A note on calcite precipitates as encrustations around sea rush roots and rhizomes and as laminae in high tidal zones of western Leschenault Inlet estuary

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Abstract

Precipitates of calcite occur in the high tidal zone of the western shore of the Leschenault Inlet estuary as encrustations around roots and rhizomes of the sea rush *Juncus kraussii*, as permineralised plant and fungal material, as laminae transgressing the encrustations, and as laminae in mud and muddy sand. The calcite forms crusts around the roots and rhizomes, as bladed crystals 0.5–1.0 mm in length, preserving the roots/rhizomes as casts, as thin horizontal sheets and micro-lenses within the sediment, and cementing the sediment. Mineralogically the precipitates are calcite and some Mg-calcite. Crystallographically, the crusts are layered, with crystal growth hiatuses marked by dissolution of calcite and by Fe-oxide and Mn-oxide precipitates. The hydrological and hydrochemical setting of the calcite precipitates is where freshwater seepage from the quartz and calcareous sand of the dune barrier delivers calcium carbonate-charged waters to the high-tidal flat. These types of encrustations and calcite laminae are absent from the eastern quartz sand shore of the estuary.

Keywords: sea rush rhizoliths, calcite encrustations, calcite laminae, permineralisation, tidal zone, estuary, Leschenault Inlet estuary

Introduction

The formation of rhizoliths, or rhizocretions, in paludal, lacustrine, riverine, estuarine, high tidal flat, and palaeosol environments by mineralisation, biomineralisation, permineralisation, or concretion of plant roots, including their calcitisation, has been documented for ancient sequences from Carboniferous to the Pleistocene (Cohen 1982; Mount & Chen 1984; Wright 1986; Liutkus *et al*. 2005). Mostly, the calcitisation or other forms of mineralisation and biomineralisation occur in ancient sequences with inferences about environment of deposition determined from stratigraphic and palaeo-environmental reconstructions. Modern analogues of such shoreline mineralisation and rhizolithification of vegetation, and the calcreting of plant roots in soils are generally lacking. Exceptions are the mineralisation of plant roots colonising the margins of Lake Bogoria, Kenya, forming *in situ* rhizoliths, composed of various minerals (Owen *et al*. 2007), diagnetic clay concretions around plant roots on the tidal shore of the Saint Lawrence River (Rousseau 1934), and tuart-tree-induced precipitation of calcrete around roots and root hairs in the Leschenault Peninsula (Semeniuk & Meagher 1981a). This contribution describes calcite precipitation in the high tidal zone of the western shore of Leschenault Inlet estuary that results in the calcitisation of the roots of fringing estuarine vegetation, and development of calcitic laminae within the muddy sediment, the former resulting in calcitised rhizoliths or rhizocretions.

The setting of the calcite encrustations and laminae precipitates

The Leschenault Peninsula, a linear dune barrier in south-western Australia, located in a subhumid climate with mean annual rainfall of 880 mm, and annual evaporation of 1300 mm, is composed of parabolic dunes in various stages of mobility and fixation (Semeniuk & Meagher 1981b). Leeward of the barrier is the Leschenault Inlet estuary, an elongate shore-parallel, shallow water estuarine lagoon, bordered to the east by a Pleistocene quartz sand ridge, and to the west by a Holocene quartz and calcareous sand dune barrier (Figure 1; and Semeniuk 2000). The estuarine lagoon is microtidal, wave dominated and wind current driven, and its waters are annually poikilohaline, with marine, brackish, freshwater, and hypersaline fields (Wurm & Semeniuk 2000). Leschenault Inlet estuary has complex western shores as parabolic dunes encroach into the aquatic environment producing varied stratigraphic/hydrologic situations. The shores support a variety of fringing vegetation linked to the geomorphology, stratigraphy, hydrology and hydrochemistry (Cresswell 2000; Pen *et al*. 2000). Along the tidal zone there is a high-tidal platform, underlain by mud or muddy sand (Semeniuk 2000), inhabited by the sea rush *Juncus kraussii* at the interface between dune barrier and high-tidal platform. The rush forms closed cover, and its roots and rhizomes produce a mat up to 10 cm thick, comprising intertwining roots, root hairs, and rhizomes. Estuarine waters inundate the high-tidal flat surface in winter, and the groundwater table is 5–10 cm below the surface in summer. This high-tidal zone is the location of the calcitic encrustations and laminae, which occur in isolated

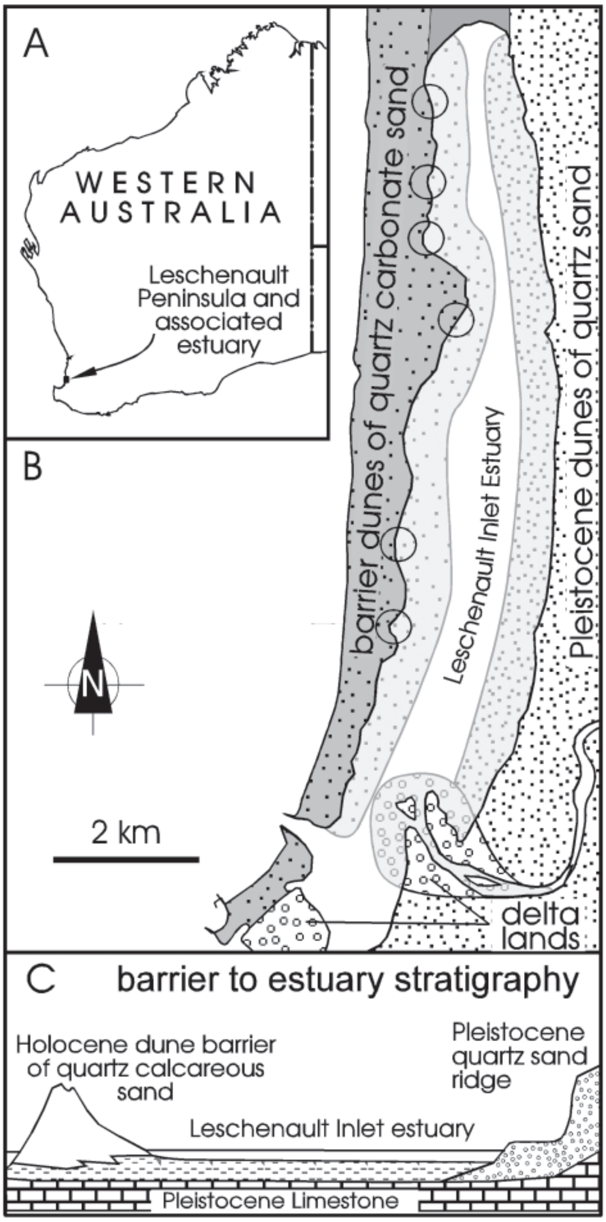


Figure 1. A. Location of Leschenault Peninsula and its associated estuarine lagoon. B. The setting of the Leschenault Inlet estuary between the Holocene dune barrier and the Pleistocene quartz ridge. Circled areas show sampling sites for specimens described in this paper. C. Stratigraphic setting of the Leschenault Inlet estuary (after Semeniuk 2000).

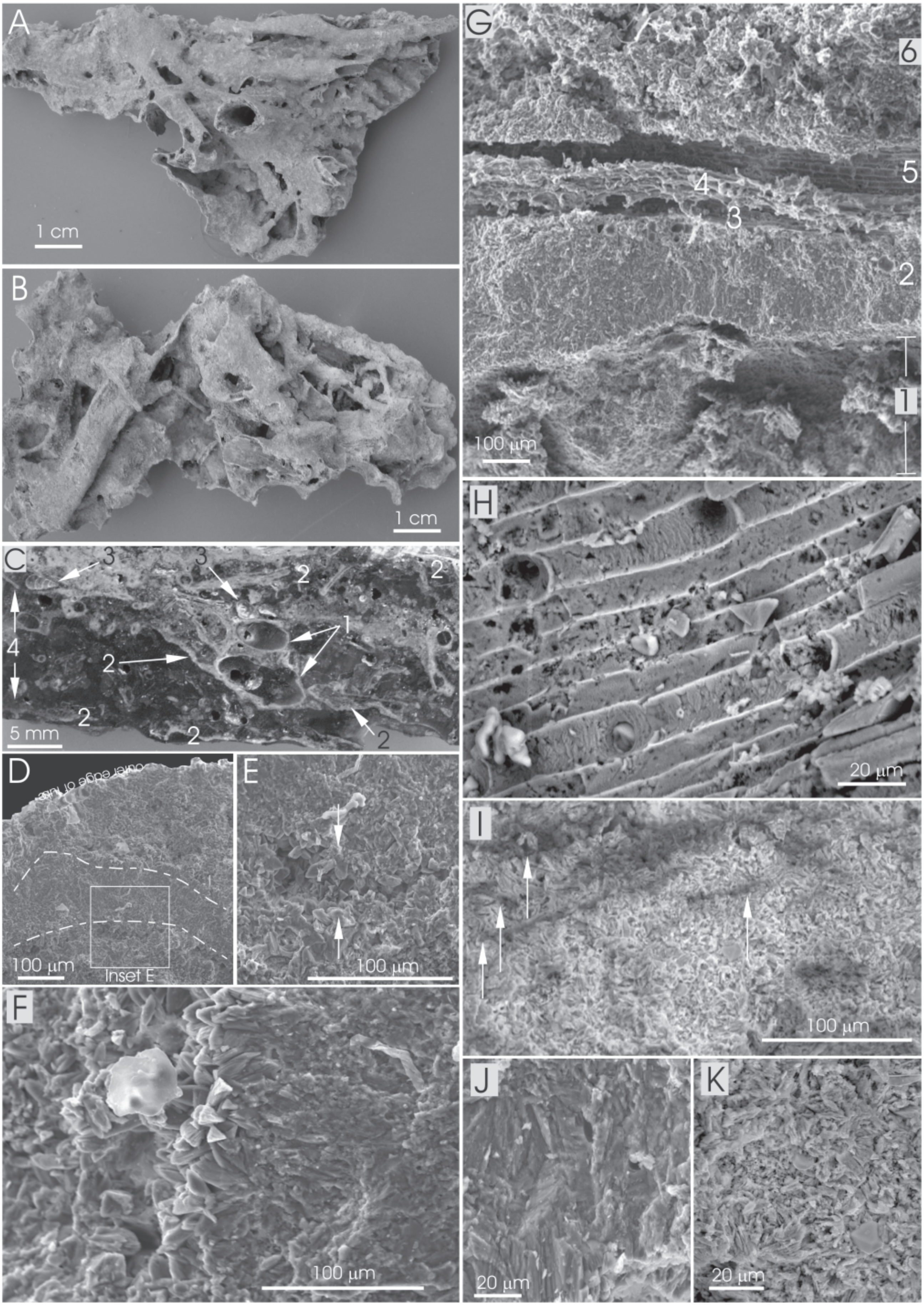
patches and lenses (rather than a continuous shore-parallel ribbon). The calcite precipitations are absent from the quartz sand eastern shore of the estuary.

Within the dune barrier there is a prism of freshwater, bordered to sea and to the estuary by saline waters. Freshwater discharging seawards results in beach rock (Semeniuk & Searle 1987). Freshwater discharging to the estuary results in variable ecological responses (Cresswell 2000; Pen *et al*. 2000; Semeniuk *et al*. 2000), and in precipitation of calcite in the muddy platform. The salinity of the groundwaters under the dune barrier near its margin with the estuary is 500–1030 ppm, and where it interfaces with the high-tidal platform it is 880–1050 ppm (Semeniuk & Meagher 1981; Cresswell 2000; Semeniuk *et al*. 2000). Freshwater seepage from the dunes into the high-tidal mud platform environment has Ca concentrations of 118–124 ppm (Semeniuk & Meagher 1981a). The salinity of the groundwaters under the rushes varies from 630–8300 ppm (Cresswell 2000; Semeniuk *et al*. 2000).

The calcite encrustations and laminae

The precipitates of calcite occur in five forms (Figure 2): 1. as encrustations on *Juncus kraussii* roots/rhizomes; 2. as permineralised plant matter; 3. as permineralised fungal threads; 4. as thin discontinuous laminae associated with the encrustations, or embedded in mud and muddy sand and displacive of sediment; and 5. interstitial to sediment. The encrustations are localised mainly on *in situ* rush roots/rhizomes (Figure 2A and 2B). After the roots/rhizomes have decayed, the precipitation structures are tubular. Since *Juncus kraussii* roots and rhizomes form an inter-twining mat, the encrustations also form an intertwining meandering and branching mass of tubes, as a sheet 1–3 cm thick, commensurate with the thickness of the mat. The geometry and intertwining of the roots and rhizomes are faithfully recorded by the encrustations. Sediment formerly between the roots and rhizomes is incorporated as inclusions in the encrustations, and also is cemented interstitially by precipitate peripheral to the encrustation. The encrustations around plant roots are 400–1500 μm thick with concentric layers, 50–200 μm thick, of varied crystal mosaics and structures (Figure 2D, 2E, 2F, 2G, 2H, 2J): radially oriented bladed crystals (the dominant type), randomly oriented discoid crystals, or permineralised fungal hyphae (2.5–7 μm in diameter and > 200 μm long)

Figure 2. A and B. Horizontal views of exhumed calcitised *in situ* roots and lower stem of *Juncus kraussii*. C. Polished cross section of (a resin-impregnated slab) of calcitised roots of *Juncus kraussii* showing (1) tubes where former roots were encrusted by calcite, (2) laminae of calcite, (3) molluscs encased in the calcitic structure, and (4) calcite-cemented sediment (= dark zone). D–I. SEM images of the samples illustrated in A, B and C. D. SEM image of cross section of the encrustation around a root (the curved outer edge of the tubular encrustation is noted); the dashed lines separate the general trend of three concentric bands within the encrustation. E. Close-up of (D) showing laminoid cavity (positioned between the arrows) embedded in a mosaic of interlocking calcite crystals, with free terminations of calcite projecting into the cavity. F. Close-up of tightly packed bladed calcite, with free terminations projecting into a laminoid cavity. G. SEM image of cross section of the wall of an encrustation around a root. The encrustation shows 6 layers: (1) in the interior of the encrustation, a tangled mass of permineralised fungal hyphae and scattered discoid calcite crystals; (2) a zone of tightly packed bladed calcite crystals oriented long axes radial to the tube; (3) permineralised plant matter, with cell structure; (4) permineralised fungal hyphae; 5. permineralised plant matter showing cell structure; and (6) towards the exterior of the encrustation, randomly oriented discoid calcite crystals. H. Close-up permineralised plant matter showing its cell structure. EDS of five sites in this field of view shows the Mg content of the calcite to vary from 1.6 to 5.5. Mol %. I. SEM image of cross section of a calcite lamina comprised of tightly packed randomly oriented discoid calcite crystals (see K below); four discontinuities in the lamina marking internal (finer laminar) structures are arrowed. J. SEM image showing close-up of a tightly-packed bladed calcite crystal mosaic (oriented vertically) from a root encrustation. K. SEM image showing close-up of a mosaic of tightly-packed randomly oriented discoid calcite crystals from a lamina. ▶


A
1 cm
B
1 cm
C
3
3
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1
4
2
2
2
2
2
5 mm
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outer edge of tufa
100 µm
Inset E
E
100 µm
F
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G
6
5
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100 µm
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I
100 µm
J
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enveloping the *Juncus* roots, or permineralised roots that show plant cell structure Figure 2G, 2H). The encrustations have local lensoid to laminar cavities parallel to the concentric layering, 15–40 μm to 100 μm high, and ~ 150–2000 μm in length, marked by calcite crystals with free terminations (Figure 2E, 2F). Calcite precipitates also form thin laminae interlayered with the root/rhizome encrustations (Figure 2C), or isolated micro-lenses (or platelets) in the mud and muddy sand, and occasionally small nodules. The calcitic laminae and micro-lenses generally form sheets 1.0–0.05 mm thick, that are flat to undulating, occurring at different levels in the upper 30 cm of the sediment profile (Figure 2C). The isolated platelets are 1.0–0.05 mm thick, as small discontinuous bodies (generally varying from 2 cm across to as small as 1 cm across, locally forming larger platelets 5 cm across and 2 mm thick). The more continuous laminae are 20 cm long, and transgress primary sedimentary structures. The small nodules are 2–5 mm in size.

Thin sections and Scanning Electron Microscopy (SEM) show the encrustations, permineralisations, and laminae to be comprised of one or more of five types of calcite aggregates: 1. even textured, epitaxial micro dogtooth spar (with free terminations where they project into cavities or form the outer crust) that predominantly comprise encrustations; they are generally 5–10 μm long, but in some mosaics 10–40 μm long (Figure 2E, 2F); 2. even textured, interlocking, long-bladed spar that comprises encrustations and laminae; they are generally 10–20 μm long, but up to 50 μm long (Figure 2F, 2J); 3. even textured, interlocking randomly oriented discoid crystals (flattened scalenohedra), 5–15 μm in size to 20–40 μm in size, that comprise the laminae and zones in root encrustations (Figure 2K); 4. very fine grained equant crystal aggregates (< 1 μm in grainsize) that comprise the permineralisations of fungal hyphae (zone 4 in Figure 2G), or of plant matter (zones 3 and 5 in Figure 2G), the former occurring as thread-like filaments, the latter showing plant cell structure; and 5. a tangled mass of permineralised fungal hyphae, with embedded scattered discoid calcite crystals (zone 1 in Figure 2G). Within epitaxial crusts in the encrustations and laminae, crystal growth hiatuses are marked by dissolution, and by Fe-oxide and some Mn-oxide precipitates (Figure 2I). For each of the SEM images shown in Figure 2, textural changes, crystal aggregate zones, and permineralisations were analysed for content of Ca, Mg, Fe, and Mn using Energy Dispersive Spectroscopy (EDS). SEM topography and EDS results show that while (low Mg) calcite dominates the mineralogy, Mg substitution in the calcite varies from 1.6 to 10 Mol % Mg, thus Mg-calcite (4–10 Mol % Mg) is also present. X-Ray Diffractometry shows the precipitates to be mainly calcite. Locally, a very thin layer of fine grained dolomite, < 1 μm thick, and composed of crystals < 1 μm in size, coats the encrustations, permineralised materials, and the laminae, but dolomite is a very minor component of the mineralogy.

Discussion

The precipitates of calcite around roots and rhizomes of the rush *Juncus kraussii*, as permineralisations, and as laminae and micro-lenses, in the shore environment of the Leschenault Inlet estuary, provide a Holocene model for similar rhizoliths, permineralisations, and calcitic laminae micro-lenses recorded in the geological record. The hydrogeological setting of the barrier and the precipitates along the shores of the Leschenault Inlet estuary points to Ca^{2+} and CO_3^{2-} charged groundwater discharging as seepages from the quartz and calcareous sand parabolic dunes. In effect, the high-tidal precipitates along the estuarine shore are the hydrogeological and diagenetic equivalent of beach rock that occurs on the oceanic western shore of the dune barrier. The internal features of the precipitates indicate that there is precipitation and dissolution of calcite crystals, with periods of dissolution marked by precipitation of Fe-oxides and Mn-oxides. The rushes and fungi appear to have biomediated the precipitation of the calcite and the metal oxides. The laminae and platelets of calcite, transgressing primary sedimentary structures, indicate that precipitation is related to a groundwater table, and the various levels of the calcitic laminae in the shallow stratigraphic profile record the varying positions of the summer water table.

Rhizoliths recorded from modern lake shores and tidal rivers banks elsewhere globally are different from those of Leschenault Inlet estuary in terms of mineralogy and formative processes. The mineralisation of plant roots around the margins of Lake Bogoria in Kenya forms root casts, moulds, tubules, rhizocretions, and permineralised root systems, and involves a variety of minerals, *viz.*, opaline silica, calcite, zeolites, and fluorite and a variety of hydrochemical processes (Owen *et al*. 2007). Silica precipitation and permineralisation of plant tissues are associated with hot-spring fluids, concentrated by evapotranspiration and capillary evaporation. Calcite precipitation is the result of evaporative concentration, evapotranspiration, and/or CO_2 degassing of Ca-bearing runoff water that infiltrated the sediment, or mixing of runoff with saline, alkaline groundwater. Fluorite precipitation results from mixing of hot-spring and meteoric waters or hot-spring fluids coming into contact with pre-existing calcite. Zeolite precipitation is the result of prolonged periods of aridity when capillary rise and evaporative pumping brings saline, alkaline waters into contact with detrital silicate minerals around roots (Owen *et al*. 2007). On the tidal shore of the Saint Lawrence River, the diagnetic induration of clays as casts around *Juncus* and *Scirpus* plant roots (Rousseau 1934) involves Fe-sulphide alteration of clay around decaying plant roots, and its later oxidation to Fe-oxide and hence induration of a clay envelope around the roots. These provide contrasting mineralogy and mineralising mechanisms for development of rhizoliths to that in the Leschenault Inlet estuary.

To date, calcitisation and permineralisation of rush roots and fungal filaments have not been recorded elsewhere in peripheral vegetation of estuaries in south-western Australia because parabolic dunes and quartz and calcareous sand dunes are not major shore types of these estuaries. Though they have local occurrences of muddy high-tidal platforms, the shores of the Swan River estuary and the Peel-Harvey estuary are bordered mainly by quartz sand terrains (*i.e.*, they are carbonate depauperate), and barrier dunes of the southern coast estuaries are generally also carbonate depauperate. Similarly, calcitised and permineralised rush roots have not even been found on the quartz-dominated eastern shore of the Leschenault Inlet estuary. A carbonate-bearing dune upland, with parabolic dune incursions into the estuarine aquatic zone (and its attendant groundwater incursions and freshwater seepages) would seem to be requisites for the development of calcitic precipitates in the high-tidal zone of an estuary. As such, with the parabolic dune encroaching into the estuary and providing corridors of calcium carbonate charged freshwater seepages (Cresswell 2000), the western shore of the Leschenault Inlet estuary is hydrogeologically and hydrochemically distinct in Western Australia. This situation also renders the western shore of the Leschenault Inlet estuary diagenetically distinctive.

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