Sandstone cementation and its geomorphic and hydraulic implications.

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Introduction

Mineral cement is the most important intrinsic factor in estimating erosion rates in sandstone regions. Its composition is a function of mineral availability in the basin and burial/thermal history of the basin. Post-depositional tectonic setting of particular segments of the basin may then control cement distribution, especially through differential fluid circulation. Most cemented sandstones are relatively resistant to weathering in outcrops, giving rise to a variety of forms of positive relief. In the subsurface, however, where flushing rate is higher, silica and carbonate cements get readily dissolved producing large volumes of easily eroded loose sand. Impressive solutional forms in quartzite can be observed in tropical (Chalcraft & Pye 1984), subtropical (Busche & Erbe 1987) as well as temperate (Battiau-Queney 1984) climatic zones, and quartz dissolution is considered a process playing a major role in the karstification of even weakly cemented quartzose sandstones worldwide (Wray 1997).

Silica cement

The very low solubilities of quartz at normal pH and temperature (~5 ppm) rapidly increase with increasing pH values, especially above the pH of 9.83 which corresponds to the first dissociation constant of silicic acid (Eby 2004), reaching values of >20 ppm at pH 10 and 25 °C. Comparable solubilities of quartz can be also achieved by rising temperature: at normal pH, 20 ppm SiO_2(quartz) dissolve at temperatures of around 50 °C. Solubilities of cryptocrystalline and amorphous silica are by one order of magnitude higher than those of crystalline quartz. Laboratory experiments are consistent with observations from deeply buried sandstones where secondary quartz overgrowths typically appear on detrital quartz grains at depths of over 1 km and temperatures of over 40 °C (McBride 1989). The main source of diagenetic silica is pressure solution at grain contacts and stylolites, and conversion of primary clay minerals due to sediment burial.

Where rapid silica precipitation takes place, chalcedony and opal are the dominant phases. This is the case of hydrothermally mobilized SiO_2 in areas of siliceous hot springs (Guidry & Chafetz 2003) or near contacts of sandstone with volcanic bodies.

A wide range of silica phases are present in silcretes, products of surface and near-surface diagenesis generally conforming to surface topography and formed either within a weathering profile or at stable groundwater levels. Silica mobilization in such settings (normal pH and low temperatures) is explained by high flushing rates over a prolonged time. The best known silcrete examples in Europe are the Fontainebleau sandstone in France (Thiry *et al*. 1988) and the sarsen and puddingstone sandstones of southern England (Hepworth 1998).

Carbonate cement

Unlike silica, carbonates can be transported in solutions of low pH and low temperature. Calcite, dolomite and siderite cements generally form patchy, strata-bound bodies in the sandstone, or isolated concretions. $CaCO_3$ is mostly derived from shells and skeletal remains of fossil organisms, or is precipitated directly from pore waters. Carbonate cement is of early diagenetic origin, and its precipitation predates deeper sediment burial.

Ferruginous cement

Iron is mobile in its bivalent form, in environments of low redox potential. In oxidative environments, within the reach of meteoric waters, ferrous iron turns into ferric iron which is difficult to mobilize, unless by fluids of very low pH.

Red colouration of sandstones (commonly referred to as red beds) indicates the presence of ferric iron: dispersed goethite/limonite after weathering of iron-rich detrital minerals, which gets transformed into hematite grain coatings after burial-induced goethite dehydration. Small amounts of cement in the red-beds sandstones have, however, only a weak effect on their permeability or geomorphic expression. Massive filling of pores in sandstone by hematite and/or goethite to form sheet-like, tube-like and spherical concretionary bodies of ferruginous sandstone is caused by fault-parallel circulation of saline fluids and hydrocarbons in the red-beds sandstones (Navajo Sandstone, Utah - Chan *et al*. 2000) or fluids laden with Fe^{2+} from the adjacent volcanic bodies (Bohemian Cretaceous Basin, Czech Republic - Adamovič *et al.* 2001).

Lateritic horizons are formed by in situ chemical weathering of rocks under tropical humid conditions favouring removal of alkalis, alkali earths and silicon and enrichment in iron and aluminium. A related term ferricrete was introduced for surface sands and gravels cemented into a hard mass by iron oxide derived from the oxidation of percolating solutions of iron salts. The process of pedogenic laterite formation is equivalent to podzolization in temperate humid regions, leading to the formation of Ortstein.

Cementation and permeability

Less permeable sheet-like and concretionary bodies of early cemented sandstone tend to be elongated parallel to the groundwater flow and are often hosted by pre-existing higher-permeability fault and fracture zones. This way, early cementation may control the direction of later fluid flow and seal the tectonically predisposed paths of fluid ascent from the basement rocks. A series of drawings in Fig. 1 schematically illustrates a progressive hydraulic compartmentation of a sandstone-filled basin after three consecutive episodes of cementation.

Porosity reduction due to quartz and chalcedony cementation of quartzose sandstone has been documented at Milštejn, northern Bohemian Cretaceous Basin, Czech Republic (Adamovič & Kidston 2004). Total porosity was measured on a profile transverse to a phonolite dyke, which supplied alkaline fluids responsible for silica redistribution. A 12 m broad proximal zone of secondary porosity due to quartz dissolution (limited outcrops but large cavities nearby) passes to a 3–5 m broad zone where porosity drops to 5 % due to grain compaction, pressure solution and microquartz precipitation. Lenses 0.2 m thick of chalcedonized sandstone with only 0.5 % total porosity follow a subvertical brecciation zone. At 22 m from the dyke, porosity increases to 25 % in a sandstone with occasional quartz overgrowths.

Cementation and morphology

Cemented sandstones are generally more resistant to weathering and form positive relief. Large cementation-induced landforms include plateaus and table mountains, ridges and walls. Rock mushrooms, arches and bridges with tops of cemented sandstone are the typical landforms on plateau rims. Microforms like ledges, knob- and tube-shaped protrusions as well as fine sculptation on rock walls are generally controlled by uneven cement distribution and the presence of concretions. In contrast, silicified sandstones shaped by silica dissolution tend to form negative relief (spherical cavities, caves) and have the appearance of karst forms in carbonate rocks. Parallels with carbonate karst also exist in the presence of accumulation forms of silica speleothems (Wray 1999).

In the Bohemian Cretaceous Basin, uneven cementation of thick bodies (>100 m) of quartzose sandstone with iron oxyhydroxides and silica results from their interaction with intrusive and effusive bodies of volcanic rocks, and produces a variety of landforms of various size (Müller 1928; Adamovič *et al*. 2001; Adamovič & Cílek 2002).

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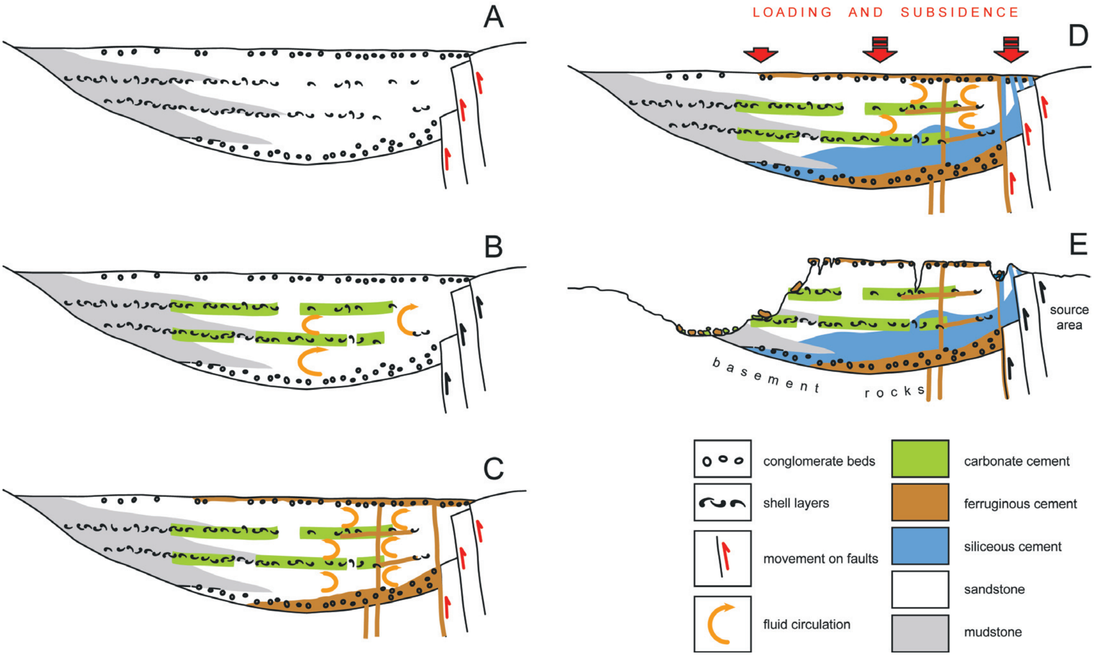

Fig. 1: A model example of the evolution of a sand-dominated sedimentary basin subjected to three stages of cementation. **A.** Sandstone packages thin away from the tectonically active basin margin on the right (source area), with conglomerate beds and shell layers preserved on sequence boundaries/flooding surfaces. **B.** Compaction of the basin fill is accompanied by formation of poikilotopic calcite cement in shell layers. **C.** Tectonic reactivation results in pulses of iron-rich fluids from the basement rocks and precipitation of ferruginous cement in high-permeability zones. **D.** Tectonic subsidence of the basin produces silica cementation along faults and in deeper-buried parts of the basin (quartz overgrowts). **E.** After tectonic inversion and emergence of the basin fill, cemented sandstones show higher resistance to weathering and erosion. Note the increasing compartmentation of the basin during its evolution, restricting the fluid circulation.

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Résumé de la présentation

Le liant du grès et ses implications géomorphologiques et hydrauliques

Mots-clés: Grès; Ciment silicieux; Ciment de carbonate; Ciment ferrugineux; Paléohydraulique; Géomorphologie; Reliefs de paysages de grès

Les ciments siliceux, ferrugineux et de carbonate sont les constituants secondaires les plus communs des grès, remplissant souvent complètement tous les espaces intergranulaires. La présence du ciment minéral rend nécessaire, d'une part, une source interne ou externe au bassin sédimentaire des éléments requis, d'autre part, la mobilisation des fluides de chimisme appropriée, du pH, et de la température pour transporter ces éléments. Et en final, rend nécessaire, la mise en place des conditions physico-chimiques dans la fenêtre de stabilité des minéraux de cimentage particuliers au bassin sédimentaire.

La variété des ciments minéraux dans les grès est une fonction du chimisme du fond du bassin, de la présence de corps intrusifs et extrusifs à proximité du bassin, et de l'histoire tectonique du bassin, particulièrement la profondeur d'enfouissement du sédiment.

Après enfouissement profond (à des profondeurs supérieures à 2,5 km), les minéraux primaires d'argile de même que les grains détritiques de quartz sont modifiés en silice mobile. La précipitation de cette silice, la plupart du temps sous forme de croissance syntaxial de quartz sur des grains de quartz eux-mêmes peut mener à la diminution importante de porosité sur de grands volumes de grès enfouis. Une faible dissolution du quartz, se produit même à des températures et des pressions beaucoup plus basses, comme mis en évidence par la silicification de grès le long des corps des roches volcaniques alcalines et par des exemples multiples de karst de quartzite partout dans le monde. Le ciment de carbonate a la plupart du temps une provenance interne au bassin, dérivé des coquilles de mollusque mises en solution lors des premières étapes de la diagenèse du sédiment. Les sources du fer pour le ciment ferrugineux peuvent être multiples, s'étendant des minéraux détritiques riches en fer présents dans le bassin aux roches encaissantes mafiques (foncées).

Comme la distribution du ciment est commandée par le flux de fluide dans le bassin, les corps concrétionnés ou en forme de feuillet du grès cimenté tendent à être allongés parallèlement au paléoflux des eaux souterraines et sont souvent accueillis par des zones de faille ou de fracture de haute perméabilité. Le ciment précoce réduit la porosité du grès, et de ce fait, limite les mouvements de liquide dans le bassin en soutenant une modification du compartimentage hydraulique.

Les grès cimentés sont généralement plus résistants à l'altération et forment des reliefs positifs. Les formes de relief de ces cémentation induites sont de diverses tailles, depuis des plateaux et des 'montagne-table', arêtes et murs, rebords de roche en forme de champignons, de bouton et de tube comme autant de fines sculptures dans les murs de roche. Beaucoup de formes de relief dans les grès silicifiés ont été dessinées par la dissolution de silice et partagent le caractère des formes de karst des roches carbonatées.

Les principes donnés peuvent être illustrés par des exemples de, par exemple, des paysages tempérés de la République Tchèque et de l'Angleterre ou des paysages arides du sud-ouest américain.

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