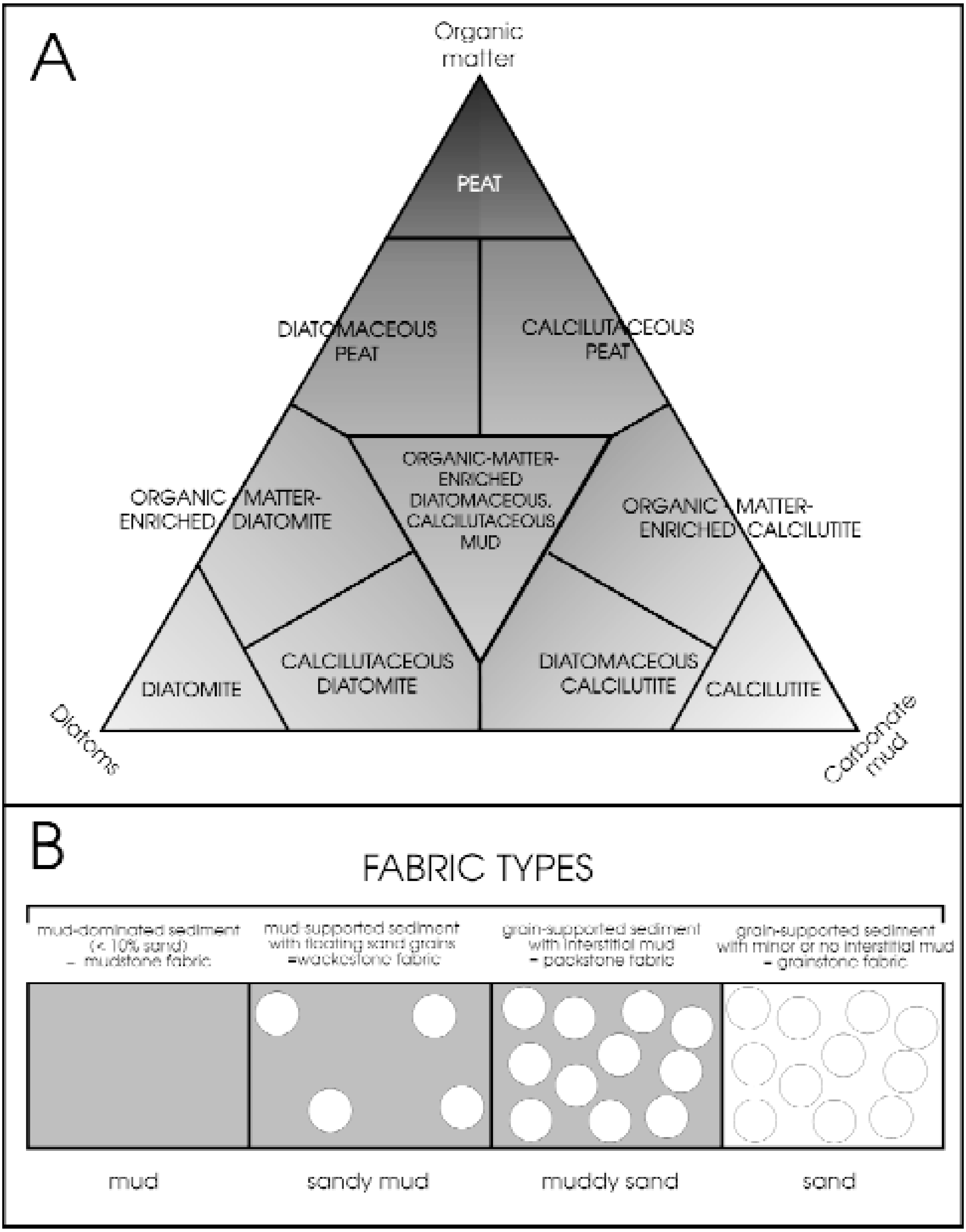


Figure 12. A. Ternary diagram illustrating the categories and the proposed nomenclature for fine-grained sediment types that occur as end-members or as mixtures involving organic matter, diatoms, and carbonate mud. B. Conceptual diagram illustrating the intergradational sediment fabrics, from grain-support to mud-dominated (after Dunham 1962), used to partition the range of sediment types between sand and mud, with intermediates of muddy sand and sandy mud. The terminology of the mud fraction in the muddy sands and sandy muds follows the classification in (A) above. Also see text for explanation, and Appendix 3 for application of the classification.

Table 5

Categories of sediments transitional between sand and mud (fabric nomenclature after Dunham 1962)

Sediment fabric category	Wetland sediment type
composed wholly of sand grains in grain-support fabric (= grainstone fabric of Dunham 1962)	sand
composed of sand grains in grain-support fabric with interstitial mud (= packstone fabric of Dunham 1962); categorisation of interstitial mud follows Figure 12A	peaty sand, diatomaceous muddy sand, calcilutaceous muddy sand, kaolinitic muddy sand, organic matter enriched diatomaceous muddy sand, organic matter enriched calcilutaceous muddy sand,
composed of sand grains floating in a mud-support fabric (= wackestone fabric of Dunham 1962); categorisation of mud follows Figure 12A	sandy peat, sandy diatomite, sandy calcilutite, sandy kaolinitic mud, sandy organic matter enriched diatomite, sandy organic matter enriched calcilutite
composed wholly of mud-sized particles (= mudstone fabric of Dunham 1962); categorisation of mud follows Figure 12A	peat, diatomite, calcilutite, kaolinitic mud, organic matter enriched diatomite, organic matter enriched calcilutite

In regards to the gradation between quartz sand and mud-sized components (*i.e.*, quartz sand and peat, diatomite, calcilutite, or kaolinitic mud), the intermediates are peaty quartz sand (Fig. 5G) and sandy peat, diatomaceous (muddy) quartz sand and sandy diatomite, calcilutaceous (muddy) quartz sand and sandy calcilutite, and kaolinitic muddy sand and sandy kaolinitic mud, respectively (Table 5). There also are intermediates between intraclast sand and calcilutite (Fig 5K) and diatomite intraclast sand and diatomite. A simplified classification and nomenclature of the fabric classes and hence sediment classes for the mixtures between sand and mud is presented in Figure 12B. Fabric rather than percentage boundaries are used to separate the classes of muddy sand and sandy mud because the category of "grain-support" will have different size of interstitial space, and hence different sand to mud ratio, dependent on grain shape and sphericity (*e.g.*, Plates I & II of Dunham 1962). While the descriptor terms "peaty", "diatomaceous", and "calcilutaceous" carry implication that these sediment types are muddy sands, we suggest that the term "muddy" be inserted between the descriptors referring to the mud fraction and the term "sand", *e.g.*, calcilutaceous muddy sand. If the mud-sized fraction is left undifferentiated as to its particle types, the sediments may be termed "muddy sand" or "sandy mud". If the composition of the muddy component of the sediment is known and has been classsified as to its position on the ternary diagram, the category of the "mud" in the muddy sand can be adfixed to the sediment name. e.g., organicmatter enriched diatomaceous muddy sand. Analyses of the fine-grained interstitial material from some 50 wetland sediments are superimposed on the ternary diagram in Figure 13B to illustrate the variability in composition of the interstitial material in these types of wetland sediments.

The "muddy" sands are intermediate sediment types between wetland sands and biogenic muds and usually form where peat, diatomite, or calcilutite accumulations are interspersed with the influx of quartz sand from wetland basin margins (Fig. 4H), or at the basal transitional infiltrational zone where the fine-grained wetland sediment fill stratigraphically rests on the underlying basement sand (Fig. 14). In the cases of peaty quartz sand, diatomaceous quartz sand, and calcilutaceous quartz sand, the mud-sized components are interstitial to the grain-support sand framework. In the cases of sandy peat, sandy diatomite, sandy calcilutite, and sandy kaolinitic mud, quartz sand is dispersed in the mud-support matrix.

While phytoliths are not abundant enough in the sediments encountered in this study to constitute an end-member wetland sediment type, locally they comprise the dominant interstitial fine-grained component of muddy sands. In this context, these sediments are termed phytolithic muddy sand.

The range of common wetland sediments encountered in this study is listed in Table 6.

Table 6

Range of most common wetland sediments encountered in this study

peat
diatomite
calcilutite
kaolinitic mud
quartz sand
quartz silt
skeletal gravel and sand
peat intraclast gravel and sand
carbonate intraclast gravel and sand
diatomite intraclast gravel and sand
peaty quartz sand
sandy peat
diatomaceous muddy quartz sand
sandy diatomite
calcilutaceous muddy quartz sand
sandy calcilutite
kaolinitic muddy quartz sand
sandy kaolinitic mud
diatomaceous peat
organic matter enriched diatomite
sandy organic matter enriched diatomite
calcilutaceous peat
organic matter enriched calcilutite
sandy organic matter enriched calcilutite
organic matter enriched diatomaceous calcilutite
sandy organic matter enriched diatomaceous calcilutite
organic matter enriched kaolinitic mud
organic matter enriched diatomaceous kaolinitic mud
phytolithic muddy sand

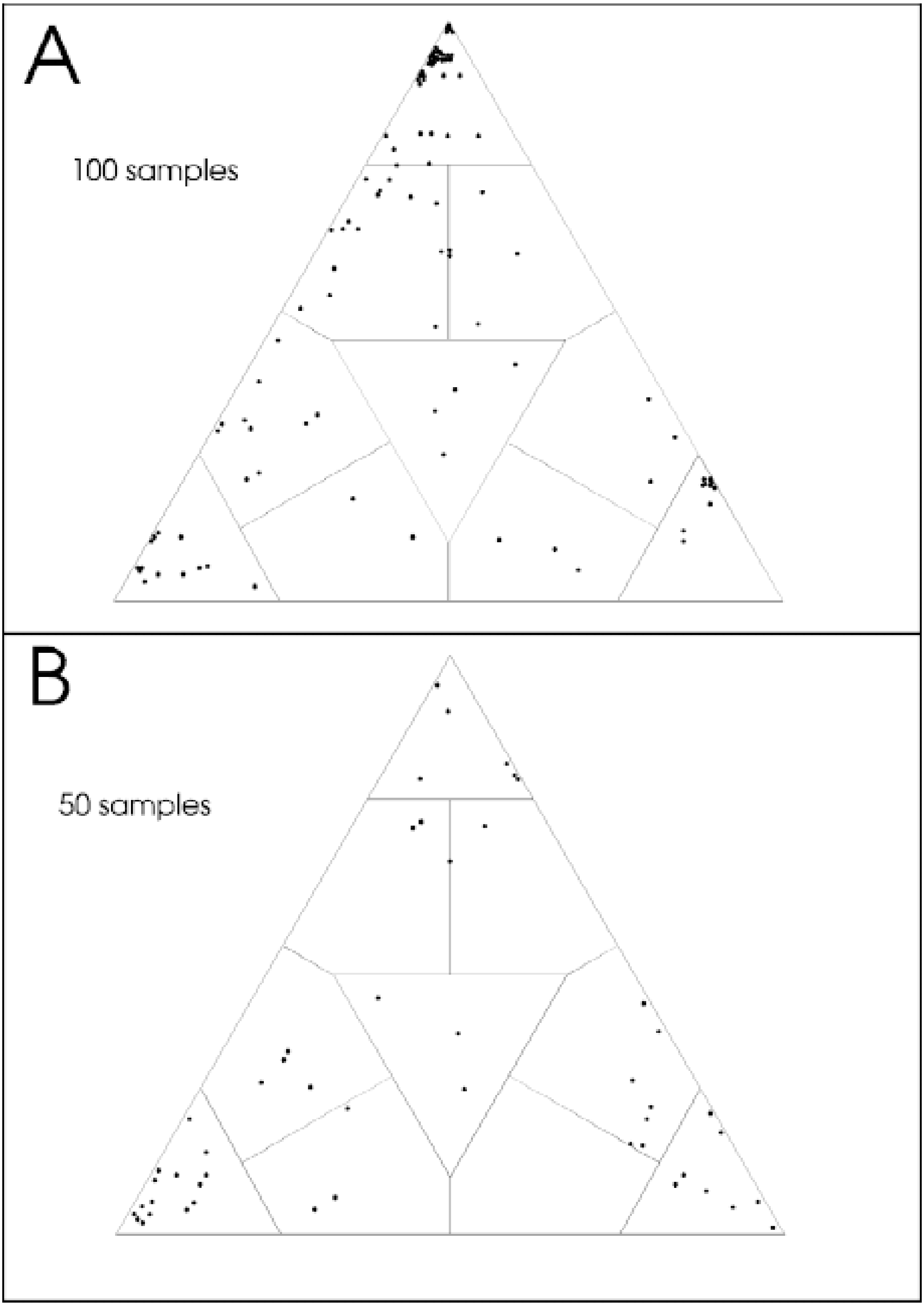


Figure 13. Ternary classification diagram of wetland sediment with superimposed results of laboratory analyses of a range of wetland sediments showing the variability of their composition. A. Results using 100 fine grained biogenic wetland sediments. B. Results using the fine grained material occurring interstitially in 50 wetland “muddy” sands.

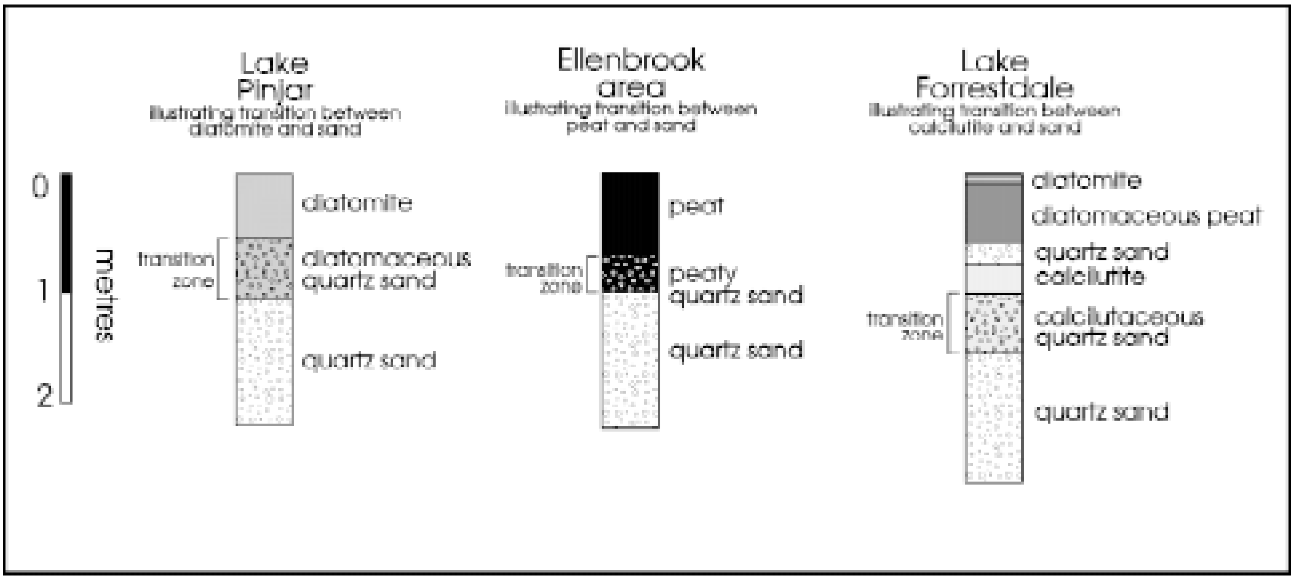


Figure 14. Examples of typical transitions of fine-grained wetland sediment (diatomite, peat, and calcilutite) into underlying basement sand to form "muddy" sand (specifically, diatomaceous sand, peaty sand, and calcilutaceous sand, respectively).

Suggested use of descriptors

The various sediment types described above can be discriminated further by use of adjectival descriptors, the most important of which are the subdominant to minor grain content, the sedimentary structures, colour or tone, and sand grain-size. For example, as noted earlier, sponge spicules do not form "spongolite" as an end-member sediment type, but they may comprise a conspicuous and / or subdominant proportion of peat and diatomite. In this context, their presence is noted by an adjectival descriptor, *viz*., spongolitic peat, or spongolitic diatomite. Similarly, if diatoms make a conspicuous contribution to the sediment, the descriptors "diatomaceous" are added to the primary sediment term, *e.g.*, diatomaceous kaolinitic muddy sand. Using sedimentary structures, for instance, calcilutite can be separated into laminated calcilutite, massive calcilutite, mottled calcilutite, and peat can be separated into massive peat, fibrous peat, laminated peat. Sediments and soils may be characterised by their colour or tone (*e.g.*, dark grey, cream, yellow), with the caveat that colour and tone may be a primary sediment attribute (*e.g.*, the colour of accumulated charophytes), or may be the result of diagenesis (*e.g.*, formation of fine-grained pyrite). Sand and gravel deposits may be divided into grades of grain-sizes (using terms of Wentworth 1922), *e.g.*, medium carbonate intraclast sand, or coarse peat intraclast sand.

The protocol for ordering the descriptors where there are a range of particle types contributing to, say, the muddy fraction, the name of the most abundant particle type is placed closest to the core sediment term. Thus, a spongolitic phytolithic diatomaceous muddy sand is muddy sand with mud-sized particle abundance diatoms > phytoliths > sponge spicules.

Processes affecting and influencing sedimentation in wetlands

Large-scale and small-scale processes influence wetland sedimentation on the Swan Coastal Plain. They are instrumental in directly contributing sediment to wetland basins, in influencing and altering the structures of sediments, and effecting changes texturally and compositionally. The large-scale processes are sedimentary, geomorphic and hydrological, while the small-scale processes encompass the physical, biological and chemical.

At the large scale, the geomorphic / geologic setting has an influence on the type of physical and chemical processes that operate within the wetland. For example, the geomorphic / geologic setting affects sedimentation through direct input of sediment, but also by determining the type and impact of sediment transporting agents that will be present, such as fluvial influx or aeolian contribution. The large-scale geomorphic / geologic setting also influences the hydrological and hydrochemical setting of a wetland, and this influences the development of various chemical environments for surface and ground waters. For instance, wetlands in a terrain of yellow quartz sand receive quartz sand into the basin through aeolian transport, whereas wetlands in terrains near Holocene coastal dunes may receive quartzo-calcareous sediment through a similar agent or through encroachment of dunes. Wetlands in quartz sand terrains will have a different groundwater chemistry to those in limestone terrains.

At the smaller scale, physical processes operating in and around wetlands that influence sedimentation and sedimentary products include: 1. sheet wash from the adjoining uplands to provide sediment fill into the wetland; 2. aeolian deposition and deflation (aeolian delivery of extrabasinal particles is evident as quartz silt and quartz very fine sand scattered in central basin deposits of peat, calcilutite, and diatomite); 3. wave action in standing water during high water periods to effect sediment winnowing, transport and the development of peripheral low-relief sandy beachridges or beaches, and the wave reworking of any sandy shores of wetlands that are bordered by sand terrain; 4. transport as a suspension load of fine-grained particles such as diatoms, organic matter, or carbonate mud from peripheral zones into deeper water, and its settling on the basin floor as ooze; 5 transport of fine-grained particles (such as diatoms) from a dried wetland floor towards the shore by aeolian processes to form low relief supra-littoral to littoral shoreline "mud" ridges; 6. the desiccation of any muddy margins of wetlands, and later in the dry season, the desiccation of the centre of wetlands if exposed; 7. local fluvial input (*i.e.*, from local channels along the wetland margin, and that are consequent to the wetland shore); 8. groundwater discharge (seepage and percolation) to deliver fine-grained sediment in suspension and to initiate chemical changes; 9. groundwater fluctuation to initiate chemical changes; and 10. evaporation resulting in soil desiccation, and in changes in water chemistry.

Examples of small-scale biological processes within wetlands include organic accumulation of detritus from flora and fauna (these include *in situ* peat beds, diatom deposits, and local shell beds), the contribution of calcitic mud by the disintegration of semi-calcareous charopyhtic algae, and bioturbation by flora and fauna (such as freshwater crustacea, insects, tortoises, reptiles, amphibians, and mammals), and the root-structuring and burrow-structuring of sediments by the biota. Bioturbation by fauna such as frogs, bandicoots, ants, and freshwater crustacea is particularly significant in the marginal facies of wetlands where interlayered sediments may be mixed, or the sediment becomes burrow-structured or burrow-mottled. Shoreline and peripheral vegetation also function in the role of sediment trapping, binding and root-structuring, and contributing directly to the sedimentary deposit as *in situ* deposits of plant material.

Examples of small-scale chemical processes within wetlands include (1) the initiation of chemical changes due to sediment influx via seepage and percolation, (2) the initiation of chemical changes due to sediment transfer via vertical water fluctuations, and (3) changes in water chemistry due to evapo-transpiration. Chemical processes within wetlands that affect sediments include precipitation of minerals such as syntaxial overgrowths on grains, precipitation of minerals as intergranular cements (*e.g.*, calcite), the stripping of clay and iron oxides from Pleistocene yellow sand grains under acidic conditions, precipitation of iron oxides, the precipitation of iron sulphides, and the transport of ions and nutrients throughout the sediment column.

At the small scale, physical and chemical processes can often trigger biological responses which can then further influence sedimentation. With wave action on a standing body of water, for instance, the physical and chemical properties of surface water within wetlands in different geomorphic settings with different types of sediments in the basins, can determine the suspended sediment content or uptake of soluble material (*viz.*, mud-sized phyllosilicate mineral content, carbonate mud content, and tannin content), which will affect turbidity and water quality, with concomitant influence on planktonic and benthic biota.

Fire is another influence on stratigraphy, structure, texture, and composition of wetland sediments (Semeniuk & Semeniuk 2005b). *Pyrosediments*, a term coined in this paper, are secondary sediments, such as residues, formed as a result of the combustion of sedimentary materials. In natural settings, periodic fires, usually ignited by lightning in summer, may destroy peat beds and reduce a complex sequence of peats and other sediments to a more simple peat-free sequence. In modern times, fire may be anthropogenic or natural. By agency of fire, sand lenses can be introduced into a dominantly peat sequence by reducing to ash those trees with sand-constructed termitaria interior to their trunks. Fire in wetlands also can alter sediments texturally (*e.g.*, it can fracture susceptible grains by intense heat to finer grain sizes, and can generate surficial breccia), and create specific types of pyrogenic surfaces and structures, such as fire-sculptured surfaces, baked surfaces, iron-oxide stained surfaces, and deep cracks, all of which influence development of subsequent sedimentary structures. Some of the buried surfaces and structures found in the subsurface in this study that had been generated as a result of fires are: buried fire-scarred (irregular to scalloped) surfaces; cracked surfaces (filled by later sediments, such as mud or intraclast breccia); *in situ* breccioid structures; and millimetre-scale lensoid structures resembling flaser layering (*cf*. Reineck & Singh 1980). Fire can also alter wetland sediment composition: pyrite is transformed to iron oxides, biogenic silica is partly transformed to crystalline silica, and wood is transformed to ash of calcite, halite, sylvite, and anhydrite (later altering to gypsum).

Diagenetic effects and overprints on wetland sediments and adjoining materials

There are chemical, biological and physical diagenetic effects on wetland sediments, but the main effects are chemical. The chemical effects and overprints of diagenesis in wetland sediments include: 1. dissolution of shells and other carbonate grains; 2. precipitation of carbonates as isolated crystals, crystal aggregates, grain rimming cements, and nodules; 3. burning of wood, other vegetation,. and peat to generate calcite and anhydrite (and gypsum), and other minerals; 4. dissolution of diatoms and phytoliths; 5. precipitation of silica; 6. precipitation of iron oxides to form ferricrete; 7. precipitation of metal and metalloid sulphides (*e.g.*, iron sulphides such as framboidal pyrite, or marcasite, or arsenopyrites) to impart a light grey to dark grey hue to sediments; and 8. reduction of iron oxide in envelopes around sand grains to form sulphides, imparting a light grey to dark grey hue to sediments and adjoining materials. Only carbonate dissolution, carbonate cementation/nodulation, silica solution and re-precipitation, and ferricrete cementation/ nodulation are described further here.

In many wetland sediments, under conditions of acidic groundwaters, molluscan shells and carbonate intraclasts commonly exhibit varying degrees of surface corrosion. With molluscs, particularly within peats, there is gradation from entire shells through to pitted shells to heavily corroded shell and vestiges. Corrosion of carbonate intraclasts results in the pitting and development of micro-relief on their surface. Within carbonate sediments there is also re-precipitation of carbonate to form thin crusts, nodules, interstitial cement, or displacive crystal aggregates: calcite and Mg-calcite locally cements carbonate; in some wetlands, aragonite has been precipitated within host carbonate sediments as an intergranular cement in intraclast and skeletal gravel and sand, or as a displacive radiating aggregate of acicular crystals within fine-grained carbonate sediment. Dolomite also locally has formed as a diagenetic mineral in a carbonate mud host sediment (similar to The Coorong; von der Borch 1976; Rosen *et al.*, 1989).

The burning of wood, other vegetation, and sulphide-mineral-bearing peat in wetlands generates a range of minerals, evident in the ash: fine grained calcite, formed where Ca released in burning wood combines with CO_2 also released during the combustion; anhydrite, where Ca released in burning wood combines with SO_2 released during the combustion (anhydrite later transforms under waterlogged conditions to gypsum); halite and sylvite (formed from the Na and K released in combustion), both of which dissolve in the ensuing wet season; crystalline silica formed from biogenic silica; and goethite and haematite formed by oxidation of pyrite (Semeniuk & Semeniuk 2005c). In this context, with the alteration of pre-existing materials to pyrogenic calcite, crystalline silica, goethite and haematite, pyrogenesis is a subclass of diagenesis.

SEM shows that the biogenic silica of diatoms, sponge spicules and phytoliths also exhibit surface corrosion, and may be progressively chemically removed. In sediments where there is such dissolution, silica is locally re-precipitated, forming micro-botryoidal crusts and coatings to particles, indurating the sediment. Dissolution of biogenic silica and its localised re-precipitation as cements and nodules may occur in diatomites, carbonate sediments, and quartz sands,

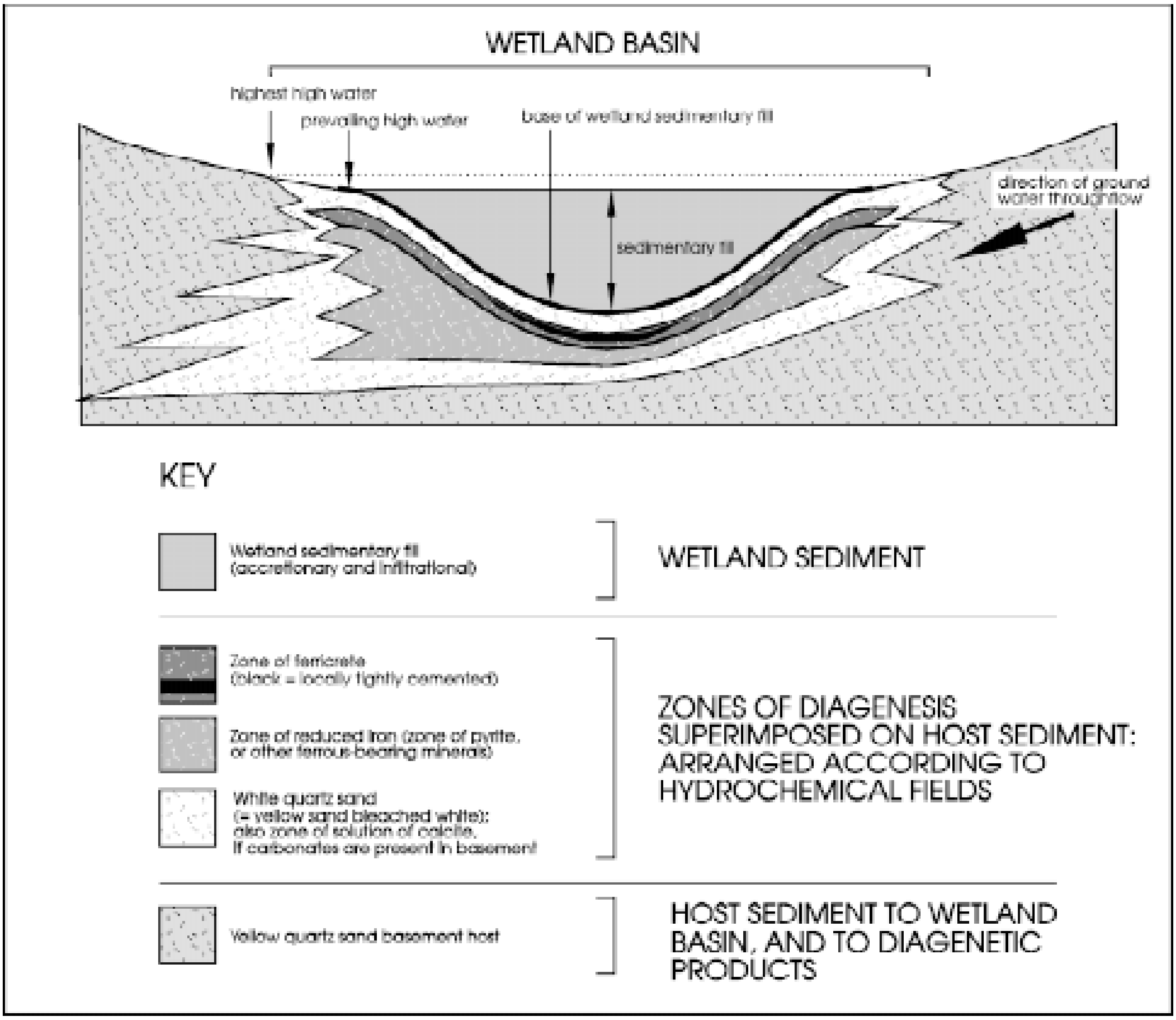


Figure 15. Idealised diagram (not to scale) showing zones of diagenetic alteration under and around wetland basins resulting from the wetland hydrochemical fields interacting with the underlying and adjoining basement sand to illustrate that the products of diagenesis are separate from the sedimentary fill of a wetland basin. In this example, diagenetic zones focus on the chemistry of Fe, but similar zones may be devised for carbonate, silica, and phyllosilicate mineral components of the host sediments around and underlying wetlands. The asymmetry in the diagenetic zones is intended to show the effect of the directional plume of groundwater flow, with interdigitation reflecting lithological or hydrogeologic influences.

forming small nodules (of induration), or interstitial grain-coating fine-grained cement.

Ferricrete is common in wetlands as an indurated sheet overprinting sandy wetland fills at levels of the water table and below. The ferricrete is a mixture of goethite, X-ray amorphous iron oxides, infiltrated kaolinite, and silica silt. Where it occurs as a weakly indurated overprint, it forms laminated rims interstitial to sand grains. Well-indurated ferricrete consists of a complex of laminated iron oxides, kaolinite, and quartz silt filling the sand interstices.

There also are diagenetic effects on the materials underlying and adjoining the wetland sediments, but these strictly are processes and products associated with acidic and Fe-enriched water derived from wetlands on underlying basement materials (Fig. 15). It is useful to clearly separate the products of diagenesis on basement materials, and diagenetic effects on wetland sediments, from primary wetland sediments themselves. These diagenetic effects include the bleaching of yellow sand on the margins and beneath wetland basins, and the translocation of mud-sized phyllosilicate mineral particles and fine quartz silt down the profile or into a wetland. Thus, while wetland sediments may fill a basin, there also is a halo effect of diagenetic alteration from the base and margins of the wetland into the underlying materials. Pre-Holocene host sediment under wetland terrains, for instance, are commonly bleached to white sand, with incomplete bleaching resulting in mottled white, cream, yellow and orange coloured sand. The host sand is yellow to orange quartz sand where the sand grains are coated by goethite-impregnated kaolinite skins (as described above). The bleached sand is quartz sand stripped of the goethite, kaolinite and quartz silt. The mud-sized phyllosilicate mineral particles and fine quartz silt are translocated to elsewhere in the profile, and the goethite is chemically translocated to precipitate as an iron oxide to form ferricrete. This style of alteration around wetlands was described in Figure 10 of Glassford & Semeniuk (1990) for yellow sand proximal to and at the water table.

Origin of sedimentary particles and wetland sediments

The origin of wetland sediment particles and wetland sediment types is diverse, ranging from intrabasinal to extrabasinal, from terrigenous to biogenic sources, and for the intrabasinal, biogenic, and chemically modified sediments, from *in situ* accumulations to reworked deposits (Fig. 16).

The sedimentary particles and the accumulated deposits can be initially categorised as intrabasinal and extrabasinal, then further differentiated as infiltrational or accretionary. Wetland particles and sediments can also be differentiated as terrigenous (*i.e.*, derived from terrestrial sources, such as quartz sand and mud-sized phyllosilicate mineral particles), or biogenic (*i.e.*, derived from biological sources such as peat, carbonate sediment, and siliceous diatoms). In this context, peats, calcilutite,

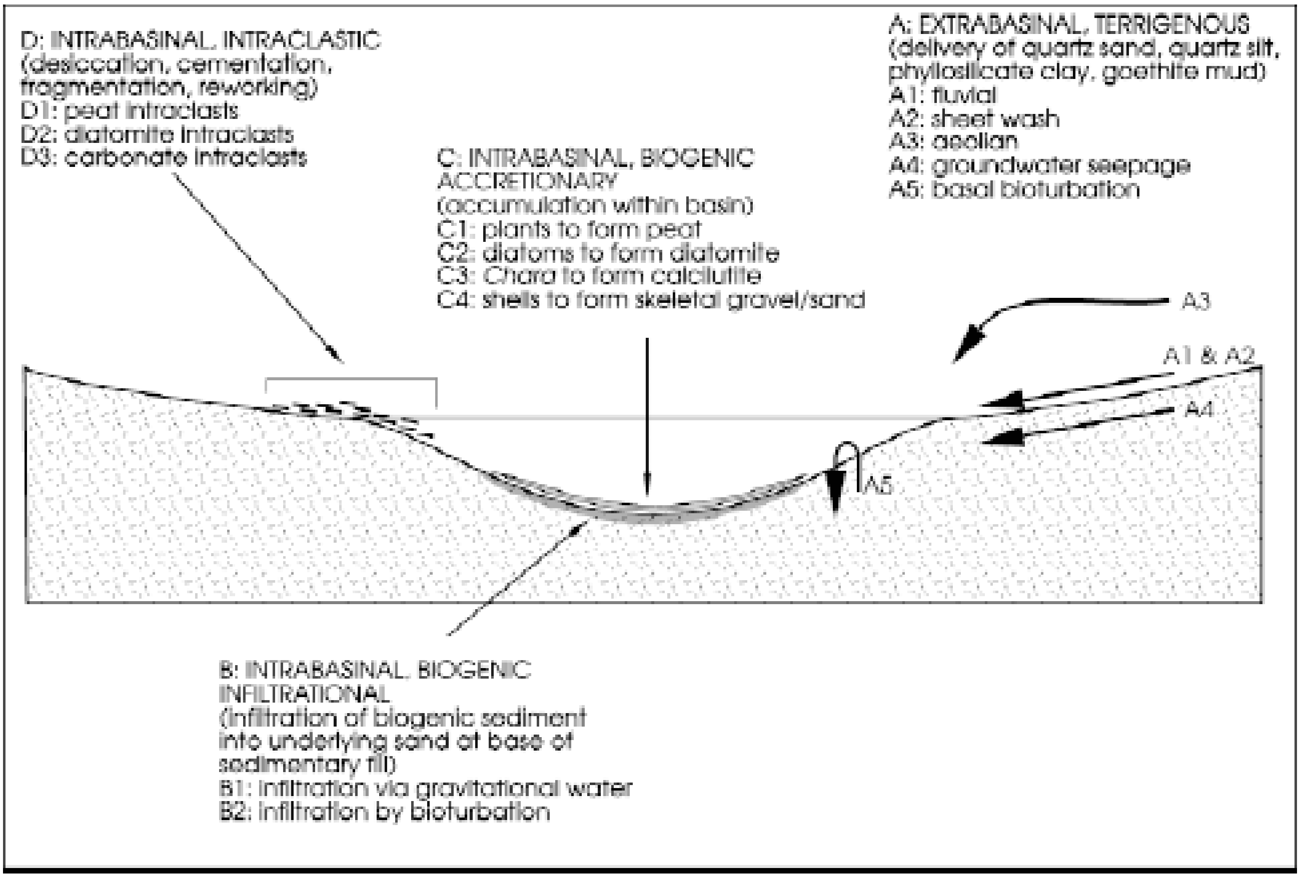


Figure 16. Origin, categories and composition of wetland sediments.

and diatomite are intrabasinal biogenic deposits in that they are definitively restricted to the wetland basin and have formed in response to water chemistry. They are also the most common accretionary deposits. Quartz sand and mud-sized phyllosilicate mineral particles are extrabasinal, since their source can be unequivocally demonstrated to be the wetland margins. The transitional muddy sediments (with the mud component being diatoms, calcilutite, or phyllosilicate mineral particles) at the base of wetland fills commonly are infiltrational, in that they have formed by the introduction of intrabasinal sediment into the underlying basement sand (Fig. 16). Muddy sediments also form along wetland margins, and here they can be accretionary in that the fine-grained component is intrabasinal, and it is mixed in with extrabasinsal sand derived by sheet wash from the surrounding uplands.

Particles and material are contributed to the sediments by the variety of biota that inhabit or visit wetlands. These particles and materials from extrabasinal sources include scats, skeletons, foreign plant material, and imported food remains from vertebrates such as reptiles and mammals, and invertebrates such as insects. Intrabasinal particles and materials include mollusc shell, other skeletons from vertebrates (*e.g.*, fish) and invertebrate fauna, tests, sponge spicules, crustacean exoskeletons, zooplankton tests, as well as plant remains from *in situ* trees and shrubs (trunks, branches, leaves, roots, flowers, fruit), herbs and sedges, algae, and phytoliths and diatoms. Biogenic silica (as diatoms, sponge spicules, and phytoliths) is conspicuous, ubiquitous, and important in wetland sediments. Diatom frustules, and fragments, for instance, can occur in a range of wetland sediment deposits, constituting a significant proportion of peaty sediments; similarly, sponge spicules contribute to peaty sediments, as well as to diatomites, and phytoliths also make contributions to wetland deposits as intrabasinal particles, especially in peats, though overall they remain in relatively low concentrations in the sediments.

Peat in wetlands derives from vegetation detritus. Under acidic and anaerobic conditions within the substrate, and under water, aerobic bacterial decay of vegetation detritus is arrested or reduced, and plant detritus cumulatively accretes to form organic-rich beds, with anaerobic microbial and fungal breakdown of the material. Sites of high vegetation productivity, coupled with low rates of organic decay, combine to develop peat beds. Peat forms in two main environments: 1. deposits of plant material, either comprising layers of plant detritus, leaves, sheaves, stems, roots, twigs, branches, and trunks, representing plant material directly accumulated under plant cover, or comprising wholly *in situ* root-structured, (buried) vertical plant stems, mixed with or alternating with horizontally accumulated plant material; these types of peat deposits tend to form root-structured and fibrous peat; and 2. deposits of organic matter, leaves, and other detritus transported to and deposited in deeper water; these types of peat deposits are structureless, or weakly laminated, and have a variable content of diatoms; these latter peat deposits may grade into diatomaceous peat to organic matter rich diatomite. For these latter peats, in extant environments where organic matter is accumulating in deeper water, the surface deposits are water-rich 20–100 cm thick deposits of flocculated organic matter, which grades downwards into an organic matter gel some up to 100 cm thick, which in turn grades into firm peat.

In Western Australia, researchers have informally subdivided peat into fibrous types, and massive or non-fibrous types, essentially implicitly recognising the two depositional environments noted above. However, from the SEM results, it would appear that the category of massive or non-fibrous peat noted by previous workers, in fact, may be partly organic-carbon-rich diatomite or diatomaceous peat. In addition, there is the issue that not all fine-grained black or dark grey sediment are peats. The dark tone to fine-grained sediments may be partly due to organic matter and partly to finely disseminated metal sulphides, particularly iron sulphide.

Peat intraclast gravel and sand form from processes of desiccation or fire. The surface of peats may dry out to form polygonal cracks, and prolonged summer drying and desiccation (particularly if regional water tables are falling during dry phases of climatic cycles), or drying by fire, leads to progressive fragmentation of the cracked surface layer and to the development of angular peat clasts that are incorporated as layers into the peat deposits. In general, peat is most desiccated along the margins of a basin, where drying out will occur first with shrinking of the water body across a basin, or where fires have resulted in the drying-out of these deposits. Once formed, peat clasts may interact with sand bodies that are peripheral to the basin, and during the following wet season, through wave action and sheet wash, they become interlayered with sand.

Calcilutites are dominantly biogenic in origin. While studies elsewhere suggest that carbonate may precipitate inorganically within lakes as calcite, or rarely as Mg-calcite or aragonite (Muller 1971; Muller *et al.*, 1972; Hakanson & Jansson 1983; Tucker & Wright 1990), in this study, particle morphology, microstructure and ultrastructure, and EDS data indicate that the < 63 mm fraction of carbonate particles is dominantly of biogenic origin derived from disintegrated semi-calcareous charophytes and carbonate-impregnated filamentous algae, and comminuted skeletons of calcareous fauna. Also, the range of mineralogy of the tests of invertebrate fauna and charophytes determined by XRD and EDS adequately explains the range of mineralogy of the calcilutites. SEM studies show that while there is some diagenetic precipitation of carbonate within a pre-existing carbonate sediment host (radiating crystals of acicular aragonite embedded in calcilutite exemplify this), and field and laboratory observations show that some calcite is generated by the burning of wood, there has been no evidence for *in situ* chemical precipitation of mud-sized carbonate as intrabasinal sediment. The restriction of carbonate mud largely within limestone terrains, and the chemistry of the wetland waters (*i.e.*, their alkalinity and salinity) indicates that such environments are favourable for charophytes and calcareous fauna which draw on carbonate, bicarbonate and calcium from the groundwaters.

Carbonate skeletal gravel and sand form in wetland basins where there is accumulation of mollusc and other calcareous invertebrate tests. Wave action along wetland margins tends to concentrate accumulations of skeletons into shoreline or nearshore ribbon deposits. Carbonate intraclasts form in wetland basins that have calcilutite and/or carbonate sand deposits. Induration of calcilutite by drying and desiccation (Fig. 4A), followed by fragmentation and reworking, yields simple intraclasts of calcilutite fragments. Cementation by carbonate, and fragmentation of the indurated sheets result in another type of intraformational clast. The host sediment may be calcilutite, skeletal gravel and sand, or earlier-formed intraclast gravel and sand. Cementation during periods of waterlogging and inundation, reworking into fragments during periods of desiccation, transport and rounding during periods of inundation, and re-cementation of clasts and mud deposits during further periods of waterlogging and inundation, generates the intraclast. Repeated cementation and re-working generates complex and polycyclic intraclasts. Reworking by wave action and accumulation of intraclasts into layers and laminae is most common along wetland margins.

Diatomite mainly forms within wetland basins that are located mainly within quartz sand settings in deep water to shoreline environments. Diatomite accumulates as whole to fragmented frustules. At the stage where diatom frustules have become so fragmented that individual particles are smaller than the microstructure of the sieved wall, the sediment no longer is composed of particles that have intergranular porosity, nor do the diatom particles pack within the sediment as a series of randomly oriented plates. This type of sediment has the bulk properties of a quartz silt or a terrigenous clay deposit, and superficially can be mistaken for a terrigenous sediment, since it does not exhibit the properties of traditional porous "diatomaceous earth". This end product of diatom disintegration produces a sediment type similar to white clay or mud which is easily misidentified as a terrigenous deposit. If there are remnants of freshwater sponge spicules in such deposits (noting that normally in studies of stratigraphy and palaeo-sedimentology, the occurrence of sponge spicules implies marine or estuarine environments), these freshwater sediments can also be incorrectly interpreted as an estuarine sediment, *i.e.*, a sponge spicule bearing estuarine clay deposit.

During drying out periods in wetlands, the exposed floor of a diatom deposit in a wetland may be reworked by aeolian processes, transported shoreward, and trapped by peripheral vegetation, to accumulate as shoreline low relief ridges, essentially as shore-parallel supra-littoral to littoral deposits of "mud". Drying out and desiccation of diatomite also leads to the formation of diatomite intraclasts. Thus diatomite intraclast gravel and sand forms within wetland basins, and particularly along their margins, where desiccation has indurated, cracked and fragmented diatomite deposits, and high water conditions have reworked and rounded them to form thin shoreline deposits (Fig. 4B–G). These intraclasts may form clean washed gravel deposits, or may become embedded in a muddy matrix. Intraclasts are embedded in a diatomite matrix where diatom mud, reworked from the wetland margin, or reworked into suspension from basin centres by wave action during high water, is transported shorewards and consequently buries, or is mixed in with, the shoreline intraclasts.

While dominantly marine organisms, sponges are known to be inhabitants of freshwater lakes (Williams 1980). On the Swan Coastal Plain, while they make important contributions to wetland sediments as intrabasinal particles, sponge spicules and their fragments do not become abundant enough to form "spongolites". As noted earlier, generally they comprise < 10% of wetland sediments.

Davis & Rolls (1987) documented freshwater sponges at North Lake, but considered them to be rare in the context of their sampling sites in the urban Perth area. During the surveys of sumplands and the marginal vegetated zone of lakes and sumplands during this study, encrusting sponges were commonly encountered on peripheral vegetation throughout the Swan Coastal Plain, though they were not abundant at a given site. However, the ubiquitous occurrence of sponge spicules and their fragments in the sediments, particularly in the stratigraphic column, suggests that they can make significant contributions to wetland sediments as silica particles beyond their seemingly apparent current rarity in many locations. The extent of their occurrence in the stratigraphic record may be a measure of their greater abundance in the past or an indication of their chemical durability as silica (and hence their increased preservation potential). While organic matter production may overwhelm the surface occurrence of sponge spicules in peat-generating wetlands at the sediment surface, in time, oxidation processes may result in the increase in concentration of spicules relative to organic matter.

Mud-sized phyllosilicate mineral particles commonly are delivered to wetland basins by fluvial processes. However, where there clearly is no major fluvial channel source (as is the case for the isolated wetland depressions bordered by high dunes), or minor fluvial channel (*e.g.*, consequent drainage bordering a basin, and deriving from the adjoining dune high ground), phyllosilicate mud beds in wetlands, and phyllosilicate muddy sand at the base of wetlands derive from wetland margins, bioturbation into the base of the wetlands, and from aeolian sources. The processes whereby fine-grained clay/silt sediment is delivered to the wetland basin is summarised in Figure 17.

In regard to mud-sized phyllosilicate mineral particles derived from the wetland margins or that occurring at the base of the wetlands, the mineralogy of these mud-sized wetland deposits is the same as that coating the yellow sand grains of the surrounding Pleistocene sediments. The stratigraphic array around and under wetlands residing in a yellow sand terrain is as follows:

1. yellow quartz sand underlies the uplands adjoining the wetland basin;
2. prior to the Holocene groundwater inundation yellow quartz sand also formed the floor of the ancestral wetland basin;
3. white quartz sand, leached of its iron oxide content, depleted of its interstitial yellow fine-grained component, and stripped of its clay/silt pellicular envelope, immediately adjoins the wetland basin at levels where either high water tables or the capillary fringe of high water tables interact with the sand;
4. white quartz sand, or grey quartz sand, similarly

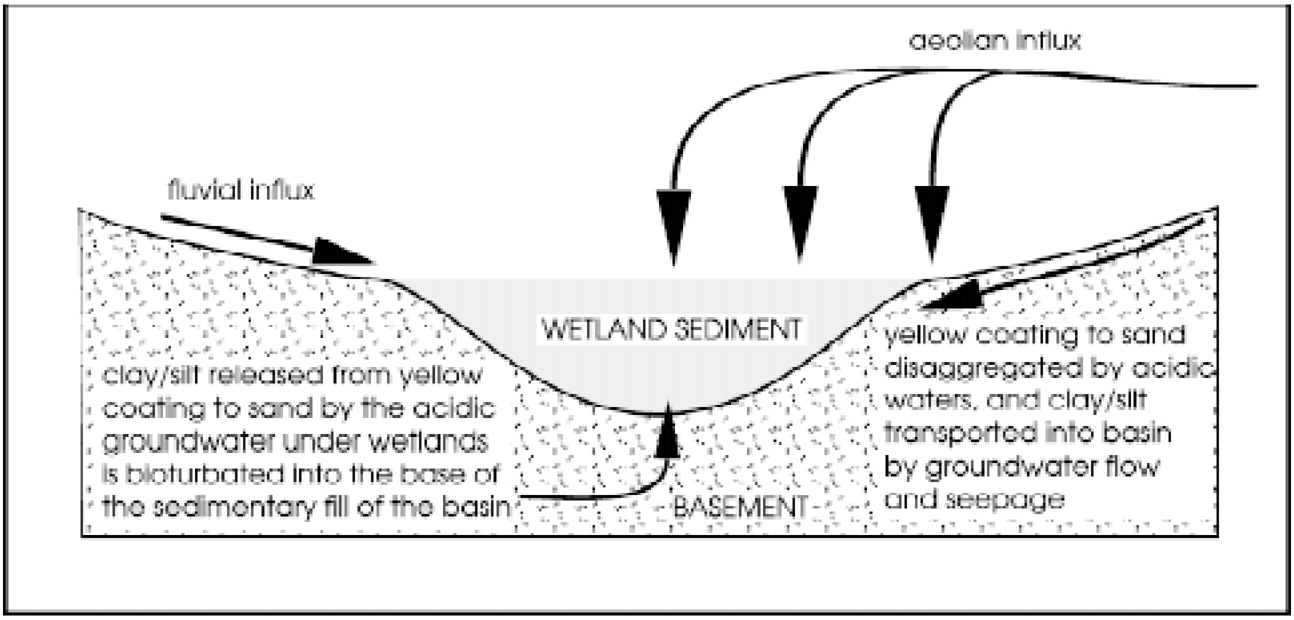


Figure 17. Idealised diagram illustrating the origin of mud-sized phyllosilicate mineral particles in wetland sediments: influx and input from fluvial, sheet-wash, aeolian, groundwater seepage, and (basal) bioturbation processes.

leached of its iron oxide content, depleted of its interstitial yellow fine-grained component, and stripped of its clay/silt pellicular envelope, underlies the wetland where the sand is permanently or seasonally saturated with water.

In this stratigraphic and hydrochemical setting, yellow sand, proximal to wetlands and water tables, under the influence of acidic groundwater associated with the wetland, or upslope humus-rich soils adjoining wetlands, is bleached white. The clay/silt and iron oxide skins that impart the yellow coating to the quartz grains, and the yellow interstitial fine-grained material are translocated vertically downwards to the water table or laterally to the wetland, or are bioturbated into the base of the wetland. During the wet season, in areas with steep hydraulic gradients, groundwater has been observed seeping into wetlands from the yellow sand margins. Such lateral seepage can carry iron in solution and clay/silt in suspension. In this context, a Pleistocene yellow quartz sand terrain that is host to the wetlands, under conditions of acidic water, in the process of becoming white quartz sand, yields minute amounts of clay/silt and iron oxides. The clay is transported and deposited into the wetland basin. Mud-sized phyllosilicate mineral particles thus can be deposited, albeit in minor amounts, into wetland basins where there is a steep hydraulic gradient into the basin from the adjoining uplands, and this clay/silt can occur in Bassendean Dune and Spearwood Dune settings, since both these Pleistocene dune systems are underlain by yellow quartz sand.

Apart from wetland soils developed directly on Pleistocene quartz sand basement material, the quartz sand that forms sedimentary fill along the margins of wetlands clearly derives from the adjoining uplands (Fig. 4G–H). This is demonstrated by the similarity of the petrography of the quartz grains of wetland fill to those of Pleistocene margins and basement, and by the tracing of the sand sheets and wedges from the wetland basin to the margin. Quartz sand is transported into the wetland margins from the sandy uplands by sheet wash, and the wave reworking of sandy wetland margins during stands of high water. Quartz sand also underlies the beachridge systems that locally form lunettes marginal to some wetlands. However, some of the quartz sand stratigraphically low in the sedimentary profile, near the contact of the accretionary sedimentary fill and the underlying basement sand, derives from bioturbation of the underlying basement sand upwards into the base of the accretionary deposit.

Particles of quartz silt and quartz very fine sand are commonly found scattered in low abundance in central basin deposits of peat, diatomite, and calcilutite. Since there is no fluvial delivery to such basins, and there is no stratigraphic unit that can be traced to the centre of these basins, these fine-grained quartz particles provide evidence of aeolian delivery to wetland basins. The deposits thus consist of accumulating intrabasinal autochthonous wetland sediments with a low volume aeolian air-fall contribution.

A summary of the common wetland sediments encountered in this study, as listed in Table 6, categorised as to primary end-member sediments, mixtures, and secondary (derivative) sediments, and as to how they formed, is provided in Table 7.

Within a given basin, sediments also partition into central deposits, marginal deposits, and basal deposits, or central facies, marginal facies, and basal facies (Fig. 18). The centres of wetlands are more consistently inundated or water saturated, and accumulate peat, diatomite, and calcilutite. The margins of wetlands, with desiccation, cementation, rising and falling of the water table generating extreme wetting and drying, wave action, reworking, sheet wash, and burrowing by vertebrate and invertebrate fauna, preferentially develop

Table 7

Classification of the main wetland sediments and their origin

Sediment	How formed
Primary end-member sediments	
peat	intrabasinal accumulation of plant material
diatomite	intrabasinal accumulation of diatoms
calcilutite	intrabasinal accumulation of disintegrated charophytes and invertebrate skeletons
kaolinitic mud	extrabasinal delivery of fine-grained sediment by fluvial or aeolian processes
quartz sand	extrabasinal delivery of fine-grained sediment by fluvial or marginal sheet wash processes
quartz silt	extrabasinal delivery of fine-grained sediment by fluvial or aeolian processes
skeletal gravel and sand	intrabasinal accumulation of invertebrate skeletons
Secondary (derivative) sediments	
peat intraclast gravel and sand	desiccation, baking, cracking, reworking and accumulation of peat mainly along wetland margins
carbonate intraclast gravel and sand	desiccation, cementation, cracking, reworking and accumulation of carbonate sediments mainly along wetland margins
diatomite intraclast gravel and sand	desiccation, cracking, reworking and accumulation of diatomite mainly along wetland margins
Mixtures of end-member sediments	
peaty quartz sand	mixing by sheet wash or bioturbation of peat and quartz sand either along wetland margins or along the base of the wetland fill; the occurrence of interstitial organic matter indicates that the sediment has formed under anoxic subaqueous or waterlogged conditions
sandy peat	mixing by sheet wash or bioturbation of peat and quartz sand either along wetland margins or along the base of the wetland fill
diatomaceous quartz sand	mixing by sheet wash or bioturbation of diatomite and quartz sand either along wetland margins or along the base of the wetland fill
sandy diatomite	mixing by sheet wash or bioturbation of diatomite and quartz sand either along wetland margins or along the base of the wetland fill
calcilutaceous quartz sand	mixing by sheet wash or bioturbation of calcilutite and quartz sand either along wetland margins or along the base of the wetland fill
sandy calcilutite	mixing by sheet wash or bioturbation of calcilutite and quartz sand either along wetland margins or along the base of the wetland fill
kaolinitic muddy quartz sand and sandy kaolinitic mud	mixing by sheet wash, fluvil processes, or bioturbation of kaolinitic mud and quartz sand either along wetland margins or along the base of the wetland fill
diatomaceous peat	accumulation of organic matter with diatoms, dominated by organic matter
organic matter enriched diatomite and sandy organic matter enriched diatomite	accumulation of organic matter with diatoms, dominated by diatoms
calcilutaceous peat	accumulation of organic matter jointly with calcilutite, dominated by organic matter
organic matter enriched calcilutite and sandy organic matter enriched calcilutite	accumulation of organic matter jointly with calcilutite, dominated by calcilutite
organic matter enriched diatomaceous calcilutite, and sandy organic matter enriched diatomaceous calcilutite	accumulation of organic matter, diatoms and calcilutite
organic matter enriched kaolinitic mud	accumulation of organic matter and kaolinitic mud
organic matter enriched diatomaceous kaolinitic mud	accumulation of organic matter, diatoms, and kaolinitic mud
phytolithic muddy sand	accumulation of phytoliths and mixing of this fine-grained material with sand either by sheet wash or bioturbation along the margins of wetlands

sedimentary structures such as vesicular structures, fenestral structures, breccioid structures, and burrow structures, and the mixing of interlayered sediment. This is the zone where there is development and accumulation of second cycle intrabasinal sediments such as carbonate intraclast gravel and sand, peat intraclast gravel and sand, and skeletal intraclast gravel and sand, and extrabasinal quartz sand aprons and tongues, and marked lithological interlayering between extrabasinal and intrabasinal sediments. During times of exceptionally low water levels, the features of wetland sediments that reflect processes of desiccation and

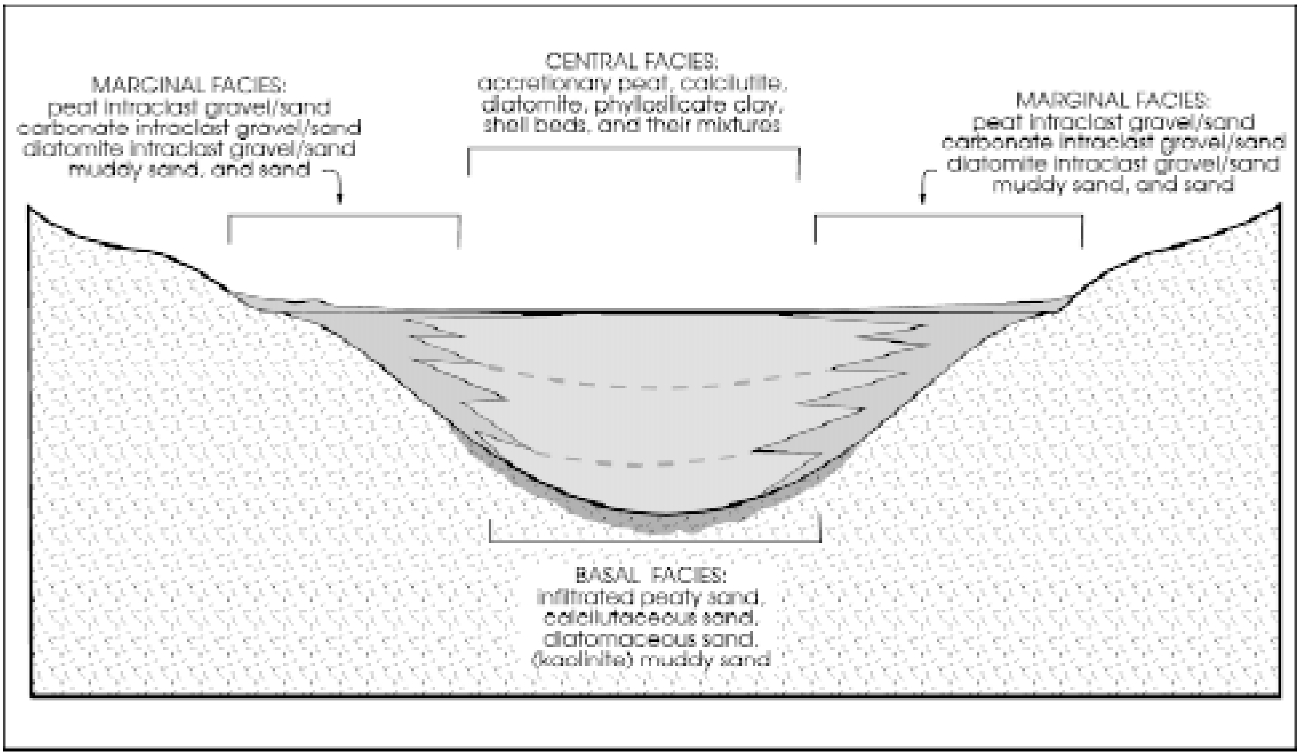


Figure 18. The major depositional environments of sedimentary particles and wetland sediments as central facies, marginal facies, and basal facies. The relevant sediment types within each facies is listed.

induration along the margins may extend across the entire wetland basin. The term "basal deposits" is applied to the infiltrational deposits at the base of the wetland, and essentially are buried deposits formed at the time of the initiation of wetland sedimentation.

Discussion and conclusions

This is the first systematic and formal description of wetland sediments on the Swan Coastal Plain. As such it provides an inventory of wetland sediment particles, wetland sediment types, a standard set of descriptors to be included in documentation of wetland sediments, and a number of defined terms for future reference. In contrast to soil nomenclature systems that involve classification of combined (segregated) layers in the pedogenic profile, a simple and comprehensive system using sedimentary terms has been employed to describe and classify wetland sediments in this paper, and provide a picture of the internal features of wetland sedimentary deposits, *i.e.*, their colour, structure, fabric, texture, and composition, that can be employed for individual layers in the stratigraphic profile. With descriptors such as intraformational, infiltrational, accretionary, intrabasinal and extrabasinal, information about the genesis of the sediments and nature of the processes of sedimentation can be included, thus further separating sediment types or sediment facies within wetland basins. The descriptive system is not aligned to any single objective, such as agricultural use, and this independence means it may be used as an adjunct in many types of surveys with a variety of purposes.

In this paper, we emphasise that true soils, as pedogenic products on pre-existing parent material, should be distinguished from sedimentary products that are infiltrational and / or accretionary. In the geohistoric reconstruction of wetland development, this is an important factor, and will provide a means of determining the beginning of a wetland's history, in separating deposits that have accumulated as part of the wetland from those materials inherited from pre-wetland conditions (Semeniuk 2005).

In terms of the sediments themselves, a wide range of mud-sized, sand-sized, and gravel-sized sedimentary particles contribute to sedimentary fill underlying wetlands, *viz.*, organic mud particles, microcharcoal and charcoal, carbonate mud particles, quartz sand and silt, diatoms, sponge spicules, mud-sized phyllosilicate minerals (kaolin, montmorillonite), goethite mud, feldspar silt, heavy minerals, intraclasts, shells and fragments, and plant material (plant fibres, detritus, leaves, flowers, fruit, twigs, branches and trunks). Deposits of invertebrate faunal skeletal material, while forming layers and laminae in wetland sediments, do not contribute in a major way to the filling of wetland basins in the settings of the Spearwood Dunes, Bassendean Dunes, and Pinjarra Plain, but can form diagnostic and environmentally significant markers within the sediment suite.

The end-member wetland sediments that are the dominant and / or key intrabasinal and autochthonous on the Swan Coastal Plain are peat, diatomite, and calcilutite. These end-member sediments similarly are recognised globally as being the predominant autochthonous deposits in wetland basins, and as signalling intrabasinal sedimentation. On the Swan Coastal Plain, the occurrence of the end-member sediments and their mixed intermediates reflects geomorphic setting as well as hydrological and hydrochemical setting (see Semeniuk & Semeniuk 2005a), and can be used as environmental indicators when preserved in the stratigraphy. All three of the key end-member sediments are fundamentally biogenic in origin, *viz.*, plant remains generate peat, diatoms generate diatomite, and charophytes and invertebrate fauna disintegrate to form calcilutite. Secondary derivatives of the key primary wetland sediment types, or their intermediates, include the intraclast gravels and sands derived from peat, diatomite, and calcilutite. They are developed most commonly as marginal deposits, as a result of processes of desiccation, cementation, induration, extreme wetting and drying from rising and falling water tables, wave action, or reworking. The effects and alterations of these various processes, although operating in the overall wetland, are most pronounced in the marginal sediments. Extrabasinal**,** allochthonous terrigenous sedimentary material, within wetlands, such as quartz sand and mud-sized phyllosilicate mineral particles, are delivered to the basins by sheet wash, fluvial transport, and aeolian transport.

Sediments composed of mixed particle types reflect one or more of several processes. They may represent the concomitant production of biogenic material (*e.g.*, diatoms within a peat-generating basin to develop diatomaceous peat; or epiphytic sponges together with plant detritus generating a spongolitic peat), or the biogenic mixing of various sedimentary layers by bioturbation. In lower parts of the stratigraphic section, mixes of sand and muddy wetland sediment may represent infiltrational sedimentation, mediated by bioturbation or gravitational water. On the wetland margins, they reflect the various contributions to the sedimentary accumulation, *e.g.*, extrabasinal allochthonous sediment brought to the wetland by sheet wash, or wave reworking of sandy wetland margins, and mixed with the feather edge of autochthonous sediment deposits generated from within the basin, or aeolian transport of fine-grained sediment from basin centres to basin margins, and the mixing of the fine-grained material with quartz sand adjoining the basin. Some mixes of sediments reflect the bioturbation of formerly interlayered environmentally distinct deposits.

In the light of the classification presented in this paper in Figure 12, and the proposed compositional boundaries within the sediments of the "peat family" between peat *sensu stricto* and diatomaceous or calcilutaceous peat, the nomenclature of peat is discussed further here. In the literature, the terms "peat" and "peaty" is applied to a large range of accreted organic matter, varying in organic content. Some authors define peat quantitatively in terms of organic matter content. For example, Dachnowski (1920) restricts the term to accumulations of plant matter > 20 cm thick and with > 60 % organic matter; in a review of peat, Clymo (1983) notes that the term is generally applied to materials with > 80% organic matter; and Leeper & Uren (1993) attach the term "peaty" to material with organic matter content > 20 %. Many other authors, on the other hand, do not define peat in relation to a quantitative content of organic matter but use the terms "peat" or "peaty" for any organic rich sediment or soils implicitly conveying the notion of rich organic content without quantification or even reference to works that define peat quantitatively. As Clymo (1983) points out, however, "peat" is not a single homogenous substance: it varies in vegetative composition, colour, structure, fabric attributes and proportion of fibre, bulk density and water content, organic matter content, concentration of inorganic solutes, occurrence of mineral precipitates, and extent of decomposition. As such it will have a variable appearance and variable properties dependent on source material, microbial, diagenetic, and pedogenic processes, hydrological setting, hydrochemistry, depth of burial, and age. In this paper, we assign the term "peat" to accreted sedimentary material with > 75% organic matter, varying in structure and fabric from fibrous (partly decomposed plants and detritus) to fine-grained (fully decomposed plants). We place the boundary for peat *sensu stricto* at 75% organic matter for practical reasons in relation to the other subdivisions of the ternary classification (noting though that the 75% threshold is close to the 80% boundary for peat of peatland scientists *cf.* Clymo 1983), and assign organic rich sediments with 50–75% organic matter to the "peat family", but with adjectival descriptors to denote the subdominant constituents in the material.

We also note that iron-sulphide-rich fine-grained sediments may be dark grey or black but not necessarily peat. Iron sulphide rich diatomaceous peat, or iron sulphide and organic matter enriched diatomite, for examples, superficially may resemble peat, and in this context it is necessary either to have determined the organic matter content of the sediment by laboratory analyses, or to have examined the material as mud particle mounts under a petrographic microscope in order to assign the sediment the correct identification.

Generally within wetland basins, carbonate sediments form the most complex suite of products, reflecting diverse biogenic, biomediated, hydrochemical and diagenetic origins, reflecting diverse mineralogic type (*viz.*, calcite, Mg-calcite, aragonite, and dolomite), reflecting the propensity for carbonate mineral species to readily undergo diagenesis, and reflecting hydrochemical and stratigraphic history (von der Borch 1976; Wright 2000; Roberts *et al.*, 2004). In this context, the environmental significance of calcilutites is discussed further here.

Calcilutites, variably known in the literature as lime muds, calcitic muds, aragonitic muds, or carbonate muds, have been documented from a range of aquatic environments in Western Australia and globally. They have been recorded in freshwater to saline hydrochemical systems, from lacustrine to marine environments (Bathurst 1971; Hakanson & Jansson 1983; Wetzel 1983; Hammer 1986; Semeniuk 1988; Backhouse 1993; Newsome & Pickett 1993; Coshell & Rosen 1994). Their mineral composition has been noted as calcitic, Mg-calcitic, and aragonitic, or mixtures of these, and with local dolomite. The origin of the different mineralogic particle types has been determined or interpreted to be biogenic, inorganic precipitations, or diagenetic (Muller 1971; Muller *et al.,* 1972; Kelts & Hsu 1978; Hakanson & Jansson 1983; Tucker & Wright 1990). For lacustrine wetlands, mineralogic types and particle types of calcilutite can be stratigraphically monotonous throughout the wetland sediment sequence. On the other hand, a wide range of carbonate mineralogic types and particle types can occur stratigraphically interlayered or form a graded sequence within the one wetland basin, either because of fluctuating water chemistry, reflecting changing hydrochemical, biotic, and climatic influences, or because of long-term evolving hydrochemistry within the wetland basin, for instance, evolving from freshwater conditions to hypersaline conditions, with attendant long-term changes in biota, hydrochemical processes, and diagenesis (Coshell & Rosen 1994; Machlus 2000).

Against this variable backdrop, the calcilutites within wetland basins on the Swan Coastal Plain encountered in this study are mainly calcitic and mostly derived by breakdown of charophytes and invertebrate biota, and while SEM studies show that there is some diagenetic precipitation of carbonate within a pre-existing carbonate sediment host (radiating crystals of acicular aragonite embedded in calcilutite exemplify this), there has been no evidence for *in situ* chemical precipitation of mud-sized carbonate as intrabasinal sediment. However, in the more saline carbonate basins such as the Coogee Suite or the Cooloongup Suite (Semeniuk 1988), calcilutites exhibit complexity in mineralogy and particle types: there is biogenically derived carbonate mud formed by breakdown of charophytes and invertebrate fauna; there is authigenic precipitation of carbonates formed within the sedimentary body (displacive crystal aggregates, or as crusts and cements of aragonite, Mg-calcite, or dolomite), and there is diagenetic replacement of pre-existing carbonate sediment. These aspects of carbonate sedimentation and diagenesis, however, will be the subject of a later paper.

As noted above, pyrogenesis creates new sediment types, *e.g.*, diatomite, or quartz sand, new textures, and new minerals, but in all cases the process acts on pre-existing sediment. Mostly, pyrogenic processes modify or transform particles within sediments, or create new structures in a pre-existing sediment. In this context, pyrogenesis is viewed as subclass of diagenesis.

The categorisation and description in this paper of wetland sediment types will assist wetland scientists, administrators and planners to address one of the fundamental attributes of wetlands, and indeed, an attribute which defines and delineates wetlands, *i.e.*, “hydric soil” (noting that we use the term “hydric soils” here without implication that all materials that underlie wetlands are wetland “soils”). The limit of “hydric soils” or wetland sediments delineates the boundary of a wetland in combination with two other determining factors, the presence of surface or near surface water, and the presence of hygrophyllic flora or fauna (Tiner 1999). The boundary of a wetland determined by the occurrence of wetland sedimentary deposits, or “hydric soils”, becomes increasingly important during periods of natural water level fall, when the characteristics of the water regime such as water presence and longevity are intermittently or cyclically altered or erratic. Wetland sediments are also an important characteristic in wetland inventories and classifications, and in an hierarchical classification system, it is one of the criteria for assigning wetland types to suites (Semeniuk 1988).

The focus on the different sediment end members and mixtures described above, should provide a basis for understanding the dynamic nature of wetlands as they develop, through deepening, infilling, and responding to changes in hydrological and hydrochemical regimes (Semeniuk 2005). Given that many of the sediment types represent particular environmental settings, either in terms of hydrochemistry or location within the basin, *viz.*, centre, or margin of basin, some of the sediment types can be used to infer palaeo-environments and to reconstruct past hydrochemical and climatic conditions. Also, given their strong palaeo-environmental implications, the sediment within a basin also can signal the nature of mechanisms contributing to the current ecological balance, as well as to predict hydrological pathways, recharge and discharge mechanisms, and provide fundamental hydrogeological information critical to the proper design of buffer zones to protect wetlands.

When sediment types are related to geomorphic and geological setting, they can further be used in a predictive capacity to provide clues about the regional and local wetland processes which may be taking place in previously unstudied settings. If sediment types have changed, as evidenced in the wetland fill, this may provide insights into wetland stability and/or identification of potential risk factors.

Wetland sediments provide a powerful tool in the reconstruction of wetland history in the Holocene, particularly if used in conjunction with fauna, flora, pollen, microcharcoal, and diagenetic products. In this context, recognising the sedimentary products of former processes provides an important key to the unravelling of Holocene palaeo-environmental, palaeo-ecological and palaeo-climatic history. For example, the marginal facies represents a distinct hydrochemical and hydrological condition, and such facies recurring as tongues along the wetland margin, or as buried sheets extending across the wetland basin provides information on former wetland conditions. Similarly, the occurrence of shell beds (or laminae), or the incursions of sand into the wetland margin by fluvial processes or by sheet wash, or the regular influx of quartz silt laminae in the stratigraphic sequence by, say, aeolian processes, signal important events in the history of accretion within a wetland, and the recognition of the processes and products of intrabasinal *versus* extrabasinal sedimentation becomes an important part of the stratigraphy of wetlands.

Acknowledgements: This work is part of the R&D endeavour of the V & C Semeniuk Research Group, registered as VCSRG R&D Project #3 with AusIndustry (the Commonwealth Government R&D Board). The specialised laboratory work was undertaken in a number of institutions. The SEM, EDS, and ancillary work was carried out using CSIRO Bentley Laboratories, Western Australia, with the assistance of Peter Austin and Rick Hughes. XRD work was carried out at the Chemistry Centre University of Western Australia during the 1980s, and at the CSIRO Bentley Laboratories in more recent years. During the 1980s, laboratory combustion work was carried out by Envirochem P/L. VCSRG P/L and the Wetlands Research Association Inc. contributed to page costs of this publication.

References

Allen A D 1979 The hydrogeology of Lake Jandabup, Swan Coastal Plain, Western Australia. West Australian Geological Survey Annual Report 1979, p. 32–40.

Allen A D 1981 Groundwater resources of the Swan Coastal Plain near Perth Western Australia. In: Whelan B R (ed) Groundwater Resources of the Swan Coastal Plain Proceedings Symposium CSIRO Division Land Resources Management / WA State Commonwealth Water Research Foundation Australia, Perth 1981, 29–74.

Arnold R W 1983 Concepts of soils and pedology. In: Wilding L P Smeck N E & Hall G F (eds) Pedogenesis and soil taxonomy. Developments in Soil Science 11A. Elsevier, Amsterdam.

Backhouse J 1993 Holocene vegetation and climate record from Barker Swamp, Rottnest Island, Western Australia. Journal of the Royal Society of Western Australia 76: 53–61.

Balla S A & Davis J A 1993 Volume 5: Managing Perth's wetlands to conserve the aquatic fauna. In: Balla S (ed), Wetlands of the Swan Coastal Plain. Water Authority of Western Australia, Perth Western Australia.

Baltzer F 1991 Late Pleistocene and Recent detrital sedimentation in the deep parts of northern Lake Tanganyika (East African rift). In: A Anadon & K Kelts (eds), Lacustrine facies analyses. International Association of Sedimentologists Special Publication No 13. Blackwell Scientific Publications, Oxford.

Bathurst R G C 1971 Carbonate sediments and their diagenesis. Developments in Sedimentology 12. Elsevier Publishing Company, Amsterdam.

Barber K E 1981 Peat stratigraphy and climate change. Balkema, Rotterdam.

Buol S W Hole F D & McCracken R J 1973. Soil genesis and classification. Iowa State University Press, Ames.

Chessman B C Trayler K M Davis J A 2002. Family and species level biotic indices for macroinvertebrates of wetlands on the Swan Coastal Plain, Western Australia. Marine and Freshwater Research 53(5): 919–930

Clarke J S 1988. Particle motion and the theory of charcoal analysis: source area, transport, deposition, and sampling. Quaternary Research 30: 67–80.

Clymo R S 1983 Peat. In: Gore A J P (ed) Mires: Swamp, Bog, Fen, and Moor, Ecosystems of the World, 4A Elsevier p159–224

Coshell L & Rosen M R 1994 Stratigraphy and Holocene history of Lake Hayward, Swan Coastal Plain wetlands, Western Australia. In: R W Renaut & W M Last (eds), Sedimentology and geochemistry of modern and ancient salinne lakes. SEPM (Society for Sedimentary Geology) Special Publication No. 50: 173–188.

Dachnowski A P 1920 Peat deposits of the United States and their classification. Soil Science 10: 453–465.

Davis J A & Rolls S W 1987. A baseline biological monitoring programme for the urban wetlands of the Swan Coastal Plain, Western Australia. Environmental Protection Authority Bulletin 265, 80p.

Davis J A Rosich R S Bradley J S Gowns J E Schmidt L G & Cheal F 1993 Volume 6: Wetland classification on the basis of water quality and invertebrate community data. In: Balla S (ed), Wetlands of the Swan Coastal Plain. Water Authority of Western Australia, Perth Western Australia.

Druckman Y Margaritz M & Sneh A 1987 The shrinking of Lake Lisan as reflected by the diagenesis of its marginal oolitic deposits. Israeli Journal of Earth Science 36: 101–106.

Dunham R J 1962 Classification of carbonate rocks according to depositional texture. In: Ham W E (ed) Classification of carbonate rocks: a symposium Memoir 1 American Association of Petroleum Geologists, Oklahoma USA p108–121

Etherington J R 1983 Wetland ecology. Edward Arnold London 67p

Faegri K, Iversen J & Krzywinski K 1989. Textbook of pollen analysis. IV Edition. John Wiley & Sons, London.

FAO-UNESCO 1974. Soil map of the World. Volume 1. Legend, Paris 59p.

Folk R L 1962 Spectral subdivision of limestone types. In: Ham W E (ed) Classification of carbonate rocks: a symposium. American Association of Petroleum Geologists Memoir 1, Oklahoma USA p62–84

Fritz S C Cumming B F Gasse F & Laird K 1999. Diatoms as indicators of hydrologic and climatic change in saline lakes. In: E F Stoermer & J P Smol (eds), The diatoms: applications for environmental and Earth sciences. Cambridge University Press, Cambridge.

FitzPatrick E A 1983. Soils. Longman Scientific & Technical, Harlow.

Gasse F Fontes J C Plaziat J C Carbonel P Kacsmarska I De Decker P Soulie-Marsche I Callot Y & Dupeuble P 1987. Biological remains, geochemistry and stable isotopes for the reconstruction of environmental and hydrological changes in the Holocene lakes from North Sahara. Palaeogeography, Palaeoclimatology, Palaeoecology 60: 1–46

Geological Survey of Western Australia 1990. Geology and Mineral Resources of Western Australia. *Memoir 3*. Department of Mines, Western Australia.

Glassford D K 1980 Late Cainozoic desert eolian sedimentation in Western Australia. PhD thesis University of Western Australia, Perth 301p.

Glassford D K & Killigrew L P 1976 Evidence for Quaternary westward extension of the Australian Desert into SW Australia. Search 7: 394–396.

Glassford D K & Semeniuk 1990 Stratification and disconformities in yellow sands of the Bassendean and Spearwood Dunes, Swan Coastal Plain, southwestern Australia. Journal of the Royal Society of Western Australia 71: 75–93

Grabau A W 1903 Palaeozoic coral reefs. Geological Society of America Bulletin 14: 337–352.

Hakanson L & Jansson M 1983 Principles of lake sedimentology. Springer-Verlag, Berlin.

Hall J 1985. The hydrogeology of Lake Mariginiup, Perth, Western Australia. West Australian Geological Survey Report 14, Professional Papers for 1983, p. 1–13.

Hammer U T 1986 Saline Lake Systems of the World. Monographiae Biologicae Volume 59, Dr W Junk Publishers, Dordrecht.

Helleren S & John J 1994. Ordination of wetlands of the Swan Coastal Plain based on diatom assemblages. 33rd Congress of Australian Society for Limnology, Rottnest Island Western Australia

Hembree D & George R W 1978 The aquatic invertebrate fauna of the northern Swan Coastal Plain. In: Faunal studies of the northern Swan Coastal Plain – a consideration of past and future changes. Unpublished report Western Australian Museum

Hunt C B 1972 Geology of soils. W H Freeman & Co., San Francisco.

Jackson J A (ed) 1997 Glossary of geology (4th ed) American Geological Institute, Virginia.

John J 1981 New species of freshwater diatoms from Western Australia. Nova Hedwigia 34: 569–576

John J 1993 The use of diatoms in monitoring the development of created wetlands at a sandmining site in Western Australia. Hydrobiologia 269 / 270: 427–436.

Kelts K & Hsu K J 1978 Freshwater carbonate sedimentation. In: A Lerman (ed), Lakes: Chemistry, Geology, and Physics. Spinger-Verlag, Berlin, pp295–353.

Kerr P F 1959. Optical mineralogy. McGraw Hill Book Co., New York

Leaney F W J Allison G B Dighton J C & Trumbore S 1995. The age and hydrological history of Blue Lake, South Australia. Palaeogeography, Palaeoclimatology, Palaeoecology 118: 111–130.

Leeper G W& Uren N C 1993 Soil Science – an introduction. Melbourne University Press.

McArthur W M & Bartle G A 1980a Landforms and soils as a basis for Urban Planning in the Perth Metropolitan North-West Corridor, Western Australia. CSIRO Division Land Resource Management Series 5.

McArthur W M & Bartle G A 1980b. Soils and land-use planning in the Mandurah-Bunbury coastal zone, Western Australia. CSIRO Australian Division Land Resource Management Series No 6.

Machlus M, Enzel Y, Goldstein S L, Marco S, & Stein M 2000. Reconstructing low levels of Lake Lisan by correlating fan-delta and lacustrine deposits. Quaternary International 73/74: 137–144.

McArthur W M & Bettenay E 1960. The development and distribution of soils of the Swan Coastal Plain. Western Australia. CSIRO Soil Publication No 16.

Maly E J Halse S A & Maly M P 1997. Distribution and incidence patterns of *Boeckella*, *Calamoecia*, and *Hemiboeckella* (Copepoda: Calanoida) in Western Australia. Marine and Freshwater Research 48(7) 615–621

Megirian D 1982 The hydrogeology of North and Bibra lakes, Perth, Western Australia. BSc Hons University of Western Australia, Perth

Meunier J D & Fabrice C (eds) 2001. Phytoliths – applications in Earth Science and Human History. Balkema, Amsterdam.

Mitsch W J & Gosselink J G 1986 Wetlands. Van Nostrand Reinhold New York p88–125

Muir B G 1983. Drainage, swamp structure and vegetation succession at Melaleuca Park, Northern Swan Coastal Plain. Western Australian Herbarium Research Notes 9, 27–39.

Muller G 1971. Aragonite inorganic precipitation in a freshwater lake. Nature 229: 18.

Muller G, Irion G & Forstner U 1972. Formation and diagenesis of inorganic Ca-Mg carbonates in the lacustrine environment. Naturwissenschaften 59: 158–164.

Newsome J C & Pickett E J 1993 Palynology and palaeoclimatic implications of two Holocene sequences from southwestern Australia. Palaeogeography, Palaeoclimatology and Palaeoecology 101: 245–261

Odgaard B V 1992. The fire history of Danish heathland areas as reflected by pollen and charcoal particles in lake sediments. The Holocene 2: 218–226.

Pickett E 1998 The late Pleistocene and Holocene vegetation history of three lacustrine sequences from the Swan Coastal Plain South West Australia. PhD University of Western Australia, Perth

Playford P E Cockbain A E & Low G H 1976 Geology of the Perth Basin, Western Australia. Geological Survey Western Australia Bulletin 124.

Playford P E & Low G H 1972 Definitions of some new and revised rock units in the Perth Basin. West Australian Geological Survey Annual Report 1971, 44–46

Prider R T 1948 The geology of the Darling Scarp at Ridge Hill. Journal of the Royal Society of Western Australia 32: 105–129.

Reineck H E & Singh I B 1980 Depositional sedimentary environments (2nd Edition). Springer Verlag, Berlin.

Roberts J A, Bennett P C, Gonzalez L A, Macpherson G L & Milliken K L 2004 Microbial precipitation of dolomite in methanogenic groundwater. Geology 32: 277–280.

Rosen M R, Miser D E, Starcher M A & Warren J K 1989 Formation of dolomite in the Coorong region. Geochimica et Cosmochimica Acta 53: 661–669.

Searle D J & Semeniuk V 1985 The natural sectors of the inner Rottnest Shelf coast adjoining the Swan Coastal Plain. Journal of the Royal Society of Western Australia 67: 116–136.

Semeniuk C A 1987 Wetlands of the Darling System – a geomorphic approach to habitat classification. Journal of the Royal Society of Western Australia 69: 95–111.

Semeniuk C A 1988 Consanguineous wetlands of the Darling system. Journal of the Royal Society of Western Australia 70: 69–87.

Semeniuk C A 2005 The Becher Wetlands – a Ramsar site: A case study of the evolution of wetland habitats and vegetation associations on a Holocene coastal plain, south-western Australia. Springer (in press)

Semeniuk C A & Semeniuk V 1990 The coastal landforms and peripheral wetlands of the peel-Harvey estuarine system. Journal of the Royal Society of Western Australia 73(1): 9–21

Semeniuk C A Semeniuk V Cresswell I D & Marchant N D 1990 Wetlands of the Darling System, southwestern Australia: a descriptive classification using vegetation pattern and form. Journal of the Royal Society of Western Australia 72: 109–121

Semeniuk V 1995 New Pleistocene and Holocene stratigraphic units on the Yalgorup Plain area, southern Swan Coastal Plain. Journal of the Royal Society of Western Australia 78: 67–79

Semeniuk V 1996 An early Holocene record of rising sealevel along a bathymetrically complex coast in southwestern Australia. Marine Geology 131: 177–193

Semeniuk V 2000 Sedimentology and Holocene stratigraphy of Leschenault Inlet. In: The Leschenault Inlet estuary. Special Issue of the Journal of the Royal Society of Western Australia 83(4): 255–274

Semeniuk V & Glassford D K 1987 Origin of limestone lenses in Perth Basin yellow sand, southwestern Australia. Journal of the Royal Society of Western Australia 70, 35–47.

Semeniuk V & Glassford D K 1988 Significance of aeolianite limestone lenses in quartz sand formations: an interdigitation of coastal and continental facies. Sedimentary Geology 57: 199–209.

Semeniuk V & Glassford D K 1989 Bassendean and Spearwood Dunes: their geomorphology, stratigraphy and soils as a basis for habitats of Banksia woodlands. Journal of the Royal Society of Western Australia 71: 87–88.

Semeniuk V & Searle D J 1986 Variability of Holocene sealevel history along the southwestern coast of Australia – evidence for the effect of significant local tectonism. Marine Geology 72: 47–58.

Semeniuk V & Searle D J 1987 The Bridport Calcilutite. Journal of the Royal Society of Western Australia 70: 25–27.

Semeniuk V & Johnson D P 1982 Recent and Pleistocene beach and dune sequences, Western Australia. Sedimentary Geology 32: 301–328.

Semeniuk V & Johnson D P 1985 Modern and Pleistocene rocky shores along carbonate coastlines, Southwestern Australia. Sedimentary Geology 44: 225–261

Semeniuk V & Semeniuk C A 1990 Radiocarbon ages of some coastal landforms in the Peel-Harvey estuary. Journal of the Royal Society of Western Australia 73: 61–71.

Semeniuk V & Semeniuk C A 2005a Sedimentary fill of basin wetlands, central Swan Coastal Plain, southwestern Australia. Part 2: distribution of sediment types and stratigraphy. Journal of the Royal Society of Western Australia (in press)

Semeniuk V & Semeniuk C A 2005b Wetland sediments and soils on the Swan Coastal Plain, southwestern Australia: types, distribution, susceptibility to combustion, and implications for fire management. Journal of the Royal Society of Western Australia (in press)

Semeniuk V & Semeniuk C A 2005c The signature of fire in wetland sediments, Swan Coastal Plain, southwestern Australia (submitted)

Semeniuk V Cresswell I D & Wurm P A S 1989. The Quindalup Dunes: the regional system, physical framework and vegetation habitats. Journal of the Royal Society of Western Australia 71: 23–47

Simpson E S 1903 Diatomaceous earth, Wanneroo. Western Australia Geological Survey Annual Report 1902, 79–81.

Sinkankas J 1964. Mineralogy. Van Nostrand Reinhold, New York.

Soil Survey Staff 1998 Keys to soil taxonomy. 8th Edition. USDA-NRCS. US Government Printing Office, Washington, DC.

Sprecher S W 2001 Basic concepts of soil science. In: Richardson J L & Vepraskas M J (eds) Wetland Soils: genesis, hydrology, landscapes and classification. Lewis Publishers Washington DC p3–18

Swift D J P 1971. Chapter 21: Grain mounts. In: R E Carver (ed), Procedures in sedimentary petrology. Wiley-Interscience, New York.

Talbot M R 1990. A review of the palaeohydrological interpretation of carbon and oxygen isotopic rations in primary lacustrine carbonates. Chemical Geology (Isotope Geoscience Section) 80: 261–279.

Teakle L J H & Southern B L 1937 The peat soils and related soils of Western Australia. Journal of Agriculture 14: 332–358.

Tebbutt, G E Conley C D & Boyd D W 1965 Lithogenesis of a distinctive carbonate rock fabric. University of Wyoming. Contributions to Geology 4(1): 1–13.

Tiner R W 1999 Wetland Indicators: a guide to wetland identification, delineation, classification, and mapping. Lewis Publishers Washington DC

Tucker M E & Wright V P 1990. Carbonate sedimentology. Blackwell Scientific Publications, Oxford.

USDA 1975. Soil Taxonomy. Agricultural Handbook No. 436. 754p.

von der Borch C C 1976 Stratigraphy and formation of Holocene dolomitic carbonate deposits of the Coorong area, South Australia. Journal of Sedimentary Petrology 46: 952–966.

Wentworth C K 1922. A scale of grade and class terms for clastic sediments. Journal of Geology 30: 377–392.

Wetzel R G 1983 Limnology, 2nd Edition. Saulnders College Publishing USA.

Williams W D 1980. Australian freshwater life. MacMillan Company of Australia, Melbourne.

Woolnough W G 1920 The physiographic elements of the Swan Coastal Plain. Journal of the Royal Society of Western Australia 5: 15–19.

Wright V P & Platt N H 1995 Seasonal wetland carbonate sequences and dynamic catenas: a re-appraisal of palustrine limestones. Sedimentary Geology 99: 65–71.

Wright D T 2000 Benthic microbial communities and dolomite formation in marine and lacustrine environments – a new dolomite model. In: C R Glenn, J Lucas, & L Prevot-Lucas (eds), Marine authigenesis: from Global to microbial. SEPM Special Publication 66: 7–14.

Appendix 1

Latitude and longitude of the 143 wetland sampling sites and their location in relation to the consanguineous suites of Semeniuk (1988). Sites are mainly ordered from north to south, but also grouped where they are proximal within a given consanguineous suite

Site		Co-ordinates	Suite
1.	Tangletoe Swamp 3	31° 19' 03" S, 115° 45' 04" E	Jandakot
2.	Tangletoe Swamp 1	31° 21' 09" S, 115° 47' 49" E	Jandakot
3.	Tangletoe Swamp 5	31° 21' 22" S, 115° 46' 35" E	Jandakot
4.	Coonabidgee Rd Swamp A	31° 21' 40" S, 115° 49' 46" E	Mungala
5.	Coonabidgee Rd Swamp B	31° 21' 56" S, 115° 51' 49" E	Mungala
6.	Lake Bambum	31° 25' 34" S, 115° 53' 23" E	Mungala
7.	Lake Nambung	31° 26' 02" S, 115° 53' 19" E	Mungala
8.	Lake Mungala 1	31° 26' 18" S, 115° 53' 42" E	Mungala
9.	Lake Mungala 3	31° 26' 29" S, 115° 53' 48" E	Mungala
10.	Bullrush Swamp	31° 29' 29" S, 115° 39' 17" E	Yanchep
11.	Yeal Swamp	31° 28' 17" S, 115° 46' 04" E	Jandakot
12.	Casuarina Swamp	31° 27' 21" S, 115° 46' 22" E	Jandakot
13.	Bullsbrook	31° 37' 39" S, 116° 00' 59" E	Keysbrook
14.	Pinjar Pine Forest 1	31° 37' 06" S, 115° 50' 00" E	Jandakot
15.	Pinjar Pine Forest 5	31° 37' 25" S, 115° 51' 28" E	Jandakot
16.	Pinjar Pine Forest 8	31° 38' 10" S, 115° 53' 04" E	Jandakot
17.	Pinjar Pine Forest 7	31° 38' 58" S, 115° 51' 44" E	Jandakot
18.	Loch McNess	31° 32' 38" S, 115° 40' 51" E	Yanchep
19.	Yonderup	31° 33' 17" S, 115° 41' 09" E	Yanchep
20.	Lake Pippidinny	31° 34' 44" S, 115° 41' 08" E	Yanchep
21.	Lake Carabooda	31° 37' 05" S, 115° 43' 21" E	Yanchep
22.	Lake Nowergup	31° 38' 00" S, 115° 43' 51" E	Yanchep
23.	Lake Pinjar north	31° 36' 12" S, 115° 47' 37" E	Pinjar
24.	Lake Pinjar south	31° 39' 15" S, 115° 48' 11" E	Pinjar
25.	Lake Neerabup	31° 39' 56" S, 115° 44' 49" E	Yanchep
26.	Melaleuca Park (Neaves Rd)	31° 40' 21" S, 115° 54' 15" E	Riverdale
27.	Melaleuca Park diatomite 1	31° 40' 21" S, 115° 53' 45" E	Riverdale
28.	Melaleuca Park diatomite 2	31° 40' 00" S, 115° 53' 38" E	Riverdale
29.	Carramar Swamp	31° 42' 46" S, 115° 46' 22" E	Yanchep
30.	Lake Adams	31° 42' 06" S, 115° 49' 26" E	Gnangara
31.	Lake Joondalup north	31° 43' 03" S, 115° 46' 18" E	Yanchep
32.	Ellenbrook A	31° 43' 26" S, 116° 01' 28" E	Ellen Brook
33.	Pinjar Pine Forest 156	31° 43' 55" S, 115° 56' 53" E	Jandakot
34.	Pinjar Pine Forest 164	31° 43' 38" S, 115° 57' 05" E	Jandakot
35.	Pinjar Pine Forest 88	31° 44' 31" S, 115° 55' 32" E	Jandakot
36.	Pinjar Pine Forest 104	31° 44' 38" S, 115° 55' 49" E	Jandakot
37.	Pinjar Pine Forest 158	31° 44' 13" S, 115° 56' 57" E	Jandakot
38.	Pinjar Pine Forest 132	31° 44' 41" S, 115° 56' 27" E	Jandakot
39.	Lake Jandabup	31° 44' 18" S, 115° 50' 32" E	Gnangara
40.	Lake Mariginiup	31° 43' 29" S, 115° 48' 54" E	Gnangara
41.	Lake Joondalup	31° 44' 32" S, 115° 47' 06" E	Gnangara
42.	Ellenbrook B	31° 44' 13" S, 116° 01' 08" E	Ellen Brook
43.	Ellenbrook C 9	31° 43' 24" S, 115° 57' 29" E	Jandakot
44.	Ellenbrook D1	31° 45' 10" S, 115° 58' 56" E	Jandakot
45.	Ellenbrook D9	31° 45' 14" S, 115° 58' 18" E	Jandakot
46.	Ellenbrook D south	31° 45' 25" S, 115° 58' 25" E	Jandakot
47.	Ellenbrook Swamp North	31° 42' 49" S, 115° 57' 17" E	Jandakot
48.	Ellenbrook Swamp middle	31° 43' 11" S, 115° 57' 11" E	Jandakot
49.	Ellenbrook Swamp south	31° 44' 41" S, 115° 57' 40" E	Jandakot
50.	Sydney Rd Swamp P	31° 46' 57" S, 115° 51' 21" E	Gnangara
51.	Sydney Rd Swamp H	31° 46' 50" S, 115° 51' 15" E	Gnangara
52.	Lake Gnangara	31° 47' 13" S, 115° 52' 11" E	Gnangara
53.	Waluburnup Swamp north	31° 47' 08" S, 115° 48' 14" E	Yanchep
54.	Waluburnup Swamp central	31° 47' 28" S, 115° 48' 25" E	Yanchep
55.	Waluburnup Swamp south	31° 48' 04" S, 115° 48' 40" E	Yanchep
56.	Beenyup Swamp	31° 47' 16" S, 115° 48' 00" E	Yanchep
57.	Lake Goolelal	31° 48' 43" S, 115° 48' 53" E	Yanchep
58.	Yarkin Swamp	31° 47' 38" S, 115° 59' 43" E	Muchea
59.	Waluburnup Swamp	31° 47' 06" S, 115° 48' 13" E	Yanchep

Site		**Co-ordinates**	**Suite**
60.	Snake Swamp	31° 48' 00" S, 115° 51' 52" E	Gnangara
61.	Balajura wetlands (now Emu Lake)	31° 50' 25" S, 115° 52' 55" E	Jandakot
62.	Marshall Rd wetland	31° 51' 19" S, 115° 54' 57" E	Bennett Brook
63.	Big Carine Swamp	31° 51' 09" S, 115° 47' 13" E	Balcatta
64.	Little Carine Swamp	31° 50' 52" S, 115° 47' 37" E	Balcatta
65.	Koondoola dampland	31° 50' 55" S, 115° 52' 30" E	Jandakot
66.	Lake Gwelup	31° 52' 43" S, 115° 47' 33" E	Balcatta
67.	Karrinyup Swamp	31° 52' 01" S, 115° 47' 17" E	Balcatta
68.	Karrinyup Road Swamp	31° 53' 26" S, 115° 53' 26" E	Balcatta
69.	Lake Herdsman	31° 55' 12" S, 115° 48' 18" E	Balcatta
70.	Brixton Swamp	32° 01 48" S, 115° 58' 21" E	Mungala
71.	Yule Brook wetlands	32° 01' 16" S, 115° 58' 52" E	Mungala
72.	Kenwick Swamp	32° 02' 21" S, 115° 57' 56" E	Mungala
73.	Canine Swamp	32° 06' 06" S, 115° 56' 05" E	Jandakot
74.	Bull Creek 1	32° 03' 11" S, 115° 51' 32" E	Jandakot
75.	Canning Vale wetlands	32° 03' 16" S, 115° 56' 27" E	Bennett Brook
76.	Piney Lakes	32° 02' 56" S, 115° 50' 11" E	Jandakot
77.	Roe Swamp	32° 05' 01" S, 115° 50' 05" E	Jandakot
78.	North Lake	32° 04' 34" S, 115° 49' 28" E	Bibra
79.	Horse Paddock Swamp	32° 04' 51" S, 115° 49' 26" E	Bibra
80.	Bibra Lake	32° 05' 17" S, 115° 49' 23" E	Bibra
81.	Manning Lake (= Coogee O)	32° 05' 34" S, 115° 46' 18" E	Coogee
82.	Coogee J	32° 07' 52" S, 115° 46' 51" E	Coogee
83.	Lake Coogee (= Coogee G)	32° 08' 15" S, 115° 46' 36" E	Coogee
84.	Lake Coogee South (= Coogee F)	32° 08' 34" S, 115° 46' 59" E	Coogee
85.	Market Garden Swamps	32° 06' 43" S, 115° 46' 42" E	Coogee
86.	Thompsons Lake	32° 08' 52" S, 115° 49' 43" E	Bibra
87.	Lake Forrestdale	32° 09' 33" S, 115° 56' 18" E	Bennett Brook
88.	Banganup Swamp	32° 09' 51" S, 115° 49' 36" E	Bibra
89.	Brownman Swamps West	32° 09' 25" S, 115° 47' 08" E	Coogee
90.	Brownman Swamps East	32° 09' 37" S, 115° 47' 20" E	Coogee
91.	Mt Brown Lake	32° 10' 26" S, 115° 47' 28" E	Coogee
92.	Long Swamp	32° 11' 55" S, 115° 48' 02" E	Coogee
93.	The Spectacles 2	32° 13' 03" S, 115° 50' 19" E	Bibra
94.	Bollard Bullrush Swamp	32° 15' 25" S, 115° 50' 11" E	Bibra
95.	Leda Swamp J	32° 15' 37" S, 115° 48' 46" E	Stakehill
96.	Leda Swamp K	32° 16' 22" S, 115° 48' 26" E	Stakehill
97.	Leda Swamp L	32° 16' 45" S, 115° 48' 34" E	Stakehill
98.	Stakehill A	32° 21' 19" S, 115° 47' 42" E	Stakehill
99.	Stakehill B	32° 22' 25" S, 115° 47' 07" E	Stakehill
100.	Stakehill C	32° 22' 44" S, 115° 47' 28" E	Stakehill
101.	Tamworth Hill Swamp	32° 19' 39" S, 115° 48' 26" E	Stakehill
102.	Anstey Swamp	32° 24' 53" S, 115° 46' 42" E	Stakehill
103.	Pipidinny Swamp	32° 26' 42" S, 115° 47' 05" E	Stakehill
104.	Hammond Rd North Swamp	32° 07' 57" S, 115° 50' 44" E	Jandakot
105.	Hammond Rd South Swamp	32° 08' 07" S, 115° 50' 26" E	Jandakot
106.	Russell Rd Swamp	32° 09' 39" S, 115° 50' 15" E	Jandakot
107.	Twin Bartram Swamp	32° 08' 29" S, 115° 51' 12" E	Jandakot
108.	Emma Treeby Reserve	32° 08' 05" S, 115° 52' 50" E	Jandakot
109.	Orton Road wetland	32° 14' 03" S, 115° 51' 15" E	Jandakot
110.	Mortimer Road wetland	32° 15' 29" S, 115° 51' 27" E	Jandakot
111.	Unnamed basin, near Folly Pool	32° 18' 51" S, 115° 49' 57" E	Goegerup
112.	Wright Lake	32° 06' 01" S, 116° 00' 04" E	Bennett Brook
113.	Piara Swamp	32° 08' 23" S, 115° 55' 22" E	Jandakot
114.	Balfour Rd Swamp 1	32° 05' 50" S, 115° 57' 23" E	Jandakot
115.	Balfour Rd Swamp 2	32° 05' 46" S, 115° 57' 20" E	Jandakot
116.	Balfour Rd Swamp 3	32° 06' 14" S, 115° 57' 15" E	Jandakot
117.	Balfour Rd Swamp 4	32° 06' 31" S, 115° 56' 46" E	Jandakot
118.	Mather Reserve	32° 08' 44" S, 115° 52' 28" E	Jandakot
119.	Shirley Balla Swamp	32° 09' 16" S, 115° 52' 48" E	Jandakot
120.	Forrestdale Road Swamp	32° 07' 51" S, 115° 52' 17" E	Bennett Brook
121.	Forrestdale swamp 1	32° 07' 49" S, 115° 55' 17" E	Jandakot
122.	Forrestdale swamp 2	32° 07' 30" S, 115° 55' 02" E	Jandakot

Site		Co-ordinates	Suite
123.	Forrestdale swamp 3	32° 07' 19" S, 115° 54' 53" E	Jandakot
124.	Kraemer Reserve	32° 08' 44" S, 115° 53' 29" E	Jandakot
125.	Bartram Rd Swamp	32° 08' 43" S, 115° 53' 53" E	Jandakot
126.	Harrisdale Swamp (Green Swamp)	32° 06' 41" S, 115° 55' 35" E	Bennett Brook
127.	Balannup Swamp	32° 06' 49" S, 115° 56' 44" E	Bennett Brook
128.	Balannup-Hale	32° 07' 04" S, 115° 56' 43" E	Bennett Brook
129.	Wright Rd Swamp	32° 08' 17" S, 115° 54' 26" E	Bennett Brook
130.	Wawa Swamp	32° 22' 23" S, 115° 45' 52" E	Becher
131.	Cud Swamp	32° 23' 57" S, 115° 45' 29" E	Becher
132.	West Corio Swamp	32° 32' 32" S, 115° 52' 37" E	Gnangara
133.	North Corio Swamp	32° 32' 18" S, 115° 52' 54" E	Gnangara
134.	Lake Mealup	32° 40' 49" S, 115° 42' 44" E	Bibra
135.	Riverdale wetlands 3	32° 58' 49" S, 115° 47' 37" E	Riverdale
136.	Riverdale wetlands 2	32° 59' 08" S, 115° 47' 39" E	Riverdale
137.	Riverdale wetlands 1	32° 59' 36" S, 115° 48' 03" E	Riverdale
138.	Willie Pool	33° 01' 12" S, 115° 47' 47" E	Riverdale
139.	Kemerton Swamps	33° 07' 22" S, 115° 46' 50" E	Jandakot
140.	Myalup Swamp	33° 07' 57" S, 115° 43' 28" E	Clifton
141.	Mialla Lagoon	33° 09' 59" S, 115° 43' 52" E	Clifton
142.	Benger Swamp	33° 10' 13" S, 115° 50' 09" E	Benger
143.	Burragenup wetland	33° 11' 01" S, 115° 43' 00" E	Clifton

Appendix 2

Description of each of the wetlands from which the 32 wetland sediment standards used in this study: were collected: wetland name, wetland sediment standard number (WSS #), co-ordinates, depth of sample, consanguineous suite and geomorphic setting, type of wetland. The number after a wetland name (*e.g.*, Lake Yonderup 2) refers to one of the study sites within the wetland.

Field name of site (locations ordered north to south); depth of sample; laboratory no	**Co-ordinates**	**Consanguineous Suite and geomorphic setting**	**Description of wetland**
Lake Yonderup 2 10-13 cm WSS-No. 26	31° 33' 17" S, 115° 41' 09" E	Yanchep Suite; karst depressions in swales of Spearwood Dunes	mesoscale linear sumpland
Lake Carabooda 2 10-13 cm WSS-No. 16	31° 37' 05" S, 115° 43' 21" E	Yanchep Suite; karst depressions in swales of Spearwood Dunes	macroscale linear sumpland
Lake Joondalup 0-5 cm WSS-No. 23	31° 43' 03" S, 115° 46' 18" E	Yanchep Suite; karst depressions in swales of Spearwood Dunes	megascale linear lake
Casuarina D 1 0-30 cm WSS-No. 20	31° 27' 21" S, 115° 46' 22" E	Jandakot Suite; basins within star dunes in Bassendean Dunes	mesoscale curvilinear dampland
Pinjar Pine Forest 8v 2-20 cm WSS-No. 33	31° 38' 10" S, 115° 53' 04" E	Jandakot Suite; basins within star dunes in Bassendean Dunes	mesoscale curvilinear dampland
Pinjar Pine Forest 8p 260 cm WSS-No. 34	31° 38' 10" S, 115° 53' 04" E	Jandakot Suite; basins within star dunes in Bassendean Dunes	mesoscale curvilinear dampland
Melaleuca Park 10 cm WSS-No. 18	31° 40' 21" S, 115° 54' 15" E	Riverdale Suite; basins in linear chains between dunes	microscale sumpland with humic muddy sand / mixed coarse and medium sand
Lake Adams 2 0-20 cm WSS-No. 25	31° 42' 06" S, 115° 49' 26" E	Gnangara Suite; basins enclosed by dune ridges	macroscale rounded dampland
Sydney Rd Swamp P 20 cm WSS-No. 11	31° 46' 57" S, 115° 51' 21" E	Gnangara Suite; basins enclosed by dune ridges	microscale rounded dampland
Lake Mungala 1 85 cm WSS-No. 15	31° 26' 18" S, 115° 53' 42" E	Mungala Suite; discharge basins for creeks in the transition zone between Bassendean Dunes and Pinjarra Plain	mesoscale rounded sumpland
Lake Mungala 3 115 cm WSS-No. 8	31° 26' 29" S, 115° 53' 48" E	Mungala Suite; discharge basins for creeks in the transition zone between Bassendean Dunes and Pinjarra Plain	microscale rounded sumpland
Bullsbrook 62-85 cm WSS-No. 13	31° 37' 39" S, 116° 00' 59" E	Keysbrook Suite; gently undulating to flat surface with incised creeks	paluslope to palusplain
Coogee F 1 80 cm WSS-No. 10	32° 08' 34" S, 115° 46' 59" E	Coogee Suite; linear interdune swale underlain by limestone	mesoscale elongate lake
Coogee J 2 65 cm WSS-No. 22	32° 07' 52" S, 115° 46' 51" E	Coogee Suite; linear interdune swale underlain by limestone	microscale ovoid sumpland
Coogee J 3 40-80 cm WSS-No. 9	32° 07' 52" S, 115° 46' 51" E	Coogee Suite; linear interdune swale underlain by limestone	microscale ovoid sumpland
Lake Manning 1 0-5 cm WSS-No. 21	32° 05' 34" S, 115° 46' 18" E	Coogee Suite; linear interdune swale underlain by limestone	microscale ovoid sumpland
Lake Manning 1 100-200 cm WSS-No. 24	32° 05' 34" S, 115° 46' 18" E	Coogee Suite; linear interdune swale underlain by limestone	microscale ovoid sumpland

Field name of site (locations ordered north to south); depth of sample; laboratory no	Co-ordinates	Consanguineous Suite and geomorphic setting	Description of wetland
Leda J 2 45 cm WSS-No. 4	32° 15' 37" S, 115° 48' 46" E	Stakehill Suite; basins within limestone ridges	microscale irregular sumpland
Leda K 1 60-100 cm WSS-No. 7	32° 16' 22" S, 115° 48' 26" E	Stakehill Suite; basins within limestone ridges	microscale ovoid sumpland
Leda K 2 0-30 cm WSS-No. 2	32° 16' 22" S, 115° 48' 26" E	Stakehill Suite; basins within limestone ridges	microscale ovoid sumpland
Leda L 2 40-60 cm WSS-No. 3	32° 16' 45" S, 115° 48' 34" E	Stakehill Suite; basins within limestone ridges	mesoscale irregular elongate sumpland
Stakehill A 1 10-38 cm WSS-No. 14	32° 21' 19" S, 115° 47' 42" E	Stakehill Suite; basins within limestone ridges	mesoscale irregular sumpland
Stakehill A 2 0-60 cm WSS-No. 30	32° 21' 19" S, 115° 47' 42" E	Stakehill Suite; basins within limestone ridges	mesoscale irregular sumpland
Stakehill B 1 60-130 cm WSS-No. 29	32° 22' 25" S, 115° 47' 07" E	Stakehill Suite; basins within limestone ridges	macroscale irregular sumpland
Stakehill B 3 40 cm WSS-No. 28	32° 22' 25" S, 115° 47' 07" E	Stakehill Suite; basins within limestone ridges	macroscale irregular sumpland
Bibra Lake SW 1 0-5 cm WSS-No. 12	32° 05' 17" S, 115° 49' 23" E	Bibra Suite; basins along the contact between the Spearwood Ridges and the Bassendean Sand Dunes	macroscale irregular lake
Banganup Swamp 2 35 cm WSS-No. 5	32° 09' 51" S, 115° 49' 36" E	Bibra Suite; basins along the contact between the Spearwood Ridges and the Bassendean Sand Dunes	mesoscale irregular sumpland
The Spectacles 2 10 cm WSS-No. 19	32° 13' 03" S, 115° 50' 19" E	Bibra Suite; basins along the contact between the Spearwood Ridges and the Bassendean Sand Dunes	macroscale round sumpland
The Spectacles 2 90-110 cm WSS-No. 17	32° 13' 03" S, 115° 50' 19" E	Bibra Suite; basins along the contact between the Spearwood Ridges and the Bassendean Sand Dunes	macroscale round sumpland
West Bollard Bullrush Swamp 35-50 cm WSS-No. 6	32° 15' 25" S, 115° 50' 11" E	Bibra Suite; basins along the contact between the Spearwood Ridges and the Bassendean Sand Dunes	macroscale round sumpland
West Bollard Bullrush Swamp 120-170 cm WSS-No. 32	32° 15' 25" S, 115° 50' 11" E	Bibra Suite; basins along the contact between the Spearwood Ridges and the Bassendean Sand Dunes	macroscale round sumpland
Balannup-Hale 150-175 cm WSS-No. 39	32° 07' 04" S, 115° 56' 43" E	Bennett Brook Suite; Bassendean Dunes with microscale creeks and flats	mesoscale irregular sumpland

Appendix 3

Description of the 32 wetland sediment standards used in this study, in terms of grain size fractions, and particle and crystal composition. om = organic matter; qz = quartz; ph = phytoliths; ss = sponge spicules; ca = undifferentiated carbonate particle; sh = shell; mp = mud-sized phyllosilicate (kaolinite, micas, montmorillonite); di = diatoms; ic = carbonate intraclasts; os = ostracods

Field name of site (ordered north to south); depth of sample; laboratory no	Sediment type	% sand	%mud	Composition of mud by analyses				Visual description under petrographic and stereo-binocular microscope		Comments[3]
				$\%CO_3$ by acid digest	%C by LOI[1]	% residue[2]	Composition by XRD	Sand	Mud	
Lake Yonderup 2 10-13 cm WSS-No. 26	organic matter enriched calcilutaceous muddy sand	46.3	53.7	71.7	15.3	13.0	calcite, quartz, amorphous silica	ic, qz = om	om, ph, di, ss,qz	calcitic carbonate mud with quartz silt and phytoliths, enriched in organic matter is interstitial to a quartz sand frame; XRD detected diatoms, sponge spiculars, and phytoliths as amorphous silica
Lake Carabooda 2 10-13 cm WSS-No. 16	organic matter enriched diatomaceous/ calcilutaceous muddy sand	53.5	46.5	14.0	37.0	49.0	quartz, goethite	om, qz	om > ss, ph, di, mp	mud-sized carbonate skeletal particles, mud-sized phyllosilicate particles, sponge spicules, diatoms and phytoliths occur in the organic matter enriched mud fraction interstitial to a quartz sand frame
Lake Joondalup 0-5 cm WSS-No. 23	organic matter enriched diatomaceous muddy sand	53.4	46.2	26.0	18.4	55.6	quartz, goethite	qz > ss	om > ss > di > mp	mud is interstitial to a quartz sand frame; the amorphous silica in the XRD analysis is diatoms, sponge spiculars, and phytoliths
Casuarina D 1 0-30 cm WSS-No. 20	diatomite	8.5	91.5	2.0	22.0	76.0	quartz, amorphous silica	ss = qz > om	ss & di > qz	XRD and grain mounts of the mud fraction are corroborative in identifying the fine-grained material as quartz silt, diatoms and sponge spicules
Pinjar Pine Forest 8v 2-20 cm WSS-No. 33	sand	82.0	18.0	30.2	1.8	68.0	quartz, microcline, kaolinite, montmorillonite	qz	mp > qz	XRD and grain mounts of the mud fraction are corroborative in identifying the fine-grained material as kaolinite and silt-sized quartz; while classed as "sand", the sediment is moderately kaolinitic muddy, but not as a packstone fabric

Pinjar Pine Forest 8p 260 cm WSS-No. 34	sand	76.7	23.3	10.5	3.2	86.3	quartz, microcline, kaolinite, montmorillonite	qz	mp > qz	XRD and grain mounts of the mud fraction are corroborative in identifying the fine-grained material as kaolinite and other mud-sized phyllosilicate minerals; while classed as “sand”, the sediment is moderately kaolinitic muddy, but not as a packstone fabric
Melaleuca Park 10 cm WSS-No. 18	diatomite	19.0	81.0	11.6	4.5	83.9	quartz, amorphous silica	qz & ss > om	ss & di > qz	XRD and grain mounts of the mud fraction are corroborative in identifying the fine-grained material as quartz silt, diatoms and sponge spicules
Adams 2 0-20 cm WSS-No. 25	diatomite	63.9	36.1	8.0	14.2	77.8	quartz, amorphous silica	qz > ss > om	ss & di > qz	XRD and grain mounts of the mud fraction are corroborative in identifying the fine-grained material as quartz silt, diatoms and sponge spicules
Sydney Rd Swamp 20 cm WSS-No. 11	sandy spongolitic diatomite	37.8	62.2	20.0	1.7	78.3	quartz, amorphous silica	qz > ss	di & ss > qz	XRD and grain mounts of the mud fraction are corroborative in identifying the fine-grained material as quartz silt, diatoms and sponge spicules
Lake Mungala 1 85 cm WSS-No. 15	phyllosilicic muddy sand	47.8	52.2	28.0	5.1	66.9	quartz, montmorillonite hydrobiotite	qz	mp > qz > ss	XRD and grain mounts of the mud fraction are corroborative in identifying the fine-grained material as mud-sized phyllosilicate minerals and silt-sized quartz; sponge spicules observed only in grain mount microscopy; sediment is not kaolinitic, hence the general term “phyllosilicic muddy sand”
Lake Mungala 3 115 cm WSS-No. 8	sand	96.1	3.9	27.0	18.5	54.5	quartz, amorphous silica	qz = om (peaty clasts, root, charcoal)	om = ss = qz	sponge spicules detected in the XRD
Bullsbrook 62-85 cm WSS-No. 13	phyllosilicic muddy sand	75.2	24.8	9.0	3.9	87.1	quartz, amorphous silica, montmorillonite, mica	qz	ph > ss > di > qz & mp	sponge spicules and diatoms detected in the XRD; mud-sized phyllosilicate mineral only detected in the grain mounts of the mud fraction; sediment is not kaolinitic, hence the general term “phyllosilicate muddy sand”

Field name of site (ordered north to south); depth of sample; laboratory no	Sediment type	% sand	%mud	Composition of mud by analyses				Visual description under petrographic and stereo-binocular microscope		Comments[3]
				$\%CO_3$ by acid digest	%C by LOI[1]	% residue[2]	Composition by XRD	Sand	Mud	
Coogee F 1 80 cm WSS-No. 10	calcilutaceous muddy carbonate intraclast sand	58.2	41.8	85.0	2.6	12.4	aragonite and calcite, quartz, amorphous silica	ic	ca > ss > om	sponge spicules detected in the XRD; SEM / EDS shows the mud-sized carbonate component to be mixed calcite and aragonite of biogenic origin; quartz silt comprises part of the mud fraction, though not conspicuous in the grain mount microscopy
Coogee J 2 65 cm WSS-No. 22	calcilutaceous muddy carbonate intraclast sand	58.2	41.8	70.5	20.2	9.3	aragonite, calcite, dolomite, quartz, feldspar, goethite, amorphous silica	ic > om	ca > ss > qz	sponge spicules detected in the XRD; SEM / EDS shows the mud-sized carbonate component is mixed calcite and aragonite of biogenic origin, and diagenetic aragonite and dolmite; minor silt-sized quartz and feldspar also present
Coogee J 3 40-80 cm WSS-No. 9	calcilutaceous muddy carbonate intraclast sand	61.2	38.8	78.9	11.0	10.1	quartz, feldspar, amorphous silica, aragonite calcite	ic	ca > ss > om & qz	sponge spicules detected in the XRD; SEM / EDS shows the mud-sized carbonate component is mixed calcite and aragonite of biogenic origin, and diagenetic aragonite; minor silt-sized quartz and feldspar also present
Coogee O 1 0-5 cm WSS-No. 21	(carbonate intraclast) sandy calcilutite	42.4	57.6	80.0	7.9	12.1	calcite, quartz, feldspar, amorphous silica	ic > ph > qz	ca > ss > ph > silt-sized ic	sponge spicules detected in the XRD; SEM / EDS shows the mud-sized carbonate component is calcite of biogenic origin; minor silt-sized quartz and feldspar also present
Coogee O 1 100-200 cm WSS-No. 24	calcilutaceous muddy carbonate intraclast sand	72.3	27.7	91.0	4.6	4.4	aragonite, calcite, quartz, feldspar, amorphous silica	ic = os	NS	sponge spicules detected in the XRD; SEM / EDS shows the mud-sized carbonate component is mixed calcite and aragonite of biogenic origin; minor silt-sized quartz and feldspar also present

Leda J 2 45 cm WSS-No. 4	peaty sand	40.9	59.1	17.1	65.4	17.5	calcite, quartz, amorphous silica	om > qz	om > ss > sh	sponge spicules detected in the XRD; grain mount microscopy corroborates combustion (LOI) results; quartz silt comprises part of the mud fraction, though not conspicuous in the grain mount microscopy
Leda K 1 60-100 cm WSS-No. 7	spongolitic peaty sand	55.6	44.4	10.0	69.5	20.5	amorphous silica	om > qz	om > ss	sponge spicules dominate the amorphous silica component
Leda K 2 0-30 cm WSS-No. 2	sandy calcilutite	35.8	64.2	77.6	14.7	7.7	calcite, quartz, amorphous silica	sh, os > om > qz	om > ss > qz & sh	calcite of biogenic origin; XRD detects sponge spicules; quartz silt comprises part of the mud fraction
Leda L 2 40-60 cm WSS-No. 3	sandy diatomaceous peat	27.1	72.9	11.4	71.4	17.2	quartz, calcite, amorphous silica	om > sh > qz	om > ss > sh	calcite of biogenic origin; XRD detects sponge spicules; quartz silt comprises part of the mud fraction, though not conspicuous in the grain mount microscopy
Stakehill A 1 10-38 cm WSS-No. 14	sandy organic matter enriched diatomaceous / calcilutaceous mud	24.7	75.3	42.0	25.2	32.8	calcite, quartz	qz > sh	sh > ss > om	calcite of biogenic (shell) origin; quartz silt comprises part of the mud fraction, though not conspicuous in the grain mount microscopy
Stakehill A 2 0-60 cm WSS-No. 30	organic matter enriched diatomaceous / calcilutaceous muddy sand	64.6	35.4	46.0	36.3	17.7	calcite, quartz, amorphous silica	om > sh > qz	ca, sh > om > ss	calcite of biogenic (shell) origin; quartz silt comprises part of the mud fraction, though not conspicuous in the grain mount microscopy
Stakehill B 1 60-130 cm WSS-No. 29	sandy peat	11.4	88.6				calcite, quartz, amorphous silica	ic > sh > qz	sh > om > ss	calcite of biogenic origin; XRD detects sponge spicules
Stakehill B 3 40 cm WSS-No. 28	organic matter enriched calcilutaceous muddy sand	47.5	52.5	74.3	16.5	9.2	calcite, quartz, amorphous silica	os & sh > qz > om	sh > om > ss	calcite of biogenic origin; XRD detects sponge spicules; quartz silt comprises part of the mud fraction
Bibra Lake SW 1 0-5 cm WSS-No. 12	organic matter enriched diatomaceous muddy sand	64.4	35.6	10.0	30.4	59.6	quartz, amorphous silica	om > ss > qz	om > di > ss > qz	calcite of biogenic origin; XRD detects sponge spicules and diatoms; quartz silt comprises part of the mud fraction
Lake Banganup 2 35 cm WSS-No. 5	sandy spongolitic organic matter enriched diatomaceous kaolinitic mud	16.5	83.5	8.1	24.2	67.7	quartz, kaolinite, amorphous silica	om > ss > qz	mp, ss, om	XRD and grain mount microscopy corroborate kaolinite as the dominant ineral in the mud fraction; quartz silt comprises part of the mud fraction

Field name of site (ordered north to south); depth of sample; laboratory no	Sediment type	% sand	%mud	Composition of mud by analyses				Visual description under petrographic and stereo-binocular microscope		Comments[3]
				$\%CO_3$ by acid digest	%C by LOI[1]	% residue[2]	Composition by XRD	Sand	Mud	
The Spectacles 2 10 cm WSS-No. 19	organic matter enriched diatomaceous muddy sand	58.8	41.2	11.3	6.0	82.7	quartz, amorphous	qz > ss = om	di > ss > qz	XRD detects sponge spicules and diatoms and corroborates grain mount microscopy; quartz silt comprises part of the mud fraction
The Spectacles 2 90-110 cm WSS-No. 17	sandy spongolitic kaolinitic diatomite	10.8	89.2	9.5	5.6	84.9	quartz, amorphous silica, kaolinite	ss = qz > om	ss > di > qz > om > mp	XRD detects sponge spicules and diatoms; grain mount microscopy corroborates XRD that kaolinite and silt-sized quartz occur as mud fraction mineral
West Bollard Bullrush Swamp 35-50 cm WSS-No. 6	sandy spongolitic phyllosilicic diatomite	39.0	61.0	6.9	9.7	83.4	quartz, feldspar, sericite	z > om	ss = di > qqz = om > mp	XRD detects sponge spicules and diatoms; grain mount microscopy corroborates XRD information that phyllosilicates and silt-sized quartz occur as mud fraction minerals; the mud fraction of this sediment is a spongolitic phyllosilicic diatomite
West Bollard Bullrush Swamp 120-170 cm WSS-No. 32	spongolitic phyllosilicic muddy sand	43.5	56.5	17.5	8.2	74.3	quartz, calcite, feldspar, mica, sericite	qz > sh > om	ss > qz > mp	only grain mount microscopy recorded sponge spicules; silt-sized feldspar, quartz, and micas occur in the mud fraction
Balannup-Hale 150-175 cm WSS-No. 39	kaolinitic muddy sand	77.5	22.5	8.0	5.2	86.8	quartz, feldspar, montmorillonite, kaolinite	qz	mp > qz	grain mount microscopy corroborates XRD information that phyllosilicates and quartz silt occur as mud fraction minerals

1. LOI at 550° C mostly removes carbon in organic matter
2. residue after acid digestion, and loss of organic matter by LOI consists of biogenic silica, mud-sized phyllosilicate minerals, quartz, other minor siliciclastic particles, oxidised metal sulphides (e.g., goethite, haematite), and the ash from organic matter (viz., sulphates and chlorides of Na, K, Ca, and Mg)
3. bearing in mind that the % residue after acid digestion and LOI is comprised of primary sedimentary particles, diagenetic particles, and residues generated as ash after combustion, the composition of the mud sized fraction is based on information on % carbonate (determined by acid digestion), % carbon (determined by LOI), % residue, and grain mount microscopy