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DELTA PLAIN

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Definition

A delta plain is a low-elevation floodplain formed at the mouth of a river.

Characteristics

A delta plain is one type of low-lying coastal plain, formed where a river empties into the sea (or, rarely, into a freshwater body, as in the case of the Selenga Delta, Figure 1a). Large deltas can generally be subdivided into an upper deltaic plain influenced primarily by fluvial processes and a lower deltaic plain, dominated by wave and tidal processes (Figure 1b). The river flows through the "active" section, but there is commonly an abandoned section containing paleochannels marking former river courses (Wright et al., 1974).

The Red River Delta in northern Vietnam (Figure 1c) can be differentiated into a river-dominated upper delta plain where channels are flanked by levées and meander scroll bars marking former river courses, a southern wave-dominated section with sequences of shore-parallel beach ridges, and an eastern tide-dominated section with numerous tapering tidal creeks (Mathers and Zalasiewicz, 1999).

Similar near-horizontal alluvial plains can form along estuaries, sometimes called deltaic-estuarine plains. For example, coastal lagoons (e.g., Coila Lake, Figure 1d) and barrier estuaries (e.g., Tuross Lake) become gradually infilled as fluvial sediment builds a bayhead delta into the estuarine basin.

Extensive, perennially or seasonally flooded, wetlands may characterize delta plains in their natural state (Figure 1a). Megadeltas in southeastern Asia are often the location for intensive rice cultivation, but also support megacities (e.g., Hanoi, Figure 1c), many of which require augmentation of levées for flood mitigation. The ease with which land can be cleared and the fertility of soils has encouraged their agricultural use (e.g., Figure 1d).

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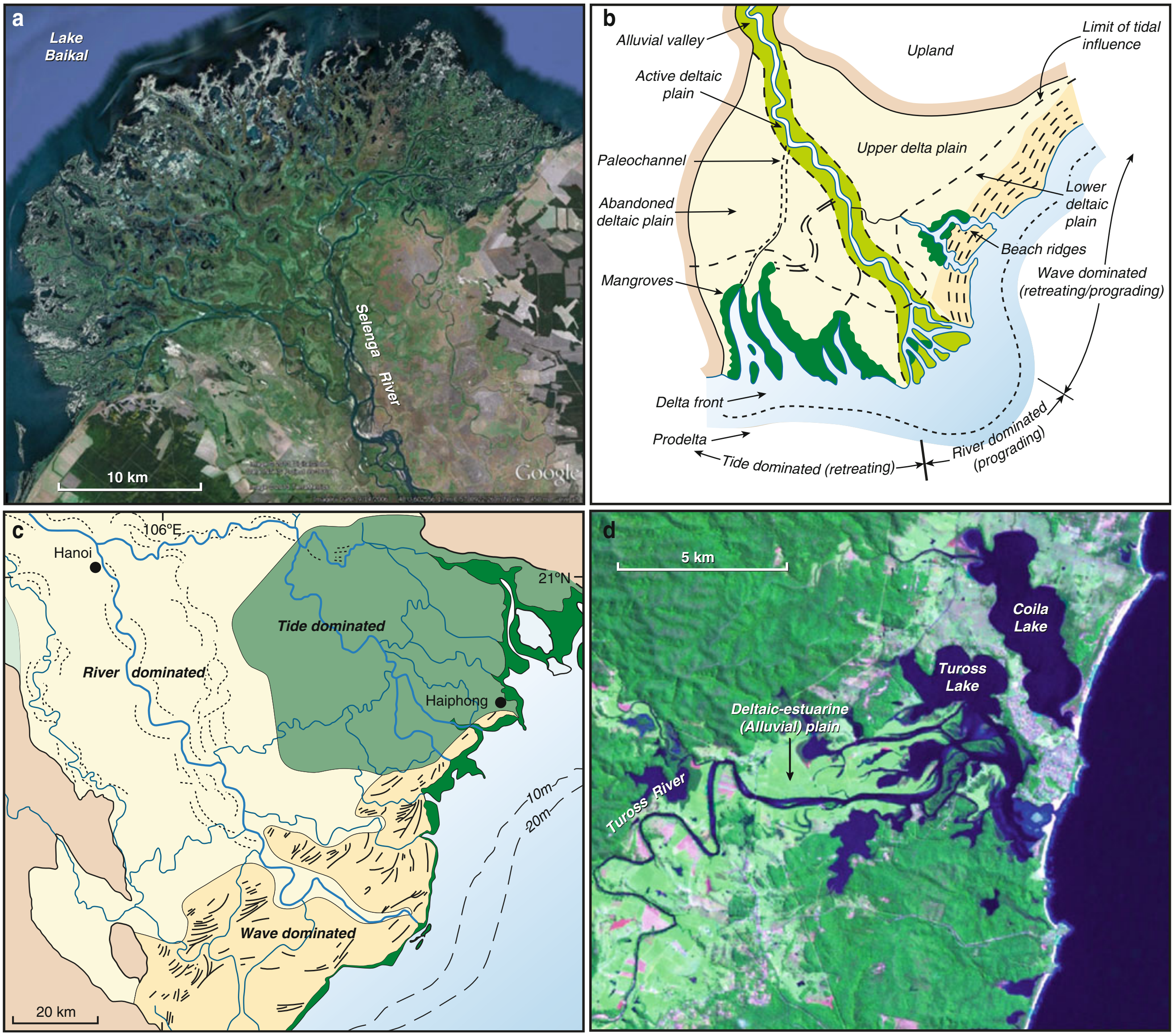

Delta Plain, Figure 1 (**a**) The Selenga River, draining into Lake Baikal, has bifurcated into numerous distributaries that dissect delta plain wetlands (Source Google Earth, © DigitalGlobe); (**b**) the principal components of a large delta plain, for example, (**c**) the Red River Delta plain (After Woodroffe and Saito, 2011); (**d**) the extensive plains flanking the Tuross River, as it drains into a barrier estuary in southeastern Australia, are much better developed than those where a smaller creek empties into Coila Lake, a coastal lagoon (Image: © Commonwealth of Australia, ACRES, Geoscience Australia).

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Cross-references

Deltas

DELTAS

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Definition

A delta is a discrete shoreline sedimentary protuberance formed where a river enters an ocean, a semi-enclosed sea, an estuary, a lake, or lagoon and supplies sediment more rapidly than it can be redistributed by basinal processes (modified after Elliott, 1986).

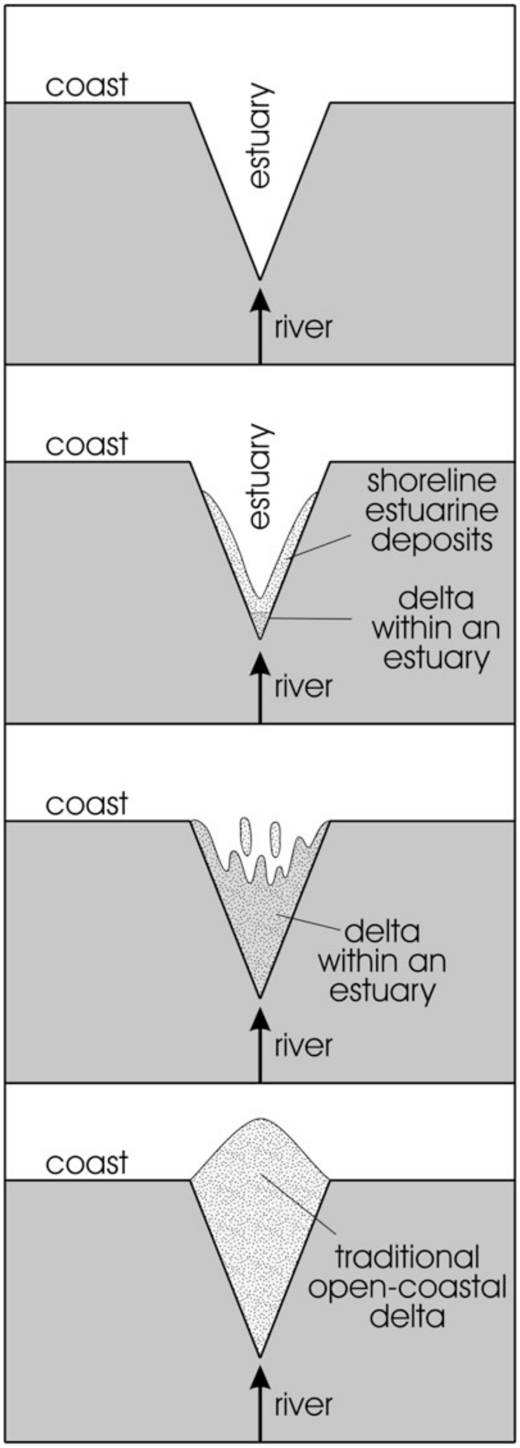
Deltas in an estuarine environment

A delta is often closely associated in time and space with an estuary (Figure 1), but frequently in the literature the two are not adequately separated, particularly for tide-dominated estuaries. For the same riverine outlet, a delta is a geomorphic and sedimentologic feature, while an estuary is a hydrochemical one where riverine freshwater flowing into a bay, a lagoon, or semi-enclosed coastal body of water mixes with seawater (Cameron and Pritchard, 1963; Pritchard, 1967; Day, 1981). Deltas may have either a perennial or a seasonal freshwater flow and hence a perennial or seasonal freshwater-to-seawater transition resulting in some parts of them being estuarine.

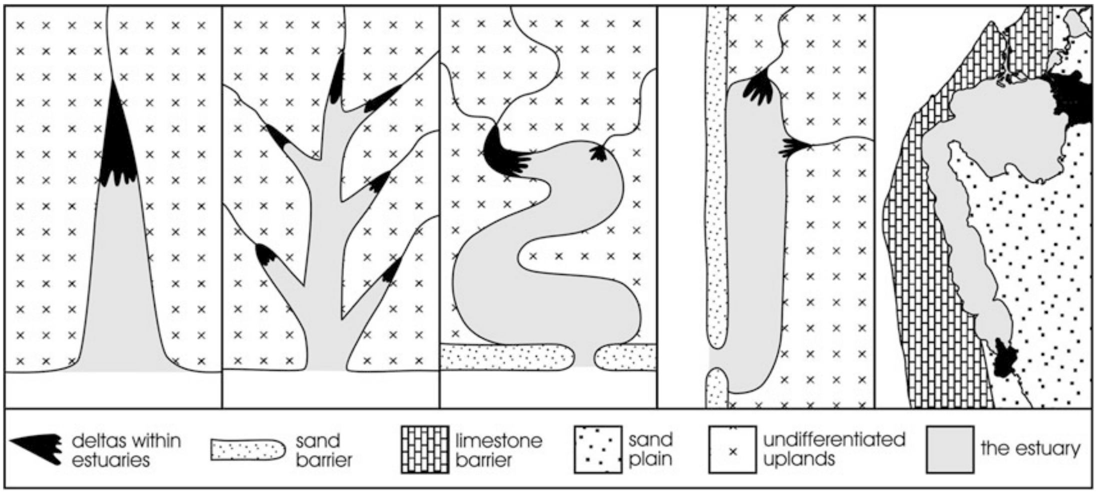
To a large extent, all deltas can be estuarine in the sense that some part of them will have a freshwater-to-seawater transition, and large estuarine environments whose basin has not been filled with sediment may contain small-scale deltas along their margins or in their headwaters (Figure 2). Geomorphologists and sedimentologists, focused on landforms and stratigraphy, generally do not deal with the hydrochemical estuarine components of deltas, and conversely, researchers of estuarine ecology, hydrochemistry, or hydrodynamics generally have focused on deltas in an estuary only in terms of geomorphology, sedimentology, or stratigraphy. This difference of emphasis becomes important here because the deltas described in this contribution are those occurring in the context of a larger estuarine setting: as such, a "delta within an estuary" is distinguished from an "estuary within a delta" (Figure 3). This contribution focuses on the "delta within an estuary."

Deltas within estuaries generally are relatively small sedimentary accumulations compared to the size of their estuarine setting (Figure 2). They have been variably termed as "bayhead deltas" (*cf.* van Heerden and Roberts, 1988; Dalrymple et al., 1992; Kindinger et al., 1994), "river deltas" (Hayes, 1975), and "intra-estuarine deltas" (Semeniuk et al., 2011). As not all of them are located in "bayheads," the term "intra-estuarine delta" is used here for those deltas occurring within estuaries.

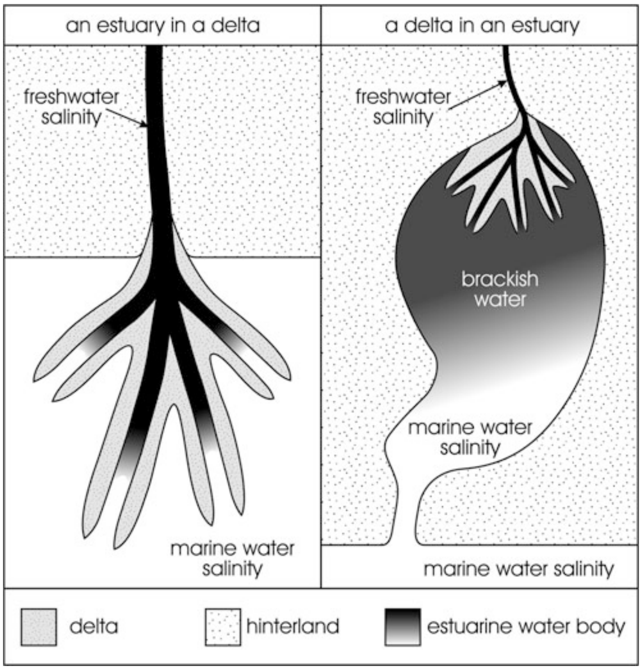
In contrast, deltas in open coastal settings generally are large sedimentary accumulations but are relevant to smaller deltas that occur within estuaries in that the principles involving hydrodynamics, geometry/morphology, mechanisms of construction, sedimentology and facies, and



Deltas, Figure 1 Idealized diagram showing the gradation from a relatively narrow v-shaped open estuary with minimal or no sedimentary fill to sediment-filling estuaries to a coastal delta where sedimentary accretion has prograded into the marine environment. Intra-estuarine deltas are present and more clearly evident in estuaries where sediments have not fully occluded them.



Deltas, Figure 2 Idealized diagram showing a range of estuary types, from an incised single valley to rias, a flooded valley on a coastal plain, a barred estuarine coastal lagoon and a compound estuary, and the occurrence of intra-estuarine deltas (*black*) therein.



Deltas, Figure 3 Idealized diagram showing the dual concepts of an estuary within a large delta and a delta within a large estuary (or an intra-estuarine delta). In each example, the field of salinity is freshwater = *black*, brackish water = *gray*, and marine water = *white*.

stratigraphy are similar. The Mississippi Delta complex, Nile Delta, Niger Delta, São Francisco Delta, Klang Delta, and Fly Delta are examples of large open coastal deltas (Allen, 1970; Coleman et al., 1970; Gould, 1970; Summerhayes et al., 1978; Dominguez, 1996; Baker et al., 2009). Such deltas have been classified as to their plan geometry in response to their hydrodynamic setting as fluvial-dominated deltas, tide-dominated deltas, and wave-dominated deltas (Galloway, 1975) or by their depositional architecture and facies (Postma, 1990). For completeness in the descriptions of deltas, the reader is referred to geomorphic and stratigraphic descriptions of such open coastal deltas in Scruton

(1960), Morgan (1970), Wright and Coleman (1973), Galloway (1975), Coleman (1976), Reineck and Singh (1980), Elliott (1986), Nemec (1990), Postma (1990), and Hori and Saito (2003).

Factors determining types of deltas in estuaries

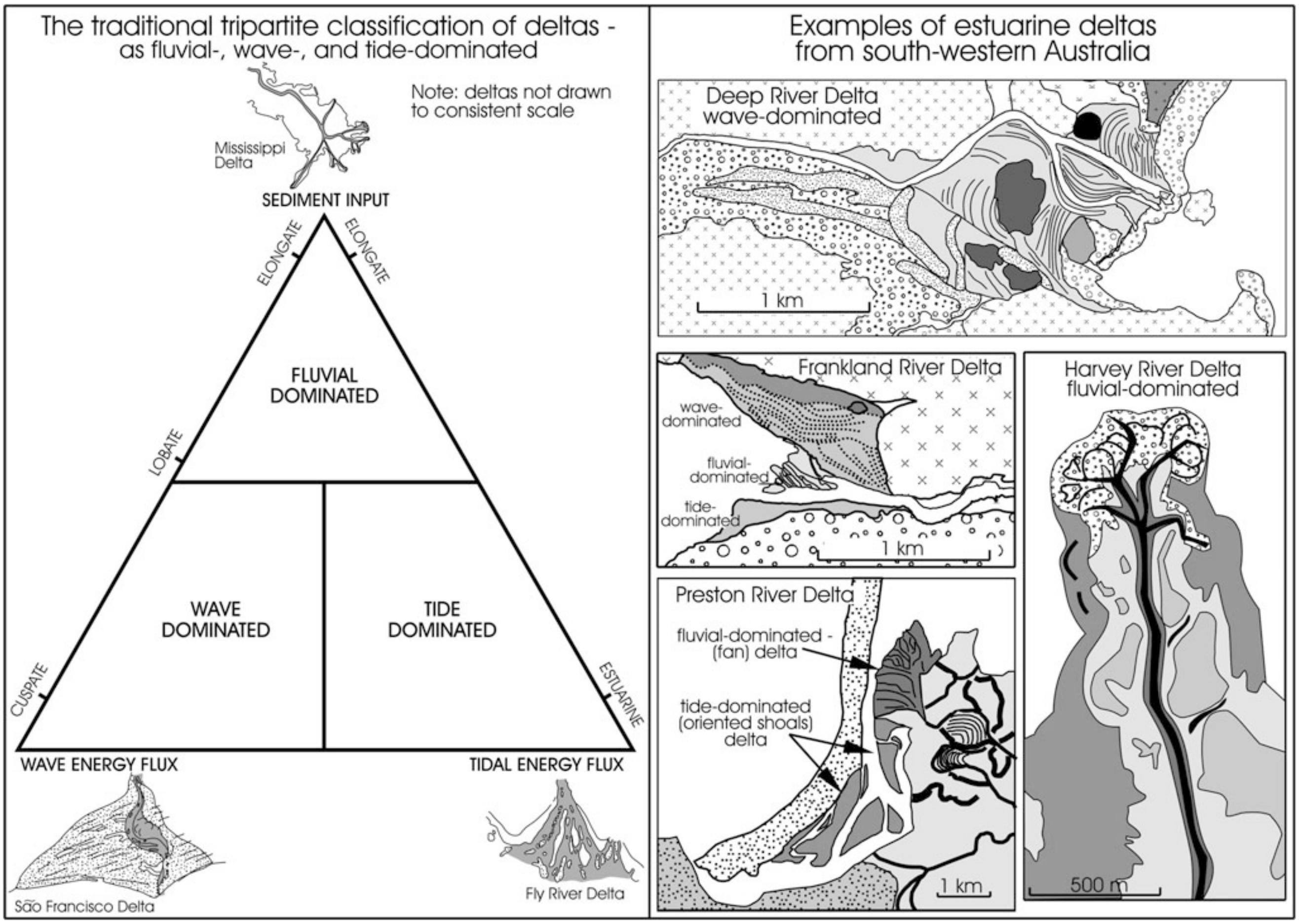
Depending on the size and shape of the estuary, a delta within an estuary can be variable in terms of plan geometry (morphology), landforms within the delta, sedimentary facies, and stratigraphy. The main factors determining the morphology and landforms of deltas in estuaries are (1) seasonality and strength of river flow, (2) the salinity of the receiving estuarine basin, (3) the magnitude of tides, (4) wind and wind waves, and (5) the shape of the estuary and where the river(s) is/are located. A number of these factors are interrelated and combine to produce a given delta type or delta form. For instance, the seasonality and strength of river flow can affect the salinity of the receiving basin in that strong perennial river flow will ensure that the receiving basin is perennially brackish, particularly where the tidal regime is microtidal. Similarly, the extent to which wind and wind waves can influence delta morphology and landforms can be dependent on the external shape of the estuary and the location of the river(s) in relation to the wind field and wave field.

The seasonality and strength of the river flow determines whether the delta will be fluvial dominated, tide dominated, or wave dominated. Perennial rivers, deriving from large drainage basins in humid climates, with strong river flow (and, commonly, concomitant strong sediment transport), produce fluvial-dominated conditions at the river outlet. In this setting, delta morphology, controlled by fluvial conditions, tends generally to be fan-shaped varying to elongate and digitate. With fluvial-dominated conditions, the salinity of the estuarine-receiving basin also can play an important part in determining the style and course of river flow into the estuary and hence the shape of any deltaic sedimentary accumulation. In this context, it should also be noted that the dynamics of sediment-laden river flow with its various amounts of traction load and/or suspension load entering and interacting with an estuarine-receiving water body of different density (ranging from fresh to brackish to marine) will result in different types of deltaic depositional morphology. Bates (1953), Wright (1978), and Orton and Reading (1993) describe this variability of depositional styles and resulting delta forms in relationship to three situations: (1) hypopycnal flows in which density of the suspended sediment flow is less than that of the receiving estuarine water body, (2) homopycnal flows in which density of the suspended sediment flow is equal to that of the receiving estuarine water body, and (3) hyperpycnal flows in which density of the suspended sediment flow is more than that of the receiving estuarine water body. Hypopycnal, homopycnal, or hyperpycnal flows also determine the nature of river mouth dynamics as to whether buoyant, inertial, or frictional factors are dominant in distributing and shaping the sediment plume and sand bars (Bates, 1953; Coleman, 1976; Wright, 1978) and the shape of any freshwater jet as it enters a more saline estuary (Wright, 1978).

Riverine freshwater flowing into an estuarine basin of denser brackish water or marine salinity will exhibit hypopycnal flow, with freshwater overlying the denser estuarine water. Riverine freshwater flowing into an estuarine basin of similar freshwater, or turbid freshwater flowing into brackish water, will exhibit homopycnal flow, with the river water invading the estuarine water of similar density in a turbulent mixing front. At the other extreme, sediment-laden turbid riverine freshwater flowing into an estuarine basin of freshwater or weakly brackish salinity will exhibit hyperpycnal flow, with the denser sediment-laden river flow (comprising sediment in suspension and transported in traction) forming a base flow under the less-dense estuarine water.

However, where riverine input is seasonal, or where the sediment-transporting river flow is inter-annual, tides and wind waves will predominate as the formative agents in delta type and in the development of its plan geometry. The flux of tides on a daily or semidiurnal basis can have a prevailing influence on determining delta shape, and river sediment delivered to the mouth of the river in a mesotidal or macrotidal estuary will be redistributed and sculptured by tidal currents and shaped into tidal-current-elongated shoals. In regions with strong winds, wind waves are generated on estuarine water bodies and impinge on delta fronts. Depending on fetch, and particularly if the river mouth is downwind in an estuary with a large fetch, deltaic sediments deposited at the river mouth will be subject to prevailing wind waves. As a result, wave-dominated deltas will develop.

The shape of the estuary and position of the river (s) within it play important roles in determining delta morphology. Relatively simple estuaries, that are v-shaped, narrow linear valley tracts with a single river mouth at the head of the estuary, are subject to interactions of river flow, tidal flux, and wind waves, and the delta developed at the estuary head will tend to be the form indicative of the locally dominant hydrodynamic condition. Complex estuaries and large estuaries with large fetch, on the other hand, can create conditions where there are complicated hydrodynamics of waves and wind-induced currents, and in situations where there is more than one river entering the estuary, each river may be subject to differing hydrodynamics. There will also be differences in the deltas where the rivers have dissimilar flow magnitudes. Within the one estuarine basin with multiple river inflows and multiple deltas, one delta may be fluvial dominated; others may be tide dominated or wave dominated. The deltas in these types of complex estuaries are even more variable if the various contributing rivers arise from different geological provenances in their respective hinterland and are delivering different suites of sediments.



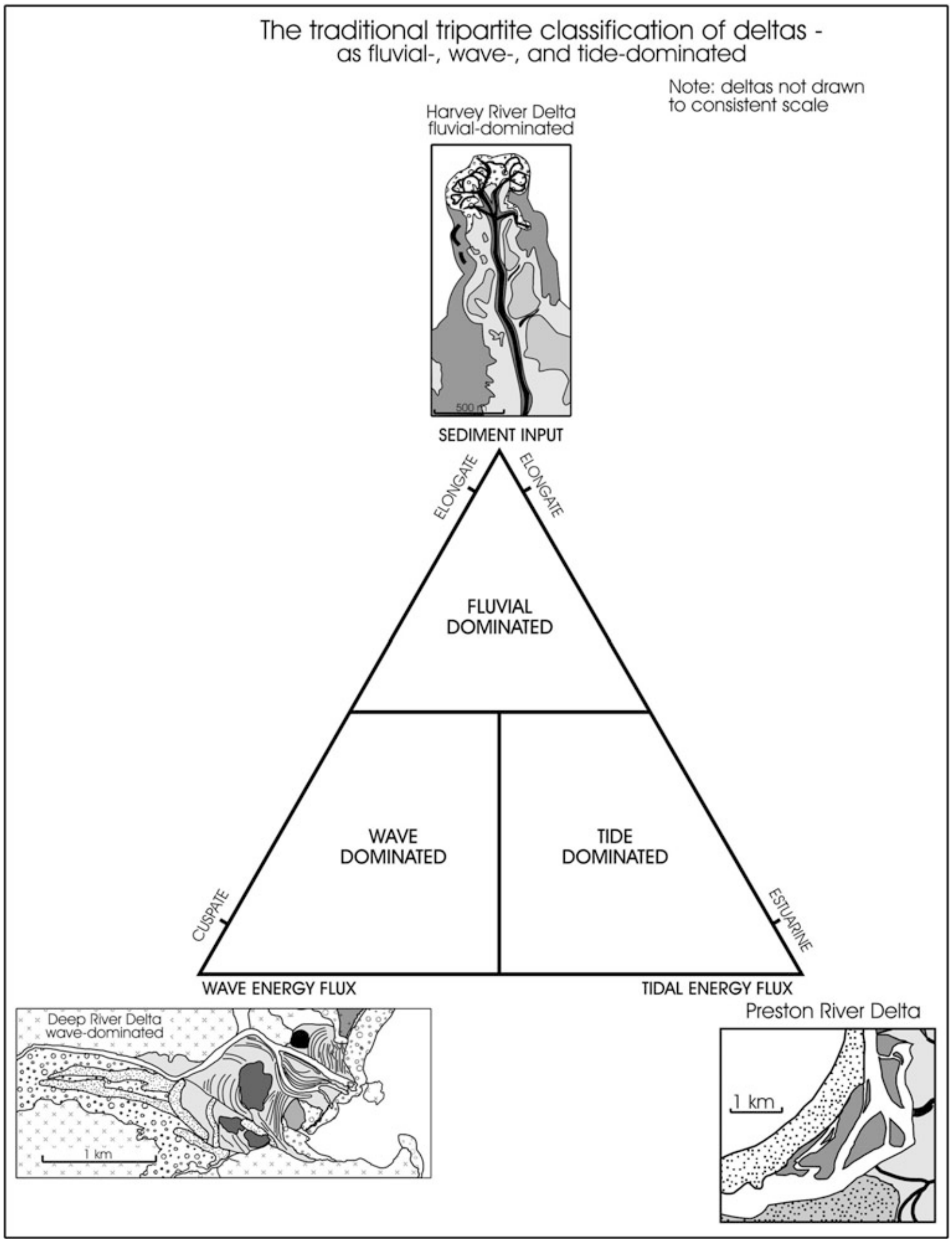
Deltas, Figure 4 The traditional tripartite classification of deltas (Modified from Galloway, 1975; Reineck and Singh, 1980) based on open marine deltas and showing the Mississippi Delta, the São Francisco Delta, and the Fly Delta as examples of fluvial-dominated, wave-dominated, and tide-dominated deltas, respectively. Examples also are shown of intra-estuarine deltas from southwestern Australia to illustrate fluvial-dominated forms (Harvey River Delta), wave-dominated forms (Deep River Delta), partly tide-dominated and fluvial-dominated forms (Preston River Delta) and a delta that shows longitudinal sectors that are fluvial dominated, wave dominated, and tide dominated (Frankland River Delta).

Types of deltas within estuaries

Given that a delta is a sedimentary deposit formed where a river enters an ocean, a semi-enclosed sea, an estuary, a lake or lagoon, the hydrodynamic forces operating on these sediments to distribute, rework, and shape them into various types of deltaic bodies are river flow (fluvial hydrodynamics), waves, and tides. If any of these hydrodynamic forces are dominant, the resulting delta will be fluvial dominated, wave dominated, or tide dominated (Figures 4 and 5). A classification of deltas based on their resultant morphology deriving from the style of hydrodynamic forcing was developed by Morgan (1970), Wright and Coleman (1973), Galloway (1975), and Coleman (1976). While the emphasis on delta classification in the literature has been on open coastal deltas, the classification can equally be applied to deltas wholly contained or confined in semi-enclosed water bodies, estuaries, lakes, and lagoons.

Deltas can be subdivided into various geomorphic/sedimentologic units related to location within the delta. These geomorphic/sedimentologic units can vary in size from delta to delta, and not all may be present in every delta. From the river hinterland to the deeper water into which the delta progrades, the units are (Coleman and Wright, 1975; Hart, 1996) alluvial feeder, upper delta plain, lower delta plain, delta front, delta slope, and prodelta. The mechanics of delta formation in different hydrodynamic situations are well summarized by Hart (1996).

Where fluvial processes dominate over the two other hydrodynamic forces, the resulting delta is termed a “fluvial-dominated delta.” Its morphology is determined by river flow transporting sediment loads in traction and suspension, and, depending on the salinity of the receiving estuarine water body and the nature of influx (whether hypopycnal, homopycnal, or



Deltas, Figure 5 The traditional tripartite classification of deltas of Figure 4 with some intra-estuarine deltas from southwestern Australia on the ternary diagram.

hyperpycnal), the delta can be lobate, fan-shaped, elongate, or digitate. The delta progrades into the estuary by subaqueous deposition of a fan of sand or bar-finger sand, shoaling to high-tidal levels and river flood levels. The fans of sand or bar-finger sands are capped by tidal deposits, levee deposits, and floodplain deposits, while interdistributary bays are filled with tidal flat deposits shoaling to floodplain deposits. The overall delta form consists of (1) a subaerial part whose plan shape is lobate, fan-shaped, elongate, or digitate and whose geomorphic/sedimentologic components include levee banks, floodplains, high-tidal to supratidal flats, lagoons, and abandoned channels; (2) a delta slope comprised of sheets, fans or bar-fingers of sand or muddy sand, and laterally intervening bays underlain by sand or mud; and (3) a prodelta usually underlain by mud that forms a peripheral apron around the delta slope.

Where wave action is dominant because the delta resides in an estuary with a strong component of wind and wind-generated waves, regardless of the mechanism that delivers sediment to the front of the river mouth (*viz.*, hypopycnal, homopycnal, or hyperpycnal), the sediment deposited at the river mouth is subsequently reworked shoreward into a series of beach ridges, or recurved spits, or bars and their leeward lagoons, all built by waves and wind to levels of the high tide and above. Progradation of the delta thus is by beach ridge accretion, recurved spit accretion, or as a series of bars and lagoons. The delta usually is a lobate complex of prograded beach ridges, a series of beach ridges and/or recurved spits with intervening swales and/or linear lagoons, or a prograded series of bars and linear, oval to circular lagoons. The beach ridges, recurved spits, and bars are underlain by sand and are often accreted to above the level of high tide. The swales and linear, oval to circular lagoons, depending on the style of sedimentary filling, are underlain by sand, muddy sand, mud, or peat. River floods, unable to reach the height of beach ridges, are confined to the distributary channels or flood into the beach ridge swales.

Where tides are the dominant hydrodynamic force, again, regardless of the mechanism that delivers sediment to the front of the river mouth, the sediment is subsequently reworked by tidal currents into tidal-current-aligned (usually shore-normal) subaqueous sand shoals that accrete vertically to levels of the high tide. Progradation of the delta thus is by tidal shoal vertical accretion to a level where the deposits are finally capped by floodplain sediments. The delta front (or delta slope) usually is a crenulate to palmate complex of prograded subaqueous to tidal shoals, and the landward part of the delta is a floodplain.

Locally in estuaries, where river gradients are relatively steep, there may be development of Gilbert-type deltas. These are a specific type of fluvial-dominated delta, usually fan-shaped and coarse-grained, with internal geometry of simple large cross-stratification corresponding to the delta morphology of topset, foreset, and bottomset (Postma, 1990).

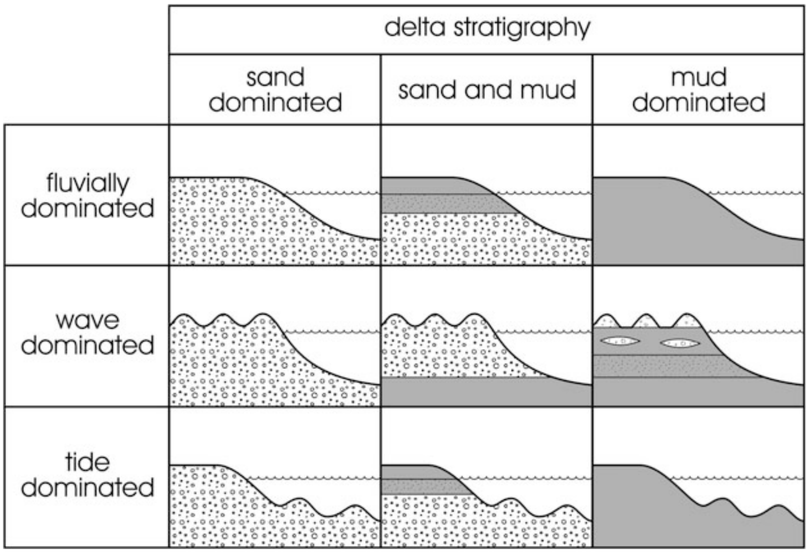
While deltas can be classified as fluvial dominated, tide dominated, or wave dominated depending on their hydrodynamic setting, often in estuaries, because of the complexity of the hydrodynamics, an intra-estuarine delta may exhibit different morphology in different parts of the delta or contrasting landforms reflective of hydrodynamic conditions in a specific part of that delta. For instance, the wave-dominated intra-estuarine delta of the Deep River in southern Western Australia (the Walpole-Nornalup Inlet Estuary; Semeniuk et al., 2011) comprises two distinct geomorphic responses reflecting different degrees of wave action and sediment transport/mobility. There are prograded beach ridges on one half of the delta and a prograded bar-and-lagoon complex on the more sheltered other half. In the same estuary, another intra-estuarine delta (the Frankland River) also reflects the variable hydrodynamic forces across the delta depositional environment. It comprises a wave-dominated part in its northern third (prograded beach ridges and inter-ridge swales), a fluvial-dominated part in its central third (prograded and shoaled digitate/palmate sedimentary accumulation), and a tide-dominated part in its southern third (prograded sand platform). Within an intra-estuarine delta in another estuary in southwestern Australia (the Leschenault Inlet Estuary; Semeniuk, 2000), one side of a fluvial-dominated palmate delta faces a 12 km fetch, and during intermittent winter storms deriving from the north-west, waves break on the shore to create a repetition of storm-wave-generated cheniers across the floodplain.

In hydrodynamically and geomorphically complex estuaries with multiple river entries, there may be a range of intra-estuarine types within the same estuary. For instance, the Peel-Harvey Estuary of southwestern Australia, with three river entries (Semeniuk and Semeniuk, 1990a; Semeniuk and Semeniuk, 1990b), has two wave-dominated deltas (composed of prograded bar-and-lagoon complexes) because they face the prevailing regional summer breezes that generate wind waves on the estuarine water body and one fluvial-dominated delta (composed of prograded fans of sand, levee deposits, and floodplain deposits) that is not subject to these wind waves. The Leschenault Inlet Estuary, with two river entries (Semeniuk, 2000), has one fluvial-dominated delta (a palmate delta) and another delta that is, in part, tide dominated (composed of tidally-aligned shoals) and, in part, fluvial dominated. The Walpole-Nornalup Inlet Estuary of southern Australia, with three river entries (Semeniuk et al., 2011), has two wave-dominated estuaries (composed of prograded bar-and-lagoon complexes, or of beach ridges) because they face the prevailing regional summer breezes that generate wind waves on the estuarine water body and one hydrodynamically complex delta that is one third wave dominated (facing the wind waves generated by sea breezes), one third fluvial dominated, and one third tide dominated (the latter two not subject to wind waves).

Factors determining the stratigraphy of deltas in estuaries

Deltas within estuaries exhibit a variety of stratigraphic sequences, depending on the sediments available, and their hydrodynamic setting. However, given that estuaries as enclosed to semi-enclosed coastal bodies of water where multiple interactions between marine and riverine environments may take place, there are other factors that result in a richness and variety of stratigraphy in intra-estuarine deltas. These differences not only occur between deltas from different estuaries but even between deltas within the same estuary. The main factors determining the stratigraphy within a delta are (1) the provenance of the contributing rivers and types of sediment entering the estuary, (2) seasonality and strength of river flow, (3) nature of tides, (4) contribution of wind and wind waves, and (5) climate.

The provenance of the contributing rivers entering the estuary, that is, the geology of the drainage basins,



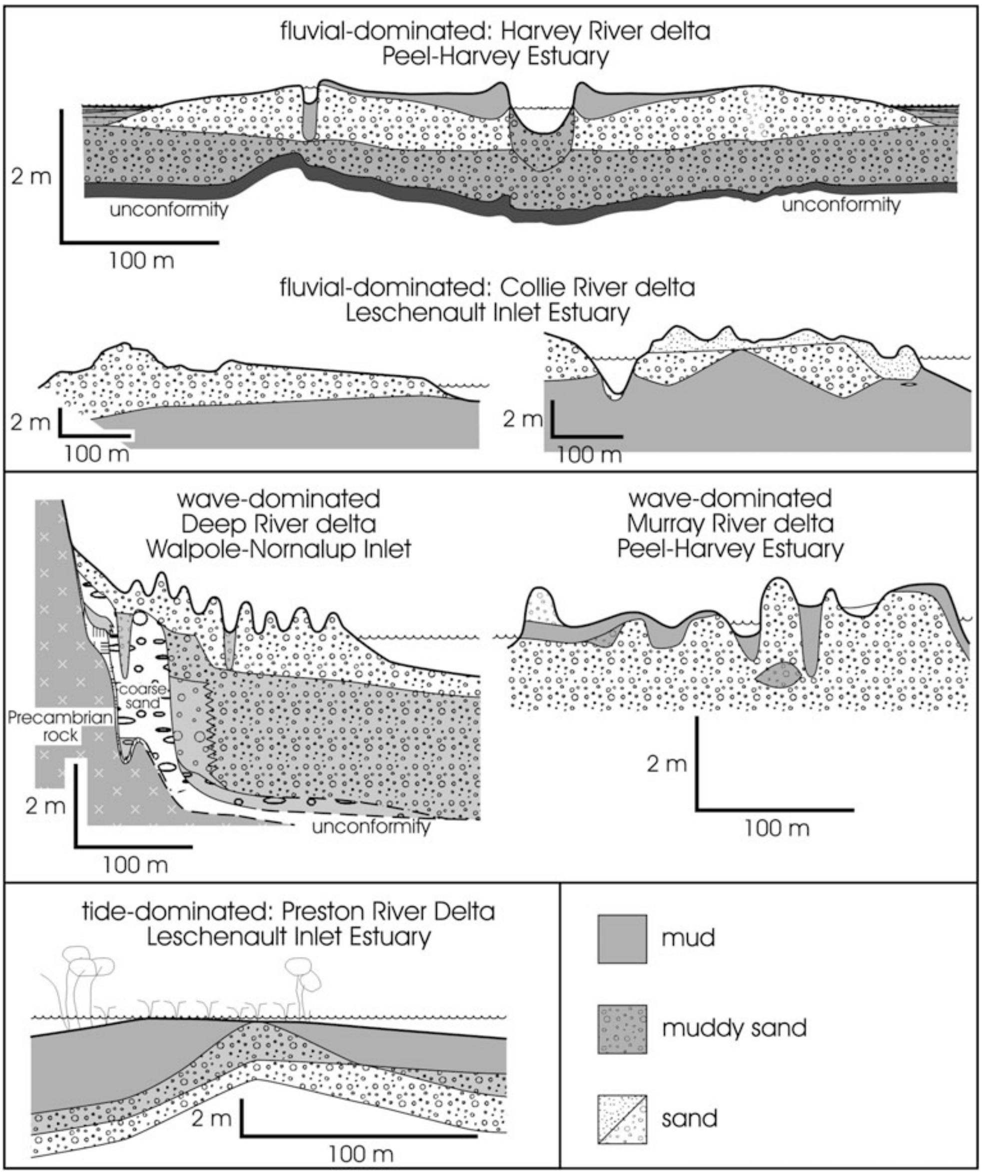
Deltas, Figure 6 Simplified and idealized stratigraphy of deltas formed in sand-dominated, mixed sand-and-mud, and mud-dominated settings under hydrodynamics conditions of fluvial dominated, wave dominated, or tide dominated. The lithologies are simplified to sand, muddy sand, and mud.

determines the supply and composition of sediment delivery. Whether the delta is sand, mixed sand and mud, or mud-dominated, how much gravel is present and the type of shoaling stratigraphy that is developed are factors dependent not only on provenance but also on the hydrodynamic factors at the interface of river and estuary. The effects of seasonality and strength of river flow, the magnitude of the tides, and the influence of wind in generating wind waves and circulation currents on intra-estuarine deltaic stratigraphy are expressed in the dominant grain size which results in, by the way in which the gravel, sand, and mud are separated into different deltaic environments, the distance the gravel, sand, and mud are transported from the river mouth, the types of sedimentological mechanisms that occur, and the range of sedimentary structures that are generated. Differences can result in upward shoaling, sediment interlayering, the development of environment-specific sedimentary structures, and the micro-stratigraphic and macro-stratigraphic sequences.

Climate plays a part in the development of deltaic stratigraphic sequences in that rainfall and evaporation can determine the nature of the high-tidal and supratidal lithologies (whether they are vegetated and replete with plant root bioturbation or are mud-cracked and have generated mud chips or contain evaporite minerals) and if organic matter-enriched sediment and/or peat forms the upper part of the stratigraphy. Climate also determines the nature of biota that colonize deltaic environments. The composition of these biota varies according to biogeographic setting, the occurrence of the biota relative to supratidal, tidal zones, and the subtidal and substrate type. The biota influence sedimentation and generation of lithotypes through shell and test production, root-structuring by trees, sedges, rushes and other salt marsh plants, bioturbation by plants and animals, and production of organic matter. Shell material contributes to the gravel and sand fraction in sediments and, through winnowing during wave action and storms, may be concentrated into sheets, lenses, and cheniers in mud-dominated sediments. The range of biota that directly contributes material to the lithotype or alter sedimentary structures by bioturbation and root-structuring include mangroves in tidal tropical environments, rushes, sedges, samphire, and other salt marsh plants in tidal tropical and subtropical environments, various crustacean-polychaete-mollusc assemblages in tidal tropical and subtropical environments, and wetland forests, sedges, and grasses in subaerial deltaic environments. Biota in intra-estuarine deltas are also described in Semeniuk and Semeniuk (this volume) in their description of Estuarine Deltaic Wetlands.

The stratigraphy of deltas within estuaries

Depending on whether deltaic sediments are dominated by sand, mud, mixtures of these sediment types, or gravel and whether the delta is fluvial dominated, wave dominated, or tide dominated, intra-estuarine deltas can exhibit a wide variety of stratigraphic types. Descriptions of the stratigraphy of intra-estuarine deltas are provided in Corner et al. (1990), Semeniuk and Semeniuk (1990a), Semeniuk and Semeniuk (1990b), Dalrymple et al. (1992), Allen and Posamentier (1993), Semeniuk (2000), and Semeniuk et al. (2011). A range of stratigraphic types in various hydrodynamic settings and with various contributions of sediment types is listed below and illustrated in Figures 6 and 7.



Deltas, Figure 7 Some case examples of the gross stratigraphy of fluvial-dominated, wave-dominated, or tide-dominated intra-estuarine deltas from southwestern Australia showing array of generalized lithology in terms of sand, muddy sand, and mud (Semeniuk and Semeniuk, 1990a; Semeniuk and Semeniuk, 1990b; Semeniuk, 2000; and Semeniuk et al., 2011).

Figure 6 shows a simplified and idealized gross-shoaled stratigraphy of deltas formed in sand-dominated, mixed sand-and-mud, and mud-dominated settings under hydrodynamics conditions of fluvial dominated, wave dominated, or tide dominated. The complications in stratigraphy due to lateral deltaic morphologic variation are not shown here. The sand-dominated deltas need not be exclusively sandy but may have a minor component of mud, and similarly, mud-dominated deltas need not be exclusively muddy but may have a minor component of sand. Sand in mud-dominated deltas can be exogenic (riverine sources) or endogenic (generated biogenically).

Microstratigraphic details of the various facies and subfacies of deltas in these different hydrodynamic environments can be found in Dalrymple et al. (1992), Allen and Posamentier (1993), and Semeniuk (this volume on "Stratigraphy of Estuaries").

The sand-dominated delta developed under fluvial-dominated conditions is a wedge of sand prograded into the estuary. The sand-dominated delta developed under wave-dominated conditions is a wedge of sand comprising sediments of the beach-to-beach ridges, stacked and prograded into the estuary. The sand-dominated delta developed under tide-dominated conditions is a sequence of tide-aligned low-tidal to mid-tidal sand shoals, bars, and lenses that have shoaled to the level of high tide and that have been covered by floodplain sand deposits.

The sand-and-mud-dominated delta developed under fluvial-dominated conditions is a wedge of sand overlain by muddy sand and in turn overlain by mud prograded into the estuary. The sand-and-mud-dominated delta developed under wave-dominated conditions is a sheet of mud and muddy sand deposited at levels below the prevailing wave base and capping by a wedge of sand of beach-to-beach ridges, stacked and prograded into the estuary. The sand-and-mud-dominated delta developed under tide-dominated conditions is a sequence of low-tidal to mid-tidal, tide-aligned sand shoals, bars, and lenses that have shoaled to the level of high tide progressing through lithologies of muddy sand and mud and finally capped by floodplain mud deposits.

The mud-dominated delta developed under fluvial-dominated conditions is a wedge of mud prograded into the estuary. The mud-dominated delta developed under (moderate) wave-dominated conditions (*i.e.*, prevailing waves hydrodynamically dominate over tides and river flow) is generally a wedge of mud prograded into the estuary, but with the wave action and intermittent storms, there is local concentration of exogenic sand and biogenic sand and gravel through winnowing. These coarser sediments find expression in sheets of muddy sand, lenses of sand, and in cheniers. Mud accumulates below the prevailing wave base. The mud-dominated delta developed under tide-dominated conditions is a sequence of low-tidal to mid-tidal tide-aligned mud shoals that have shoaled to the level of high tide to form mud sheets that have been covered subsequently by floodplain mud deposits.

Case studies of the gross stratigraphy of fluvial-dominated, wave-dominated, or tide-dominated intra-estuarine deltas from southwestern Australia demonstrating generalized lithology in terms of sand, muddy sand, and mud are illustrated in Figure 7. The fluvial-dominated Harvey River delta shows a finger of sand (the prograded fans of sand at the delta front) overlying prodelta muddy sand and levee deposits of mud. The fluvial-dominated Collie River delta shows a sheet of riverine sand overlying prodelta mud and a capping of finer sand that has developed by construction of cheniers. The wave-dominated Deep River delta shows a stratigraphy of delta front and prodelta subtidal muddy sand overlain by the sand of beaches and beach ridges, with muddy sand filling inter-beach ridge swales. The wave-dominated Murray River delta shows a stratigraphy of delta front and prodelta subtidal sand overlain by sand of beaches and beach ridges and bars, with muddy sand filling inter-beach ridge swales and lagoons in a prograded bar-and-lagoon sequence. The tide-dominated Preston River delta shows a stratigraphy of subtidal sand that has shoaled through muddy sand with a capping of low-tidal to high-tidal mud.

Discussion and conclusions

Intra-estuarine deltas (also termed "bayhead" deltas) are the fluvial deposits that accumulate where one or more rivers enter an estuary. As with deltas formed in open marine coastal environments, these deltas can be classified as to morphology based on the response of the riverine sedimentary deposits to hydrodynamic setting. As such, deltas developed by fluvial-dominated, wave-dominated, or tide-dominated conditions can be identified. However, unlike the open marine coastal environment where the hydrodynamic conditions are regionally more uniform, deltas in estuaries experience a diversity of hydrodynamic conditions in the one deltaic setting and across the estuary. This is particularly the case where the estuary is large and complex in shape and where there is a strong component of wind that directs surface currents and wind waves. The main factors determining the morphology and landforms of deltas within estuaries are (1) the seasonality and strength of river flow which determines hydrodynamic conditions and the supply of sediment; (2) the salinity of the estuarine-receiving basin which determines the style of interchange of the river water with estuarine water (hypopycnal flow *versus* homopycnal flow *versus* hyperpycnal flow), the style of sediment delivery into the estuary, and, to some extent, the shape of the delta; (3) the magnitude of tides and wind waves which, in concert with the magnitude of river flow, will determine whether the hydrodynamic conditions will be dominated by fluvial, wave, or tidal processes; (4) the shape of the estuary; and (5) where the river(s) is/are located. Relatively simple estuaries, *e.g.*, narrow linear valley tracts with a single river mouth, are subject to interactions of river flow, tidal flux, and wind waves, with the delta morphology reflecting the locally dominant hydrodynamic condition. Complex estuaries and estuaries with large fetch create conditions where complicated hydrodynamics of waves and wind-induced currents interact with the shores of the estuaries and act on the deposits of the river or rivers entering the estuary, each river potentially being subject to differing hydrodynamics.

The morphology and landforms of intra-estuarine deltas respond to fluvial, wave, and tidal conditions. Fluvial-dominated deltas can be lobate, fan-shaped, elongate, or digitate. Wave-dominated deltas can be a lobate complex of prograded beach ridges, a series of beach ridges and/or recurved spits with intervening swales and/or linear lagoons, or a prograded series of bars and linear, oval to circular lagoons. The delta front of tide-dominated deltas usually is a crenulate to palmate complex of prograded subaqueous to tidal shoals, and the landward part of the delta is a floodplain. Complexity of local hydrodynamics may result in an intra-estuarine delta with different morphologies in different parts of the delta or contrasting landforms reflective of hydrodynamic conditions in a specific part of that delta.

Stratigraphy of intra-estuarine deltas is variable from delta to delta within the one estuary and variable between deltas in different estuaries because of the sediment types available and the hydrodynamic setting of the delta. The richness and variety of stratigraphic types in intra-estuarine deltas are due to (1) the provenance of the contributing rivers and types of sediment entering the estuary, (2) seasonality and strength of river flow, (3) tides, (4) wind and wind waves, and (5) climate. Climate plays a part in the development of delta stratigraphy in that rainfall and evaporation determine the nature of the high-tidal and supratidal lithologies and can determine if organic matter-enriched sediment and/or peat forms the upper part of the stratigraphy. Climate also determines the nature of biota that contributes shelly material as gravel and sand.

Depending on whether deltaic sediments are dominated by sand, or mud, or mixtures of sand and mud, or contain gravel, and whether the delta is fluvial dominated, wave dominated, or tide dominated, intra-estuarine deltas exhibit a variety of stratigraphic types. Sand-dominated deltas in fluvial-dominated conditions comprise a wedge of sand, while under wave-dominated conditions comprise a wedge of sand of beach-to-beach ridges stacked and prograded into the estuary, and those formed under tide-dominated conditions show a sequence of tide-aligned sand shoals, bars, and lenses aggraded to the level of high tide and that have been covered by floodplain sand deposits. The sand-and-mud-dominated deltas in fluvial-dominated settings comprise a wedge of sand overlain by muddy sand and in turn overlain by mud, while in wave-dominated settings are a sheet of mud and muddy sand deposited below the prevailing wave base with a capping of sand of beach-to-beach ridges stacked and prograded into the estuary. Those developed in tide-dominated settings show a sequence of tide-aligned sand shoals, bars, and lenses shoaled to the level of high tide through lithologies of muddy sand and mud and covered by floodplain mud deposits. Mud-dominated deltas in fluvial-dominated conditions are a wedge of mud prograded into the estuary, while those developed in wave-dominated settings comprise a wedge of mud but with local sand and gravel in sheets of muddy sand, lenses of sand, and cheniers with mud accumulating below the prevailing wave base. Mud-dominated deltas in tide-dominated settings comprise a sequence of tide-aligned mud shoals that aggrade to the level of high tide as mud sheets and are covered by floodplain mud.

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Cross-references

Delta Plain
Estuarine Deltaic Wetlands
Estuarine Geomorphology
Sediment Erosion
Shoreline Changes
Species Zonation
Stratigraphy of Estuaries
Tidal Hydrodynamics

DENSITY STRATIFICATION

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Definition

Density stratification can be defined as the vertical distribution of water masses into separate, distinct horizontal layers as a result of differences in density. These differences can also be attributed to differences throughout the water layers in dissolved solids, temperature, or suspended solids.

Description

The *density stratification* is extremely sharp, so that pure freshwater and pure saltwater are vertically adjacent. Such conditions can increase as density increases with depth and then the greater the vertical gradient will be, resulting in higher stability of the stratification.

Variations in the distribution of ocean density control the large-scale movements of water masses, and are important features in the dynamics of ocean surface currents, and drive the circulation of estuaries (Kjerfve, 1979). The less dense freshwater has a tendency to remain primarily in the surface layers. In estuaries where the tidal range is small, the tidal energy is limited during neap tides, and the water column becomes stratified vertically because of denser bottom water and a less dense surface layer.

In the North Atlantic Gyre, there are four distinct water masses that resulted from *density stratification*, creating interconnected currents with different flow characteristics and temperature: North Equatorial Current (NEC), North Atlantic Current (NAC), Gulf Stream (GS), and Canary Current (CC) (Talley et al., 2011).

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Cross-references

Estuarine Circulation
Residual Circulation
River-Dominated Estuary
Tidal Hydrodynamics

DETERMINING GEOHERITAGE VALUES

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Definitions

Geoheritage. The heritage value assigned to features of a geological nature encompasses globally, nationally, statewide to regionally, and locally significant features of earth science that are intrinsically important or culturally important, offering information or insights into the evolution of the earth or into the history of earth science, or that can be used for research, teaching, or reference (Brocx, 2008). It encompasses the variety of rocks types, stratigraphy, structural geology, geomorphology, and hydrology and covers a large variety of processes and products across a wide range of scales, from global tectonics, mountain building, landscape evolution to local surface processes and products such as weathering, erosion and sedimentation, cliff faces, fossils sites and mineral localities, and, at the microscale, diagenesis and deformation.

Geoconservation. This term refers to an action that works toward the preservation of sites of geoheritage significance for heritage, science, or education purposes. It can encompass all important geological features from the regional scale to the individual crystal, involving specific sites (special sites), or ensembles of geological sites. A "specific site" is where a significant geological feature occurs in isolation or may have historical or cultural significance; these have been formally identified in the British Isles as (geological) site(s) of special scientific interest (SSSI) or regionally important geological/geomorphologic sites (RIGS) (Ellis et al., 1996).

Geodiversity. Geodiversity is the natural variety of geological, geomorphological, pedological, and hydrological features of a given area and geological processes forming them (Brocx and Semeniuk, 2007). Use of the term, which etymologically means "the diversity of geological features," should be applied only in a region-specific or site-specific sense, i.e., not as a synonym for geology.

Geosite. This is a term used to denote small sites of geoheritage significance used for education, science, geotours, and reference.

Geopark. Geopark is used to denote large sites of geoheritage significance, usually an ensemble of geosites used for education, science, geotours, and reference.

Introduction

Estuaries stand as a distinct environment along the coast in that they bridge the aquatic hydrochemical environmental gap between freshwater and seawater. They can bring another aspect in addition to this hydrochemical setting because the landscape and geomorphic/sedimentologic setting of an estuary provide variability to the "mixing bowl" where freshwater and seawater interact. The emphasis on the landscape and geomorphic/sedimentologic settings of estuaries has resulted in their being classified according to a geomorphic framework or according to their origin (Fairbridge, 1980; Nichols and Biggs, 1985; Perillo, 1995). In this context, with their geologic, geomorphic, and sedimentologic characteristics and variability, they fall into the realm of geodiversity and geoheritage. As such, estuaries, in addition to the complexities and variability of styles of hydrochemical mixing, which is their first tier criterion of identification, provide a rich assortment of geologic, geomorphic, sedimentologic, mineralogic, and biogenic attributes such as shell deposits and bioturbation structures, not only in regard to the features within the estuaries themselves but also in the geology, geomorphology, and hydrology of the immediately surrounding landscape that frames or that has built them. Consequently, they hold potential to contain features and sites of geological significance or geoheritage value and lend themselves to qualifying as sites of geoheritage significance. This is especially the case in that estuaries, as sedimentary repositories, reside in various types of geologic and geomorphic settings, from rias to coastal plains to structural controlled (Fairbridge, 1980; Perillo, 1995), which results in a variety of geomorphic and sedimentologic estuarine types, and occur in a wide range of climates from tropical to temperate and from humid to arid, which also results in a variety of geologic/geomorphic, sedimentologic, and geochemical/mineralogic expressions. A large diversity (or geodiversity) of estuary types can be expected therefore from the perspective of the earth sciences.

Before a description is provided of the procedure to determine geoheritage values, the terms "geoheritage," "geoconservation," "geodiversity," "geosite," and "geoparks" are defined. They are associated with the concept of geoheritage, the enactment of geoconservation, and the inscription of geosites/geoparks.

Identifying and assessing sites of geoheritage value using the geoheritage tool kit

Identifying estuaries in different geological regions and the geoheritage essentials (i.e., the geological features that characterize an area) of these estuaries provides the first step in identifying sites for geoheritage. Clearly not all aspects of estuaries on earth are present in the one region, and not all aspects of an estuary in a region may be of geoheritage significance – the former recognizes the uniqueness, rarity, or representativeness of some estuarine features, and the latter requires some measure of assessment of significance. There are a number of ways that sites of geoheritage significance may be identified, and the British and European literature provides a history of how this has been achieved, with the final outcome being an inventory-based approach (Doyle et al., 1994; Wimbledon et al., 1995; Wimbledon, 1996; ProGEO, 2002; for discussion see Brocx, 2008).

The British and European approach to compiling an inventory of features of significance in the realm of geology has been successful in that numerous and varied aspects of geology have been identified and secured, but the approach has been thematic within a context of known geology and nationally specific geology. This is largely because the geology of European countries is reasonably well known, and these countries are relatively small (compared to, say, Australia, an island continent with a surface are of ~7.7 million km^2, and Africa with a surface area of ~30 million km^2). Australia has its own geological history with a vast array of geological features, from Archaean terranes to Proterozoic rock systems to Phanerozoic stratigraphy, lithology, paleontology, mineralization, etc., representing a wide diversity of processes and products developed under igneous, sedimentary, metamorphic, pedogenic, metallogenic, hydrologic, and diagenetic conditions. As such, Australia's estuaries also present exceptional geodiversity, reflecting the range of their geologic, oceanographic, and climatic settings. Therefore, to provide the framework for a category-based inventory of sites of geoheritage significance, Brocx and Semeniuk (2009, 2011) developed the geoheritage tool kit, to systematically identify and categorize sites of geoheritage significance. This method has been adapted to determine the geoheritage values of estuaries. The geoheritage tool kit uses six steps to identify geological features across various geological regions and at various scales, assign geological sites to various categories of geoheritage, and assess their levels of significance, and case studies are used here to illustrate the diversity of Australia's estuaries (Figure 1; Brocx and Semeniuk, 2009).

Step 1 identifies geological regions, providing a natural boundary to the estuary being investigated in terms of geological and geoheritage features, and an indication of the types of geological features that may be expected. It also ensures that comparisons in assessing significance are undertaken wholly within similar regions. Figure 2, for instance, shows the main regions of estuaries in Australia.

Step 2 identifies the geological essentials of a region and requires listing those geological features that *characterize* or are *peculiar* to a given natural region. For an estuary, it involves listing aspects such as the geological setting, estuary type, effects of climate, oceanography, and tidal range and interior features (such as flood-tidal deltas, shoals, tidal flats, deltas, basin type) and small-scale features (such as mineral precipitations, bioturbation types, and unusual or distinct sedimentary structures). The geological essentials of a region can be identified by drawing on the literature, interviewing scientists and, after identifying gaps in information, systematically obtaining further information from fieldwork. The list is termed the "geoheritage essentials" of an area.

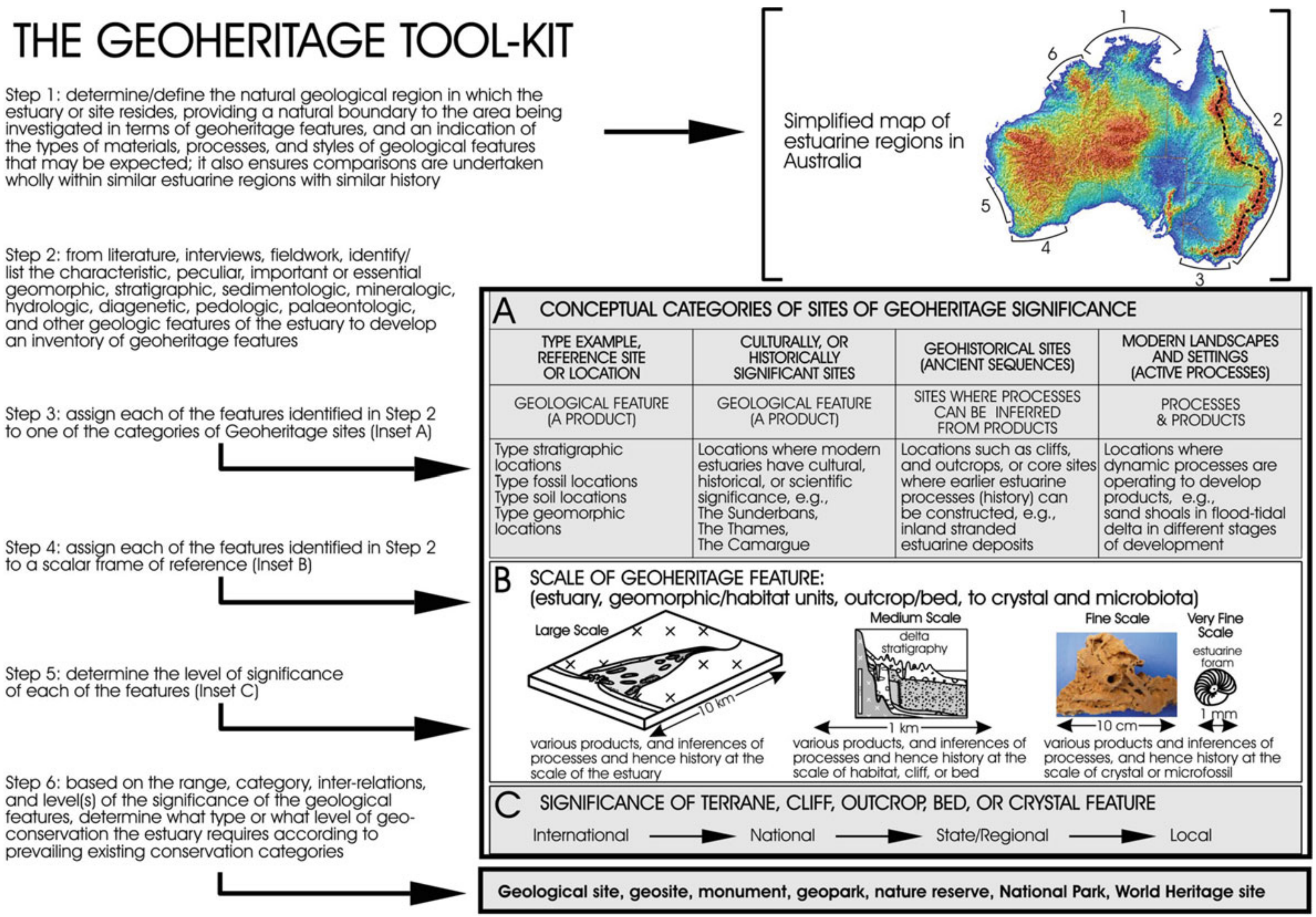
Step 3 allocates each unit of the inventory to a category of geoheritage, viz., a reference site, cultural site, geohistorical site, or a modern active landscape, so that comparisons in assessing significance are undertaken within similar categories. In regard to reference sites and/or type locations, once estuaries have been classified as to a type, the reference locations of end-member type or best example of an estuary can be identified and allocated as an international or national heritage locality. In this context, for comparisons of estuaries for geoheritage evaluation, it is important to have a worldwide applicable estuarine classification and nomenclature scheme that can be used systematically and comparatively to differentiate types based on landform/coastal setting, climate, shape and size of estuary, tidal and wave regime, sediment assemblages, seawater/ freshwater mixing style, and biota. A selection of estuaries that stand out globally as distinct and geomorphically significant because of either their size, internal landforms, representativeness, or naturalness and that could be used as estuarine reference sites and/or type locations are Lake St. Lucia (Natal, South Africa), Solway Firth (Scotland), Gironde Estuary (France), the Elbe (Germany), the deltaic complex of the Ganges-Brahmaputra (Sundarbans National Park, India), Walpole-Nornalup Inlet Estuary (Western Australia), Fitzroy River Estuary (Queensland), Gulf of Saint Lawrence (Canada), Chesapeake Bay (North America), and the Amazon Estuary (Brazil).

In regard to cultural or historical significance, estuaries may function as highly significant systems or may carry historical significance. The Camargue in the estuary of the Rhone (France) is an example of the former, and Port Hacking (Australia) and the Thames (the United Kingdom) are examples of the latter. Estuaries also can function as geohistorical sites showing ancient sequences where earth history can be determined. In regard to their stratigraphy and stranded geomorphology, they retain records over the past 7,000 years when sea level stabilized to its present position of coastal history and valley-fill history (Roy et al., 1980). Estuarine sequences that record estuarine evolution in Australia and North America (Fisher, 1969; Roy et al., 1980; Semeniuk, 2000) provide examples of the geohistorical importance of estuaries and illustrate the variety of pathways an estuary may take in its development. Estuaries also retain records of previous estuarine history in their stratigraphy and older estuarine geomorphology.

Estuaries illustrate modern landscapes and settings where earth processes are still active. They represent an environment where fluvial sedimentation interacts with basin processes to mobilize and deposit sediments into shoals, platforms, and basin-fill sheets. Flood and ebb tides form flood and ebb tidal deltas, and a plethora of biological, geochemical, hydrochemical, and physical processes at the finest scale result in various sedimentary deposits, biogenic deposits, sedimentary bedforms and structures, and mineral precipitates.

Some estuaries may belong to more than one geoheritage category. For instance, as a World Heritage area, the estuary of the Ganges-Brahmaputra river system serves as a reference site and as a location of modern landscapes and settings where estuarine and deltaic earth processes are still active in the largest tidal-dominated system in the world.

Step 4 allocates the geologic features to a scale, so that comparative assessments of levels of significance can be undertaken within a similar scale. The various scales



THE GEOHERITAGE TOOL-KIT

Step 1: determine/define the natural geological region in which the estuary or site resides, providing a natural boundary to the area being investigated in terms of geoheritage features, and an indication of the types of materials, processes, and styles of geological features that may be expected; it also ensures comparisons are undertaken wholly within similar estuarine regions with similar history

Step 2: from literature, interviews, fieldwork, identify/list the characteristic, peculiar, important or essential geomorphic, stratigraphic, sedimentologic, mineralogic, hydrologic, diagenetic, pedologic, palaeontologic, and other geologic features of the estuary to develop an inventory of geoheritage features

Step 3: assign each of the features identified in Step 2 to one of the categories of Geoheritage sites (Inset A)

Step 4: assign each of the features identified in Step 2 to a scalar frame of reference (Inset B)

Step 5: determine the level of significance of each of the features (Inset C)

Step 6: based on the range, category, inter-relations, and level(s) of the significance of the geological features, determine what type or what level of geo-conservation the estuary requires according to prevailing existing conservation categories

Simplified map of estuarine regions in Australia

A CONCEPTUAL CATEGORIES OF SITES OF GEOHERITAGE SIGNIFICANCE

TYPE EXAMPLE, REFERENCE SITE OR LOCATION	CULTURALLY, OR HISTORICALLY SIGNIFICANT SITES	GEOHISTORICAL SITES (ANCIENT SEQUENCES)	MODERN LANDSCAPES AND SETTINGS (ACTIVE PROCESSES)
GEOLOGICAL FEATURE (A PRODUCT)	GEOLOGICAL FEATURE (A PRODUCT)	SITES WHERE PROCESSES CAN BE INFERRED FROM PRODUCTS	PROCESSES & PRODUCTS
Type stratigraphic locations Type fossil locations Type soil locations Type geomorphic locations	Locations where modern estuaries have cultural, historical, or scientific significance, e.g., The Sunderbans, The Thames, The Camargue	Locations such as cliffs, and outcrops, or core sites where earlier estuarine processes (history) can be constructed, e.g., inland stranded estuarine deposits	Locations where dynamic processes are operating to develop products, e.g., sand shoals in flood-tidal delta in different stages of development

B SCALE OF GEOHERITAGE FEATURE: (estuary, geomorphic/habitat units, outcrop/bed, to crystal and microbiota)

various products, and inferences of processes and hence history at the scale of the estuary

various products, and inferences of processes and hence history at the scale of habitat, cliff, or bed

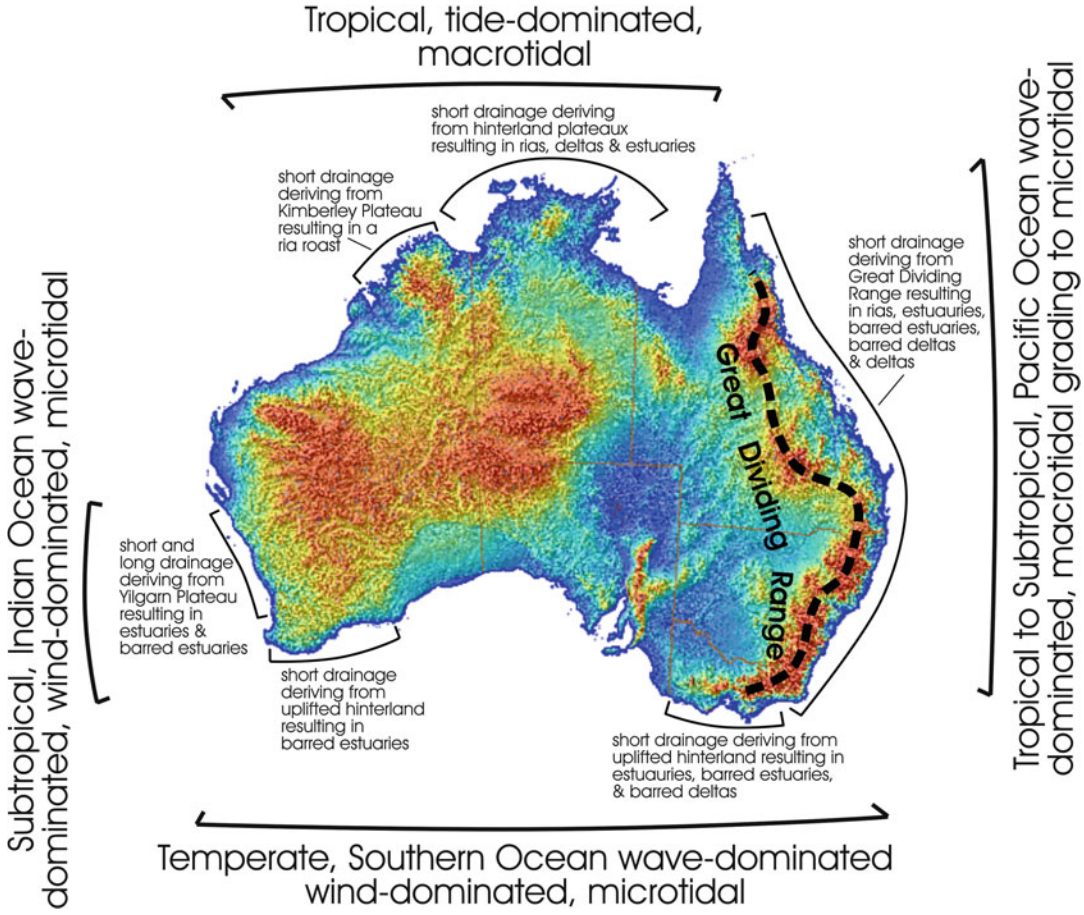
various products and inferences of processes, and hence history at the scale of crystal or microfossil

C SIGNIFICANCE OF TERRANE, CLIFF, OUTCROP, BED, OR CRYSTAL FEATURE

International → National → State/Regional → Local

Geological site, geosite, monument, geopark, nature reserve, National Park, World Heritage site

Determining Geoheritage Values, Figure 1 The six steps in the use of the geoheritage tool kit to identify geological features across various regions leading to designation of types of geoconservation. The *boxed* text and illustrations labeled *A*, *B*, *C*, from Brocx (2008), summarize the scope of geoheritage in terms of its categories, scales of application, and potential levels of significance that can be assigned to geosites.



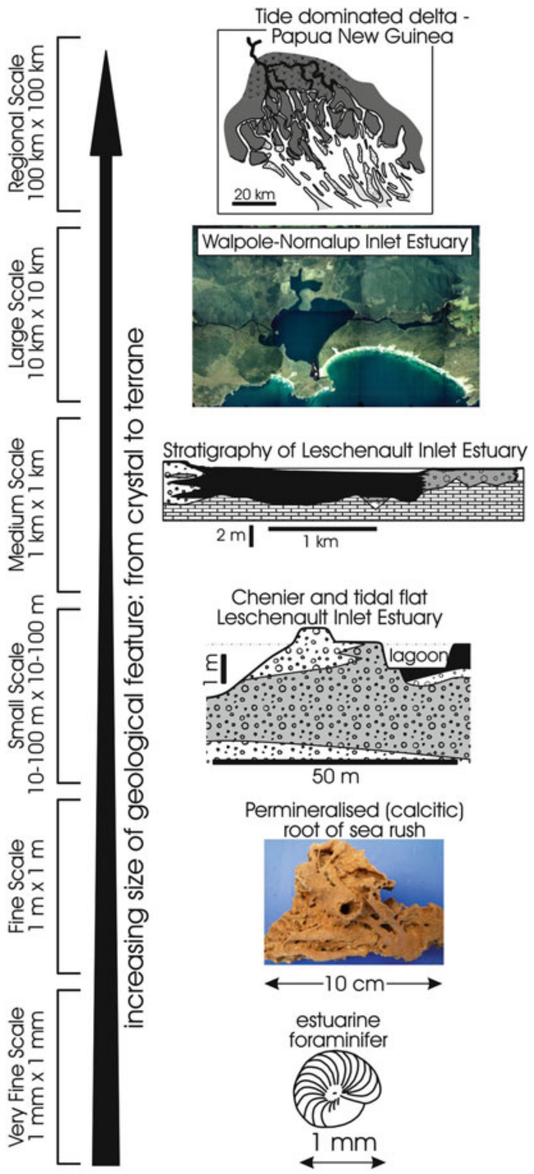
Determining Geoheritage Values, Figure 2 Simplified map of the main regions of estuaries in Australia based on geological setting, oceanography and tidal regime, and climate.

used in dealing with sites of geoheritage significance are regional, large, medium, small, fine, and very fine scales (Figure 3). Scale is important to consider in geoheritage/geoconservation since features of significance can range from crystals, bedding planes, and outcrops to that of landscapes and mountains. In many locations, sites are important because of crystal-sized phenomena and crystal fabrics (e.g., dolomite or permineralization in estuarine shorelines) or because of outcrops and bedding scale features (such as elevated estuarine fossil deposits). In the case of estuaries, the largest scale involves the size of the estuarine embayment, which may be tens of kilometers in size, and can involve the lower reaches of the drainage basin.

Step 5 assesses the level of geoheritage significance of the geological features regardless of their scale (Figure 4). The level of importance attributed to a given feature of geoheritage significance is related to how frequent or common is the feature within a scale of reference and/or how important is the feature to a given culture. Levels of significance are (Brocx and Semeniuk, 2007) (1) international, (2) national, (3) statewide to regional, and (4) local. Levels of significance of geoheritage features of (and within) estuaries are illustrated in Figure 4.

After an assessment of the range, categories, interrelationships, and level(s) of significance of the geological features, the final step is Step 6 which will determine what type and what level of geoconservation are assigned to the estuary whether in toto or in part.

Large estuaries, or sites within estuaries that are of geoheritage significance, or an amalgamation of numerous smaller sites of geoheritage significance can be assigned to geopark status. The Global Geoparks initiative supported by UNESCO sees geoparks as a territory encompassing one or more sites of scientific importance, not only for geological reasons but also by virtue of its archaeological, ecological, or cultural value. An estuary thus can qualify for this designation. The European Geoparks Network, established in 2000 (Zouros, 2000), defines a geopark as an area to conserve and valorize



Determining Geoheritage Values, Figure 3 Scales of features of geoheritage significance in estuaries.

geological heritage through the integrated and sustainable development of their territories. Similarly, an estuary can qualify also for this designation. The Asia Pacific Geoparks Network, founded in 2007, defines geoparks as nationally protected areas containing a number of geological heritage sites of particular importance, rarity or aesthetic appeal. These earth heritage sites are part of an integrated concept of protection, education, and sustainable development. An estuary can qualify also for this designation. All these initiatives aim to protect geodiversity, promote geological heritage, and support local sustainable economic development, thus involving community and commercial interests.

Estuaries lend themselves to designation as geoparks because they inherently have multiple uses (fishing, boating, shoreline nature walks, areas of conservation for waterbirds) and often illustrate interrelated features of landscape, geology, estuarine geomorphology, and sedimentology that can be utilized for science and education and tourism. Brocx and Semeniuk (2009) identified the Walpole-Nornalup Inlet Estuary in Western Australia as an integrated geopark, wherein the various Cenozoic and Holocene geological and estuarine features could be used as features for nature tours. Thus, estuaries can be viewed as potential geoparks, i.e., conservation, and promotional entities focused on geological and geomorphological attributes for local sustainable development.

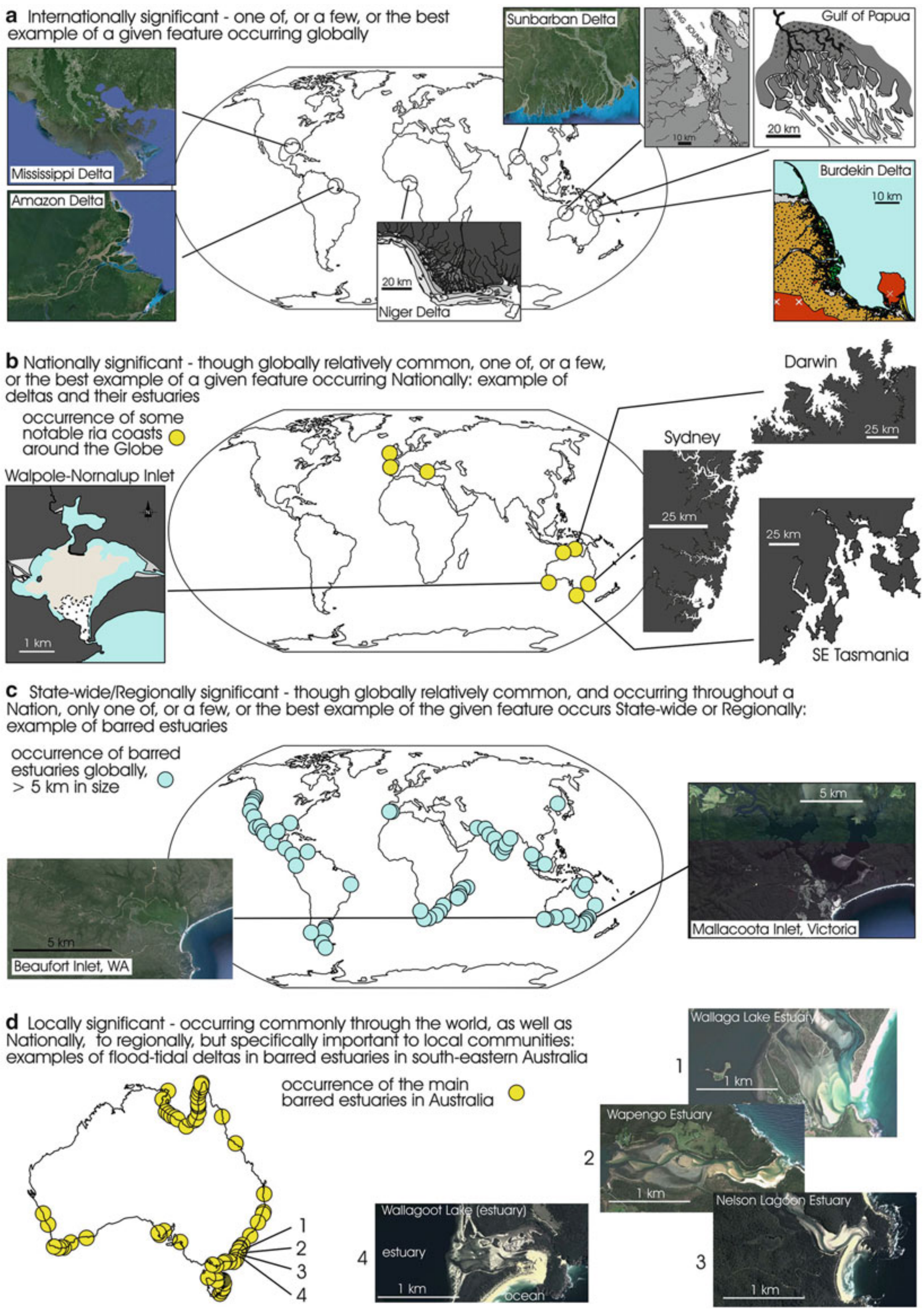
The leschenault inlet estuary and walpole-nornalup inlet estuary: case studies

The Leschenault Inlet Estuary and Walpole-Nornalup Inlet Estuary provide examples of the application of the geoheritage tool kit to identify and assess features of geoheritage significance in the estuaries. Both present two extremes of types in Western Australia. The Leschenault Inlet Estuary, a barrier dune barred estuarine lagoon, with two contributing rivers at its southern end, is located in a subhumid part of Western Australia, facing the swell-dominated Indian Ocean (Brocx and Semeniuk, 2011). Brocx and Semeniuk (2011) identify 10 features of geoheritage significance in the estuary. Of these, one feature is assessed as internationally significant, two as nationally significant, and seven as being of statewide or regionally significant (Figure 5). Brocx and Semeniuk (2011) proffer that the estuarine system, with its geological framework, complex shores, estuarine geomorphology and stratigraphy, and multitude of important small-scale features, also could function as geopark for geotours, research, and education.

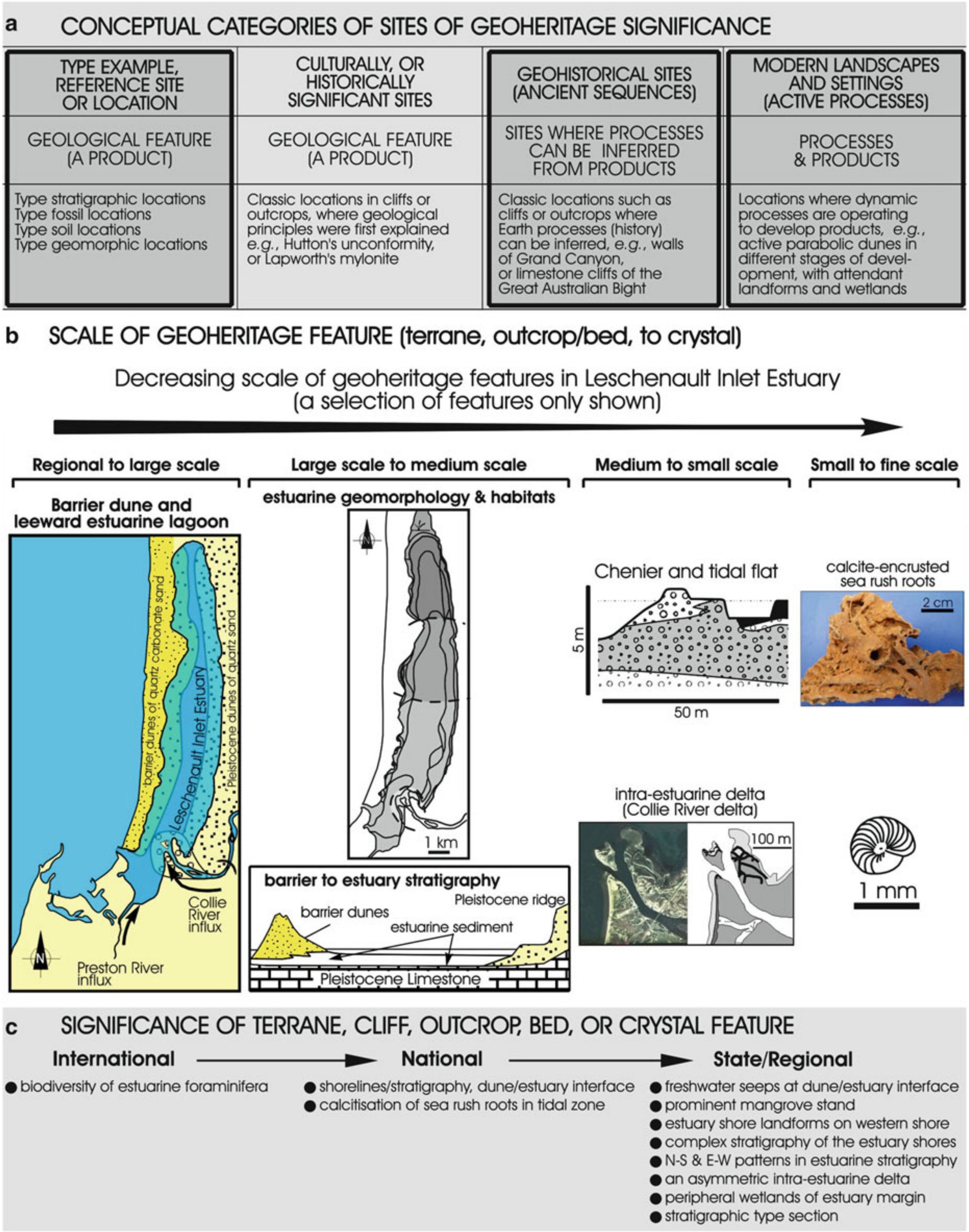
The Walpole-Nornalup Inlet Estuary, a twin ria estuary with a dune barrier and three contributing rivers, is located in the most humid part of Western Australia, facing the high-energy Southern Ocean (Semeniuk et al., 2011). Semeniuk et al. (2011) identify 22 features of geoheritage significance that include its intra-estuarine delta and peat-floored peripheral wetlands. Of these, one feature is assessed as internationally significant, two as nationally significant, and 19 as statewide or regionally significant (Figure 6). Semeniuk et al. (2011) proffer that the estuarine system of Walpole-Nornalup Inlet, with its geological framework, estuarine geomorphology and stratigraphy, and multitude of important small-scale features, could function as geopark for geotours, research, and education.

Summary

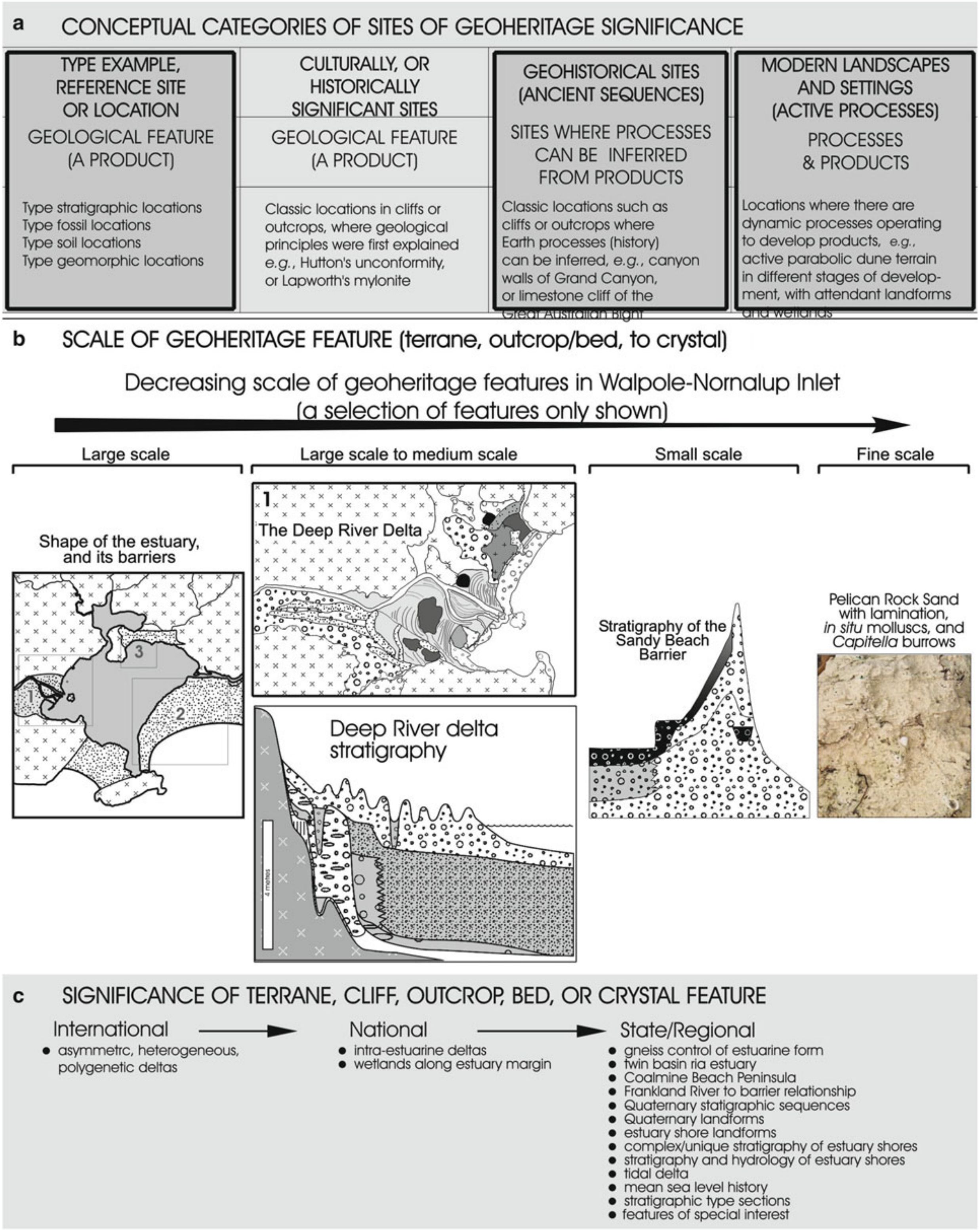
In estuaries, to date, there has been emphasis on their biological significance, e.g., their vegetation complexes, productivity, invertebrate fauna, and fisheries, and hence their conservation and management from a biological perspective, and less on the importance of their geology, geomorphology, sedimentology, hydrology, and geohistorical



Determining Geoheritage Values, Figure 4 Assessment of the level of geoheritage significance (based on the approach described by Brocx and Semeniuk 2007 but modified to focus on estuaries and deltas). The examples used to illustrate nationally significant geoheritage features are ria coasts of Tasmania, New South Wales, and Northern Territory (from Australia) and shown in their global context. The examples used to illustrate statewide/regional significance are barred estuaries (>5 km in size), drawn from Australia and shown in a comparative global and national context. The examples used to illustrate local significance are flood-tidal deltas from barred estuaries of southeastern Australia shown in a context of barred estuaries in Australia (See also "*Geoheritage*").



Determining Geoheritage Values, Figure 5 Application of the geoheritage tool kit to the Leschenault Inlet Estuary (Modified from Brocx and Semeniuk 2011). *Inset A* – the categories of geoheritage applicable to this area are highlighted in gray. *Inset B* – selected features of geoheritage significance are illustrated, graded in decreasing scale from *left* to *right* (a map of the barrier and lagoon, a map of estuarine habitats, cross section of barrier-to-lagoon stratigraphy, a chenier perched on a tidal flat, map of the Collie Delta, calcitized sea rush roots, and an estuarine foraminifer). *Inset C* – geoheritage features are allocated to a level of significance.



Determining Geoheritage Values, Figure 6 Application of the geoheritage tool kit to the Walpole-Nornalup Inlet area (Modified from Semeniuk et al. 2011). Most of the estuarine geoheritage features rank as regional to statewide significance, while some are national significance, and one feature of international significance.

evolution. However, there are two components to estuaries, i.e., the biotic and the abiotic (that underpins biodiversity). Geoheritage and geoconservation are concerned with the recognition and preservation of the abiotic world and in this context can be directed to the recognition and preservation of the geodiversity of estuaries. For instance, based on a world map of estuary types and their uniqueness or representativeness, it can involve the recognition and geoconservation of end-member types of estuaries as global "type examples" of the variety forms expressed around the world in response to climate, hydrodynamic setting, sediment types, and framework geology. At this scale, geoheritage recognizes the range of estuarine systems that are manifest around the world and attempts to address the significance of the variety of these estuaries that have formed in different geological, hydrological, sedimentological, and climatic settings within a variable biogeographic context. At the next level, geoheritage and geoconservation can involve the geoconservation of geological processes and products operating and occurring within estuaries, e.g., deltaic sedimentation and its variety of landforms, sand platforms and their surface bedforms, evolution of estuarine stratigraphy, stratigraphic/hydrologic interactions, and styles of hydrochemical mixing. At the finest scale, geoheritage and geoconservation can involve the recognition and geoconservation of microscale processes and products, often specific to an environmental setting and climate, e.g., diagenetic features such as calcitization of shoreline rush rhizomes, occurrence of dolomite, formation of pyrite nodules, the permineralization of skeletons, and the effects of freshwater seepage.

It should be noted that just as biologic systems are diverse, geological systems are also diverse (geodiversity), and in the case of estuaries, estuarine systems are also diverse and there are a large range of estuarine types, as exemplified by variation in their setting, shape, size, estuarine landforms, hydrology, and internal functioning. The classification of estuary types, using the geoheritage tool kit, has attempted to address this. Similar to the objective of nature conservation, to conserve the vast diversity of life forms, an objective of the conservation of sites of geoheritage significance in estuaries would be the conservation of the variety of their forms on the earth. In this context, the conservation of a single "estuary" as an example of an estuarine system as representative of the full variety of estuarine types globally is insufficient. If estuaries, for instance, exhibit a large diversity of geometric and hydrologic types, stratigraphic fills, and origins, then at the least their conservation should encompass an example of each of the types.

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Cross-references

Geoheritage

DETRITUS FOOD WEBS

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Synonyms

Decomposer food web food; Detritus cycle; Microbial loop

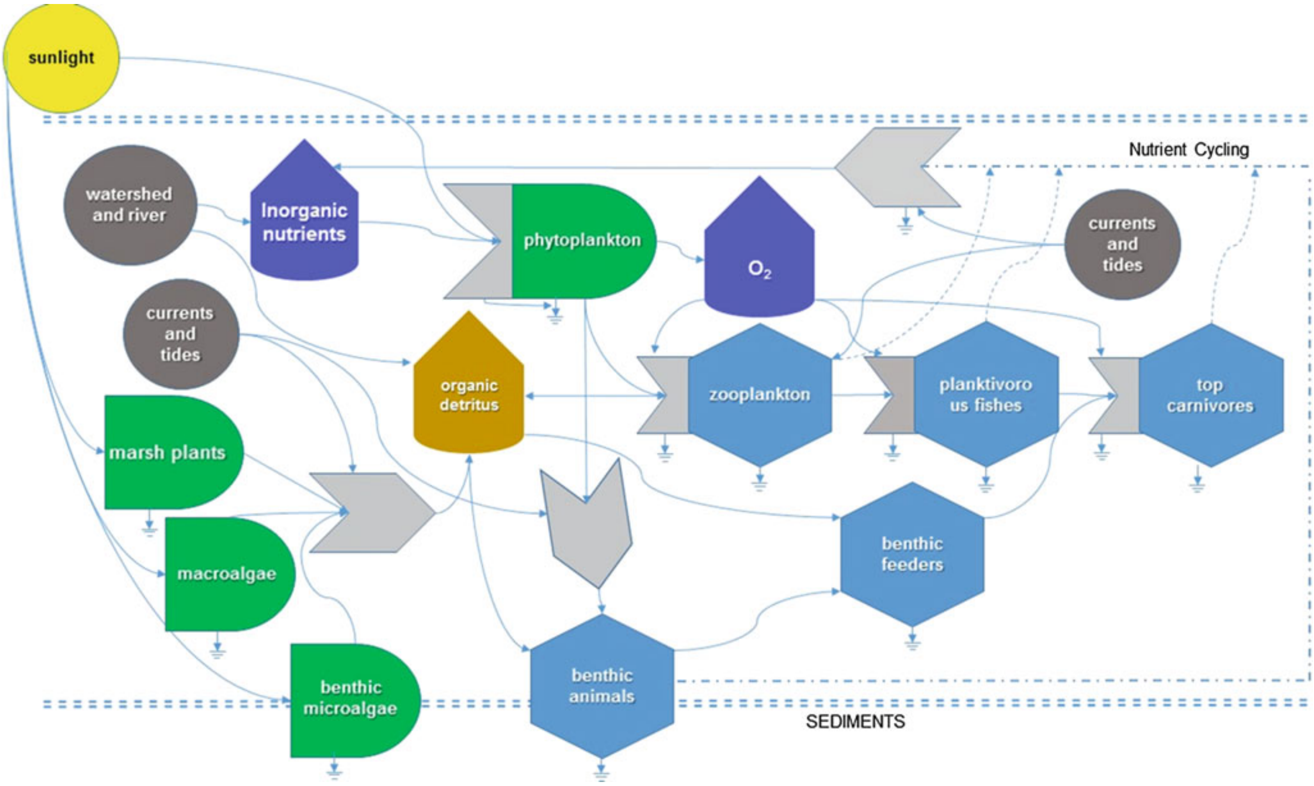
Definition

Food webs or portions thereof that are based on the decomposed particles of dead plants and animals, mediated by saprotrophic and scavenger organisms that break down organic matter into its constituent compounds.

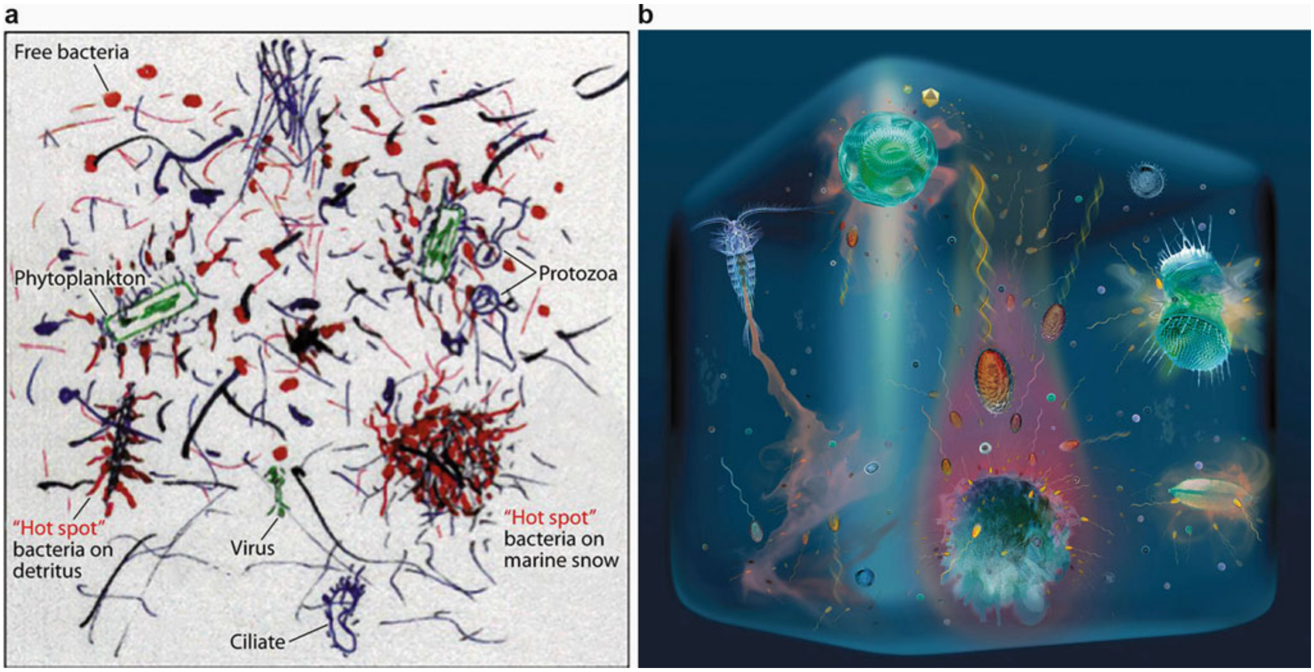
Summary

While the basic photosynthetic production processes supporting all but extremophile-based food webs do not differ among most ecosystems, from an energy flow perspective (see *Food Web/Trophic Dynamics*), the pathways whereby organic compounds reach metazoan consumer organisms can be both intricate and often confusing. This is especially the case in estuaries, wherein diverse living and detrital organic matter sources support mixed autotrophic and heterotrophic production (Figure 1). As opposed to direct herbivory (“grazing”) of living plants, food webs based on detritus involve the decay of photosynthetic products and even dead consumer organisms; however, whether or not detritus should be defined as including associated living decomposers and other microorganisms (Figure 2) has always been somewhat of a philosophical dispute (Darnell, 1967).

While detritus is the predominant food web source in some ecosystems, such as in soils, the occurrence and contribution of detritus to aquatic food webs have been more debatable. About the same time that Sir Alistair Hardy (1924) was describing a food web that supported Atlantic herring wholly by autotrophic production from algae, Summerhayes and Elton (1923) diagrammed a “nitrogen cycle” for Bear Island (Bjørnøya), Svalbard, that illustrated a more complex network also involving detritus from aquatic and terrestrial plants being decomposed by bacteria and protozoa before sustaining detritivores and ultimately higher-level consumers. With the discovery of



Detritus Food Webs, Figure 1 Detritus food web. Estuarine food web energy flow indicating interactions among autotrophic (*green*: phytoplankton, marsh plants) and heterotrophic (*brown*: detritus) pathways of organic matter production, consumption (*blue*: consumers), inorganic resources (*purple*), transformations and storage (*light gray*) and energy (*dark gray*) (Modified from Day, J. W., Jr., B. C. Crump, W. M. Kemp and A. Yáñez-Arancibia (eds.) 2012. Estuarine Ecology, 2nd Edition, Hoboken, New Jersey: Wiley-Blackwell).



Detritus Food Webs, Figure 2 Illustration of the different forms of detritus and microbial microenvironments common to estuaries, including (left image; from Stocker and Seymour 2012 Microbiol. Mol. Biol. Rev. 76:792-812) "hot spots" of microbial activity in association with detritus, marine snow particles, and phytoplankton cells, and (right image; modified from the cover of Science, 5 February 2010; original image credits: R. Stocker, J. R. Seymour, G. Gorick) organic matter source, including zooplankton excretions (left), phytoplankton exudation (the "phycosphere") (top; bottom right), phytoplankton lysis (top right), settling marine snow particles (center bottom), and copepod excretions (left).

"marine snow" (Alldredge and Silver, 1988) and the attendant "microbial loop" driven by dissolved organic matter (POM) (Pomeroy, 1974; Azam et al., 1983), even presumed autotrophically dominated ocean food webs were found to have highly integrated detritus pathways (Figure 2b). While detritus has long been considered to be a major driver of food web pathways in estuarine sediments (e.g., Newell and Field, 1983), it also became even more relevant to estuaries overall (Crump et al., 2012), especially with increased understanding of gravitational circulation processes that promote estuarine turbidity maxima as "biogeochemical reactors" (Baross et al., 1994; Savoye et al., 2012). What has become increasingly obvious from the more recent application of isotope and other biomarker sampling and experimentation in estuaries is that although detritus fuels and may even dominate many estuarine food webs, the extent to which it does varies considerably as a function of the type and region of estuary and the time frame (Odum, 1984; Peterson et al., 1985; Peterson and Howarth, 1987; Deegan and Garritt, 1997; Akin and Winemiller, 2006).

In many respects, estuaries have often been the nexus of the debate about the role of detritus food webs, touching on the core of many fundamental issues in ecological theory such as labile versus refractory organic matter sources (Mann, 1988); the importance of allochthonous, spatial subsidies (Polis et al., 1997); outwelling (Childers et al., 2000); compartmentalization (Raffaelli and Hall, 1992); community stability (Huxel and McCann, 1998); and top-down versus bottom-up control on food web structure (Power, 1992). While the prominence of detritus in estuarine food webs is less debatable, its role in shaping estuarine ecosystem dynamics and regulating the productivity of important consumers such as commercial fisheries is still somewhat controversial.

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Cross-references

Food Chain
Food Web/Trophic Dynamics

DIAGENESIS

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Definition

The chemical and biological environment within sediments is very different from the overlying water column from which the particles settled. During burial, particles undergo diagenesis: the transformation of sediment and organic matter by physical, biological, and chemical processes. Early diagenesis refers to the transformations that occur while sediments are submerged, temperatures do not exceed 140 °C, and burial is less than a few 100 m (Berner, 1980).

Description

Physical processes alter sediments after deposition. Sediments are compacted by the weight of overlying sediments, which decreases the ratio of interstitial water to sediment. If oxygen is present in overlying water, benthic macrofauna will mix sediments. Bioturbation is most intense near the sediment-water interface and decreases with depth. In specific settings, soft sediments deformation structures can form, including dewatering structures, slumped beds, and load structures.

The chemical and biological environments change with distance from the sediment-water interface. Exchange between interstitial water and overlying water is restricted, allowing for the composition of interstitial water to differ from overlying water. Moving deeper into sediments, interstitial water becomes more reducing as oxidants are consumed during respiration (Froelich et al., 1979). Respiration also increases the acidity of interstitial water, reducing the pH. The composition of interstitial water is further influenced by uptake and release of compounds in biotic and abiotic reactions. These changes to interstitial water chemistry allow for different transformations of organic matter and sediments to occur.

Most organic matter deposited in sediments is removed by respiration of benthic organisms. However, some organic matter is transformed from characterized compounds, such as lipids, carbohydrates, and amino acids, into uncharacterized humic substances. This likely occurs biologically through the selective utilization of more reactive components of organic matter, with some contribution of abiotic recombination of smaller molecules (Burdige, 2007). Humic substances tend to be refractory, persisting for long periods in the sediment. The diagenesis of organic matter depends on the redox conditions, with greater preservation of humic substances under more reducing conditions.

Inorganic sediments also undergo diagenesis from a variety of mechanisms. Sediments may be transformed as they pass through the gut of detritus feeders. Mineral dissolution of carbonates and silica may occur. In anoxic sediments, oxidized minerals, such as Fe_2O_3 and MnO_4, can be removed by microbial respiration. Further, the loss of these high surface area minerals can greatly reduce the adsorption capabilities of the sediment. Adsorption and desorption reactions can also occur due to changing pH and Eh conditions. Ion exchange can occur in clays, altering their composition. Authigenic minerals, including phosphates, carbonates, and sulfides, may precipitate out of solution. Some precipitates can cement sediment grains, reducing the ratio of interstitial water to sediment.

During later stages of diagenesis that occur with greater burial, compaction and heating of sediments can lead to the loss of water from hydrous minerals, cementation of sediments, and lithification of sediments. As a result, the physical structure and chemical composition of buried sediments and sedimentary rocks depends both on the initial composition of the material deposited and the diagenesis that occurs during burial.

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Cross-references

Anoxia, Hypoxia, and Dead Zones
Sediment Toxicity

DIFFUSION

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Synonyms

Scatter

Definition

Diffusion is defined as free or random movement of molecules from a higher concentrated to lower concentrated region. Concentration gradients are part of this random movement.

Description

Lewis (1997) defined two criteria for molecular motion to be considered diffusion. First, the number of molecules moving in two directions (from high to low or vice versa) must be equal. The occurrence of an unbalanced condition is called advection. The second criterion is the occurrence of a concentration gradient between two regions.

Free molecular motion, as molecular diffusion, is described by Fick's law and diffusion equation. The movement of particles under turbulent motion can be defined as turbulent diffusion or eddy diffusion. The difference in turbulent diffusion is explained by the eddy diffusion coefficient (Fischer et al., 1979) (Figure 1).

For a one-dimensional case, diffusive transport can be expressed by using Fick's law as follows:

$$J = -D.\frac{\partial C}{\partial x} \tag{1}$$

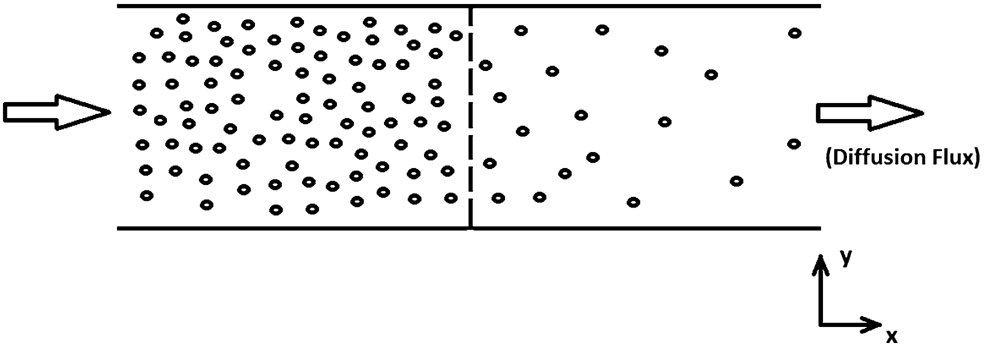
where J is the diffusion flux as the molecular amount of particles or substance per unit area per unit time (mol.m^{-2}.s^{-1}), D is the molecular diffusion coefficient (m^{2}.s^{-1}), and $\frac{\partial C}{\partial x}$ is the concentration gradient (mol.m^{-4}). The negative sign in the equation indicates the flux from high concentrated to less concentrated regions.

The turbulent diffusion (1) can be redefined as

$$J = -K.\frac{\partial C}{\partial x} \tag{2}$$

where K is the coefficient of eddy diffusion or turbulent diffusion.

The molecular diffusion coefficient can be taken as a constant at a defined temperature and also can be regarded as a property of the fluid. Conversely, the turbulent or eddy diffusion coefficient depends on the



Diffusion, Figure 1 Diffusion is the free or random movement of molecules from a higher concentrated to lower concentrated region.

Diffusion, Table 1 Molecular diffusion coefficients at infinite dilution in 25 °C water (Cussler, 2009)

Solute	Coefficient ($\times 10^{-5}$ cm^2/s)
Ammonia	1.64
Carbon dioxide	1.92
Hydrogen sulfide	1.41
Oxygen	2.10

strength and size range of the eddies in the turbulent motion, and it is not constant in all the fluid body (Lewis, 1997).

In general, the coefficient of eddy diffusion or turbulent diffusion (K) is a thousand times higher than the molecular diffusion coefficient (D) (Lewis, 1997). The diffusion coefficient affects the movement of particles or molecules (Table 1). The most common method for estimating diffusion coefficients for liquids uses the Stokes-Einstein equation.

Estuaries are semi-enclosed coastal bodies of water where freshwater mixes with saltwater and multiple factors affect the system hydrodynamics such as tides, currents, waves, Coriolis force, freshwater inflow, saltwater inflow, meteorological effects, and bathymetry (Dyer, 1973). Estuarine transport therefore is a complex process (Ambrose, 1990).

Mostly in estuaries, the primary mixing mechanism is not caused by the molecular viscosity or diffusion, but turbulent mixing. Turbulent eddies transfer a water body into other parcels having different mean velocities causing different water properties (Martin and McCutcheon, 1998).

Total mixing depends on diffusion which is the sum of molecular diffusion and turbulent or eddy diffusion, and coefficients can be summed ($D + K$). However, the molecular diffusion coefficients are considered negligible since they are so much smaller than the turbulent or eddy diffusion coefficients (Martin and McCutcheon, 1998).

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Cross-references

Dispersion
Tidal Hydrodynamics

DISPERSION

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Synonyms

Dissipation; Scattering

Definition

Dispersion in estuaries is the spreading or scattering of dissolved or suspended substances due to a combination of shear (or nonuniform velocity profile) and turbulent diffusion (Baretta-Bekker et al., 1995).

Description

The main difference between diffusion and dispersion is the longitudinally or laterally nonuniform velocity profile. Dispersion reflects the scattering of a cross-sectional mean concentration, whereas diffusion represents the scattering of a local concentration (Gulliver, 2012).

Dispersion coefficients have been determined for estuaries and other water bodies. These values have been compiled and listed in many publications. Dispersive mixing is not turbulent diffusion, but rather is due to nonuniformities in velocities and concentrations (Martin and McCutcheon, 1999). The collection of field data is very important for determining dispersion coefficients because many parameters in estuaries and other water bodies affect hydrodynamic mixing.

The fundamental papers on shear dispersion were published in the early 1950s by Geoffrey Ingram Taylor. His theoretical work applied to open channel flow (Elder, 1959) and to coastal waters (Bowles et al., 1958).

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Cross-references

Diffusion

DISSOLVED OXYGEN

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Synonyms

Elemental oxygen; Dioxygen; DO; O_2

Definition

Dissolved oxygen (DO) is the amount of elemental oxygen (chemical symbol O_2, molecular wt 31.99 g/mol) dissolved in fresh or salt waters.

Controlling factors of dissolved oxygen

The measurement of dissolved oxygen in water is provided in mg/L or ml/L units for environmental regulatory purposes but is usually measured in µMol for chemical and oceanographic studies. Table 1 provides conversions for these units. Most dissolved oxygen in estuarine waters is due to exchange with the atmosphere at the seawater surface. Atmospheric oxygen (O_2) presently constitutes 20.9 % of the atmosphere by volume and 23.1 % by mass. The maximum amount of DO at equilibrium with the atmosphere (100 % saturation) depends on the atmospheric pressure (partial pressure) of oxygen and the temperature and salinity of the water. As temperature and salinity increase, dissolved oxygen saturation decreases, while increases in atmospheric pressure increase saturation concentration. Additionally, photosynthesis by primary producers can increase surface water concentration to supersaturation levels, while aerobic respiration processes can decrease it to hypoxic levels at depth. Therefore, dissolved oxygen concentration is not conservative and is strongly affected by biotic organisms. Accurate calculation of the exact saturation value is a quite complex function of temperature, salinity, and pressure. Due to very slight discrepancies in results using the Weiss equations (Weiss, 1970; USGS, 1981), the United States Geological Survey (USGS) has changed saturation equations (USGS, 2011) using more recently published equations (Benson and Krause, 1984; Garcia and Gordon, 1992). The USGS revised its methodology in 2011 to follow the Benson and Krause equations. The USGS maintains a Web site that provides such calculations for saturation values at specific temperatures and salinities (USGS, 2013).

Measurement methodologies

The classic method to measure dissolved oxygen in water involves titration of treated water samples using the Winkler (iodometric) method (Winkler, 1888) and is considered one of the most accurate methods assuming all precautions are followed in the sampling procedures, handling and addition of reagents involved. The original method has been modified due to interference from nitrite, ferrous or ferric iron, and organic matter (Carpenter, 1965; Strickland and Parsons, 1968; APHA, 2005), while iodate may still cause problems (Wong and Li, 2009). Poor handling can expose water samples to gas bubbles during the initial addition of reagents to fix the sample in the field and introduce significant overestimate errors. The method is considered precise for lab analyses, but other methods are recommended for measurements in situ (Lewis, 2006). Because accurate Winkler measurements are difficult at extremely low DO levels, spectrophotometric methods using special dyes such as Rhodazine D are sometimes recommended for such situations (Broenkow and Cline, 1969; White et al., 1990; Lewis, 2006). The use of amperometric techniques for real-time field measurements has been accepted as a suitable method to determine in situ dissolved oxygen in fresh and salt waters as long as corrections based on temperature and salinity are made (usually provided within the instrumentation). This method requires careful calibration of the sampling device. The "Clark"-type amperometric method uses a silver (Ag) anode and a gold (Au), platinum (Pt), or palladium (Pd) cathode surrounded by an ionic fluid (usually KCl). A thin, gas permeable Teflon® membrane allows exchange of oxygen with the electrodes. Because the reaction at the electrode consumes oxygen, accurate membrane response requires flowing water to achieve steady equilibrium conditions, leading to a need for mixing or forced flow of the water being sampled across the membrane as well as time for equilibrium to be achieved. Another oxygen probe type (galvanic) has a self-polarizing amperometric cell that uses a lead (Pb) or zinc (Zn) anode and a gold (Au) or silver (Ag) cathode. An electrolyte of NaCl or NaOH surrounds the electrodes (Eutech Instruments Pte Ltd., 1997). If either of these sensors is deployed for long periods, overgrowth by biofilms and fouling organisms on the membrane can interfere with the gas exchange, so membrane replacement is required at certain intervals. Manufacturers recommend various antifouling techniques to decrease the rate of biofouling growth at the membrane. Anoxic waters with high levels of hydrogen

Dissolved Oxygen, Table 1 Conversions for various measures of dissolved oxygen at 100 % saturation at 760 mmHg; ρ is the density of the sample based on the equation of state (Unesco, 1981).

ml/L DO to mg/L	mg/L DO to ml/L	ml/L DO to µMol/L[a]	µMol/kg
ml/L DO * 1.42903 = mg/L	mg/L DO * 0.6998 = ml/L	ml/L DO * 44.660 = µMol/L	$\frac{uMol}{L}/\rho = \mu\mathrm{Mol/kg}$

[a] Common oceanographic CTD instrumentation and others use this historic method to calculate uM/L, but exact measurements required more sophisticated calculations for exact uMol concentration (Thierry et al., 2011)

sulfide (H_2S) can “poison” the electrodes, decreasing the response to oxygen concentrations. In more recent years, a luminescent technique has become commercially available using a sensor called an optode with a membrane impregnated with a dye which emits red light frequencies when excited by a blue laser. Both the intensity and duration (lifetime) of the fluorescence signal are affected by temperature and are quenched by DO in a linear response at low to mid saturation levels. Because of this, temperature measurements of high precision are required. This method has a number of advantages, including less interference from H_2S and biofouling and greater sensitivity under low DO conditions since oxygen concentration decreases the fluorescence response, so the strongest signal occurs under anoxic conditions. However, at high saturation values, the response is more complex and requires a complex polynomial relationship between DO, temperature, and the fluorescence signal. The dye can degrade over time and so requires membrane replacement at set intervals (Mitchell, 2006; YSI, 2009). Some sensors measure the intensity, while others measure the lifetime of the emitted signal.

Summary

Dissolved oxygen (DO) is the amount of elemental oxygen (Chemical symbol O_2, molecular wt 31.99 g/mol) dissolved in fresh or salt waters. It is measured as mg/L or ml/L for environmental regulatory purposes but is usually measured in uMol for chemical and oceanographic studies. The maximum amount of DO in water at equilibrium with the atmosphere (100 % saturation) depends on the atmospheric pressure (partial pressure) of oxygen and the temperature and salinity of the water. As temperature and salinity increase, dissolved oxygen saturation decreases, while increases in atmospheric pressure increase saturation concentration. Dissolved oxygen concentration is not conservative and is strongly affected by biological processes such as photosynthesis and respiration.

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Cross-references

Aerobic Environments
Anaerobic Environments
Ecological Monitoring
Estuarine Total Ecosystem Metabolism
Eutrophication
Halocline
Microbial Degradation
Oxygen Depletion
Water Quality
Well-Mixed Estuary

DREDGE AND FILL

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Synonyms

Sediment disposal; Sediment excavation

Definition

Dredge-and-fill operations are conducted in coastal areas mainly to re-nourish beaches, to restore wetland habitat, to remove excessive amounts of bottom sediments from waterways, and to construct lagoons and roads. Dredging in estuaries is carried out to create new harbors, berths, and waterways or to improve navigation. "Large estuaries, such as Coos Bay, Oregon (U.S.), that function as deep-water ports for large freighters, tankers, and other ships require the deepest channels and most frequent channel maintenance" (Oberrecht, 2005).

Fill is an operation that is conducted mostly in coastal regions using sand, rocks, gravel, shell, earth, and concrete as filling materials. Filling activities in estuaries, lagoons, and coastal wetlands may include restoring and modifying areas by deposition of sediments.

Characteristics

Dredgers are used to excavate bottom sediments from estuarine water bodies that can then be dumped at appropriate locations. "Dredging is accomplished basically by two mechanisms: (1) hydraulic dredging – removal of loosely compacted materials by cutterheads, dustpans, hoppers, hydraulic pipeline, plain suction, and sidecasters, usually for maintenance dredging projects; and (2) mechanical dredging – removal of loose or hard compacted materials by clamshell, dipper, or ladder dredges, either for maintenance or new-work projects" (San Francisco Bay Conservation and Development Commission, 2001).

Dredge-and-fill operations may be deleterious or beneficial to certain species of organisms in estuaries and wetlands. Johnston (1981) noted that the ways to mitigate adverse effects of dredge-and-fill operations should include careful pre- and post-construction environmental studies. Dredge-and-fill activities are regulated in the USA by municipal, state, and federal government agencies.

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Cross-references

Dredging

DREDGING

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Definition

Dredging is the process of excavating bottom sediments from the estuarine floor for disposal at another location, most frequently to increase the depth of a channel to facilitate navigation by floating vessels.

Introduction

Early navigators were in many cases limited by naturally occurring depths in water bodies. As ships grew larger, dredging became necessary to increase water depths to allow safe passage. In some cases, dredging was used to create navigable water where land previously existed, with the Suez and Panama Canals serving as two prominent examples from the nineteenth and twentieth centuries, respectively. However, the digging of canals predates recorded history.

Tidal inlets connect rivers and estuaries to adjacent seas and are thus important for marine commerce. The natural depth within an inlet is typically controlled by a balance between tidal currents sweeping through, in alternating directions, and waves and longshore currents pushing sediment into the inlet. Dredging can effectively increase the depth in the channel. But without any changes in the tidal prism that defines the volume of flow through the inlet per tidal cycle, the channel is then deeper than its equilibrium configuration and subject to shoaling (van de Kreeke, 1992). This implies that dredging to greater depths will result in an increased need for maintenance dredging.

Dredging is also critical for maintenance of ship berthing areas and turning basins. It is widely employed for land reclamation purposes, habitat creation, sand mining, and beach nourishment activities. Project scope can range from maintenance of a small boat launching area up to major land reclamation projects involving many millions of cubic meters of sediment (e.g., Ports of Los Angeles in the United States and Rotterdam in the Netherlands; Palm Islands in Dubai). Bray and Cohen (2010) provide other examples of projects around the world.

Equipment and techniques

Dredging has been conducted by a wide range of equipment and schemes and for a wide variety of purposes (U.S. Army Corps of Engineers, 1983; Huston, 1986; Herbich, 1992; Bray et al., 1996; PIANC, 2009; Bray and Cohen, 2010). Most approaches are categorized as either mechanical or hydraulic, with the latter referring to a scheme that involves pumping a water-sediment slurry, often after mechanical loosening of the material being dredged.

A steel I-beam or other device dragged across an underwater high spot can remove a navigation hazard by redistributing sediment underwater and is thus a crude form of mechanical dredging. A clamshell bucket deployed from a standard construction crane on a floating barge can remove submarine sediment and is another example of a mechanical approach. Likewise a backhoe on a barge can function as a dredge in shallow water. Material can be deposited on or in a barge or truck and hauled away for offshore or onshore disposal.

Suction dredges are common for larger projects, and the suction pipe is often equipped with a rotary tool, yielding what is known as a cutterhead suction dredge (Figure 1). The dredge is typically held in place by rigid, vertical spuds, and the cutterhead (Figure 2) lowered to the river- or seabed. The cutterhead can be moved in a sweeping motion across the work area, either by the vessel winching itself or being pushed sideways or by moving the dredge head relative to the vessel (swinging ladder dredge). In this way, the drill head operates a bit like a moving drill bit, biting into the sediment, while a vacuum pump lifts the resulting slurry and pumps it to a barge or neighboring site. Since the material is mechanically mobilized for hydraulic transport, this approach could be defined as a hybrid mechanical/hydraulic scheme.

In many cases, an inline booster pump is used with the hydraulic or hybrid schemes, to overcome head losses within the discharge pipe, allowing discharge at greater distances from the work area. Floating pipe is often utilized to get the slurry to the disposal site. By this approach, dredged materials may be pumped to distances of many kilometers.

Many other types of dredges have been developed. Examples include the horizontal auger dredge, the dustpan dredge, the trailing suction hopper dredge, and the bucket dredge. Suitability of any given design for a particular project depends on the scope of the job, mobilization costs, water depths, sediment characteristics, environmental operating conditions, distance to disposal site, quality and mode of transport of dredged material (spoil), and other factors.

Schemes have also been developed to put sediments into suspension so that naturally occurring water currents will move them away from problem areas. This would obviously increase turbidity significantly, which is often undesirable or prohibited. In other cases, curtains or structures have been installed to reduce the tendency for siltation that would require subsequent dredging.

Material disposal and environmental considerations

The dredged material may simply be disposed of at a convenient site, or it may be moved to a new location where its deposition is considered beneficial, such as for land reclamation or beach nourishment. Offshore disposal is employed in some cases and can often be the least

Dredging, Figure 1 Cutterhead dredge, with spuds deployed at rear, and cutterhead suspended from opposite end.

Dredging, Figure 2 Cutterhead tool lifted clear of the water.

expensive option, but in recent years, more emphasis has been placed on keeping material dredged from coastal areas within the littoral zone, when its characteristics are suitable, to avoid loss of sediments from beaches.

In some cases, the dredged material contains contaminants that must be sequestered. Often this material is placed within an upland confined disposal facility that is dewatered as the material settles (U.S. Army Corps of Engineers, 1987; PIANC, 2002). It can also be placed in a pit underwater and capped (U.S. Army Corps of Engineers, 1998). Vellinga (1997) and Bray (2008) discuss the handling of dredged material containing contaminants. The problem is unfortunately quite common because many of the oldest and largest cities in the world are closely tied to ports and waterways.

Turbidity resulting from dredging activities is often a concern and may restrict available operating times for dredging. Other environmental concerns arise at selected locations and times. In the southeastern United States, for example, dredging is restricted during periods when marine turtles are likely to be in the vicinity of dredging equipment. Many tidal inlets feature shipwrecks that in some instances influence dredging plans or are discovered during dredging.

Summary

Given the large human populations worldwide that reside in coastal areas, and the increasing internationalization and magnitude of commerce, dredging is likely to remain an important global industry. Port capacities will need to continue to be increased, and many ports have the potential to be seriously impacted by relative sea level rise. Dredging schemes will need to be continually improved to increase efficiency and reduce environmental impacts.

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Anthropogenic Impacts
Dredge and Fill
Mass Physical Sediment Properties
Sand Mining/Beach Sand Mining