Early diagenetic ferruginous cementation in the intertidal zone: example from Noirmoutier Island, France

André STRASSER *, Paul BERNIER b
* Département de Géologie et Paléontologie, Université de Genève, 13, rue des Maréchaux, 1211 Genève 4, Switzerland.
* Département des Sciences de la Terre, Université Claude-Bernard Lyon 1, 27-43, boulevard du 11-Novembre-1918, 69622 Villeurbanne Cedex, France.

Received 29/6/87, in revised form 23/4/88, accepted 3/5/88.

ABSTRACT
An example of sub-Recent, early diagenetic cementation in a siliciclastic and temperate environment is presented. A permeable sand layer in the intertidal zone shows initial stabilization by organic filaments and clay infiltration, and subsequent consolidation by iron-rich cement. The iron was mobilized under reducing conditions in the silty sediment and precipitated in the well-oxygenated sandy layer. Sulphur and phosphorus are present; manganese occurs locally. The surrounding silty sediment is not consolidated. During erosion in the intertidal zone, the preferentially cemented sandy layer is fractured into pebbles.


INTRODUCTION
Early cementation is well known from shallow tropical and subtropical carbonate environments. Rapid consolidation by aragonite and/or calcite cements is particularly well developed in intertidal beachrocks (e.g., Purser, 1980). In siliciclastic and temperate settings, examples of early cementation are less frequent. The cements are commonly calcitic, and iron compounds may be associated.

James (1985) described cementation by calcite, gypsum and limonite in Quaternary sand and gravel deposits. Calcite and siderite nodules have been found in coastal marsh environments (Coleman, 1966; Pestrong, 1972).

Replacement of rootlets by iron oxide has been described by Pestrong (1972). Nelson and Lawrence (1984) showed that in temperate climatic conditions high-Mg calcite cements were formed in the presence of methane released by decomposing organic matter. A particular case has been published by Adams and Schofield (1983): gravels adjacent to a sunken ship off Scotland are cemented by carbonates and hematite. Cementation was stimulated by anaerobic bacteria.

On Noirmoutier Island (Vendée, France), south of the Loire embayment (Fig. 1), we have observed non-carbonate, ferruginous cementation in the intertidal zone. The climate there is temperate (with temperatures ranging from 0 to 25°C). Rainfall is moderate (550 mm...
per year) and occurs mostly in winter. Evaporation in summer is rather high and allows local salt production. Selective precipitation of iron compounds is a common phenomenon in coastal environments. However, ferruginous cements in northern and western France have, to our knowledge, never been studied in detail. The present paper is a case study and illustrates one example of early diagenetic ferruginous cementation.

DESCRIPTION OF THE SEDIMENT

The bay which forms the entrance to the harbour of Noirmoutier (and which has subsequently been modified by the construction of jetties) represents a well protected depositional environment. It is filled with fine-grained sediment (clays and silt) and emerges at low tide. The tidal range is 6 to 7 m. Outside the bay, where water energy is higher, sediments are mostly sands (locally gravels) which are constantly redistributed by tidal currents. Along the main channel leading to the harbour, as well as along some distributary channels of the bay, small cliffs (20 cm to 2 m high) expose the cohesive sediment and allow for the study of sedimentary structures and diagenetic features (Fig. 2a).

The surface of the tidal flat is covered by a greenish mat of cyanobacteria and algae which may attain 2 cm in thickness in summer, but is much reduced during winter. In similar environments, Hommeril (1967) mentions the presence of principally Microcoleus and Lyngbia. The sediment below the mat is dark-grey in colour and displays fine, mm-sized laminations which reflect deposition by tides (Fig. 2b). The layers have been stabilized by organic filaments such as are growing now at the surface. Bioturbations are common and can be attributed to worms (Nereis) and burrowing bivalves (such as Scrobicularia and Macoma) typical of protected environments (Fig. 2c). The burrows are usually lined by a thin oxidized zone. Parts of the cohesive silty-clayey sediment frequently break away due to erosion and form soft pebbles which accumulate at the bottom of the small cliffs (Fig. 2a, b, d). They are transported and rounded by tidal currents, but desin...
tegrate rapidly. Locally, lenses of sand are interstratified. They measure 1 to 7 cm in thickness and display a dark rusty colour. The sand lenses are cemented and produce fragments which are angular and more resistant than the non-cemented silty soft pebbles (Fig. 2d). The sands have probably been washed into the bay during high-energy events such as storms or spring tides. The silty sediment below the sand layer is dark-grey to black. The differences in colour indicate that the limit between oxic and anoxic zones is situated at the base of the cemented lenses, and that oxygen circulated preferentially in the burrows and in the permeable sandy layers (Fig. 3).

The sands are composed of well-rounded, often polycrystalline and fractured quartz grains (50 to 60%), of feldspars and micas (5%), and of shell fragments (5%). The red-yellow colour is due to a ferruginous matrix and cement which are distributed very irregularly and constitute 5 to 10% of the sediment. Porosity varies between 20 and 30%.

**Figure 3**

*Sketch of section in small cliff bordering a tidal channel. The limit between oxic and anoxic zones is situated at the bottom of the sandy layer.*

**ASPECTS AND ANALYSES OF MATRIX AND CEMENT**

Thin sections show that the grains of the sandy layer are commonly bound by organic filaments (algae, cyanobacteria, and/or fungi?). A fine-grained ferruginous matrix and ferruginous cement cover the grain surfaces in irregular patterns and locally form bridges (Fig. 4a, b), thus linking the grains and consolidating the sandy sediment. The bridges resemble meniscus cement, well known from recent and fossil carbonate rocks and indicative of the vadose zone (Purser, 1980; Bernier, 1984). Cementation of the organic filaments may further strengthen the bridges (Fig. 4b, c). The matrix often has a peloidal aspect (Fig. 4a).

Under SEM, matrix and cement can well be distinguished: small anhedral, platy or prismatic crystals form...
the peloids, cover the grain surfaces, and build the bridges (Fig. 4d, f). The cement commonly has an amorphous aspect, as it displays smooth, undulated surfaces (Fig. 4c) and only rarely develops crystal faces (Fig. 4d). It usually covers the fine-grained matrix (Fig. 4d), but can be locally superposed by the matrix (Fig. 4e). The organic filaments are found non-cemented in the pores (Fig. 4b), between matrix and cement (Fig. 4d), or covered by the fine-grained matrix (Fig. 4f).

Mineralogical identification of matrix and cement is difficult. X-ray analyses, performed on powder obtained from scraping the grain surfaces and from washing out loose material in distilled water, indicate only traces of kaolinite.

Microprobe analyses of cement and matrix (including peloids) indicate varying compositions. The bulge at the beginning of the spectra (Fig. 5) points to the presence of badly crystallized or amorphous matter. Representative quantitative data could therefore not be obtained. The qualitative analyses (from which a few spectra have been selected for Figure 5) show the relative abundance of iron. EDAX analyses (Fig. 5b) demonstrate that the cement contains more iron than the matrix. Na, Mg, Al, Si, K and Ca indicate the presence of clay minerals. These show as small platy crystals under SEM (Fig. 4d, f). Si and Ca may also stem from quartz grains and shell fragments underneath the analyzed layer. Phosphorus and sulphur (Fig. 5a) probably originated from organic substances. Manganese can locally be very abundant.

The preferentially cemented sandy layer also displays early diagenetic alterations. Aragonitic and calcitic shells have locally been impregnated by iron-bearing solutions which circulated along grain contacts, crystal boundaries and microperforations (Fig. 6a). Partial dissolution of carbonate fragments on grain contacts is common. Feldspars are altered and locally destroyed (Fig. 6b).

DISCUSSION

Ferruginous cement and matrix occur only in the sandy layer. The silts above and below are not consolidated. Permeability plays an important role in permitting the circulation of fluids which transport the substances necessary for consolidation and cementation. James (1985) noted that in terrigenous deposits the distribu-
ration of the interstitial water, settles on grain surfaces or as internal sediment. The meniscus-shaped bridges (Fig. 4b) clearly indicate the vadose zone.

The close association between clay minerals and iron oxides has been demonstrated in terrestrial environments (Kessler, 1978; Molenaar, 1986), as well as in marine settings (Gygi, 1981). Iron oxides can be transported as fine layers coating clay platelets (especially kaolinite and halloysite; Carroll, 1958).

Microbial activity in the organic-rich silts above and below the sandy layer leads to oxygen depletion and consequently to reduction and solubilization of the iron (Nealson, 1983a). Ferrous iron is mobilized by percolating water or migrates by diffusion. Contact with oxygen in the permeable sandy layer then causes precipitation of ferric hydroxides (Berner, 1980). Transformation to crystalline goethite and hematite occurs later in diagenesis (FitzPatrick, 1980). This path of reduction and oxidation of iron is common in soils (FitzPatrick, 1980; Molenaar, 1986). Manganese is mobilized and reprecipitated in a similar manner (Buurman, 1980; Nealson, 1983b). The early stage of decomposition of sedimentary particles (Fig. 6) is probably due to organic acids produced by microbial activity (Berthelin, 1983; James, 1985).

Sulphur is present in seawater and organic molecules and drives the microbial sulphur cycle in sediments (Jørgensen, 1983). Phosphorus is released after decay of organic material (in estuaries mostly marsh grass and benthic algae; Pevear, 1966). These elements occur in grain coatings, matrix and peloids of the sandy layer (Fig. 5).

The sandy layer exhibits a selective and preferential cementation due to its high permeability, the particular physical and chemical properties of its interstitial waters, and the (direct or indirect) influence of microbial activity. Erosion by tidal currents and storms removes the non-consolidated silty sediment, whereas the cemented sandy layer is fractured into pebbles. In the fossil record, such pebbles may be the only relics of an eroded intertidal zone.

Acknowledgements

We thank Eric Davaud and three anonymous reviewers for their constructive comments on the manuscript. Jean Wüst carried out the SEM photography, Roland Oberhansli the microprobe analyses, Dave Adams the EDAX analyses. Their help is gratefully acknowledged. Travel to Noirmoutier and the stay on the island for A.S. were financed by the Swiss National Science Foundation as part of project No. 2.897.083, for P.B. by the Unité Associée No. 11 of the French CNRS.

REFERENCES


