Carbonate concretions as proxy for methane-enriched fluid flow in high-porosity sandstone: example from the Crotone Basin, Italy

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1. Introduction: Selective cementation in siliciclastic sequences is crucial for the exploitation of reservoirs, easing the definition of available volumes and the quantification of petrophysical properties. We propose a study focused on the selective cementation of a coarse-grained, high-porosity siliciclastic sequence.

2. Geological setting: The studied analogue is in the Crotone Basin, South Italy, where an Early Pliocene, fluvial to deltaic formation is affected by selective cementation.

3. Outcrop description: The studied formation onlaps above the Sila Massif crystalline basement and is made of very coarse-grained sandstone beds dipping 5-15° towards SE.
Beds are affected by brittle deformation in the form of deformation bands and secondary faults. Host sandstone preserves high porosity and is almost devoid of diagenetic cement.

Concretion type	Concretion shape	Size (m)	Main geometrical features
A	Single elongate	0.1 - 0.5	Bedding-parallel drop-shaped bodies
B	Coalescent elongate	0.5 - 3.0	Bedding-parallel elongate merged bodies
C	Elongate cigar-shaped	5 - 100	Bedding-parallel cylindrical bodies
D	Tabular	0.3 - 4.5*	Bedding-parallel lens-shaped bodies
E	Globular bodies at joint tips	0.1 - 0.3	Masses at joint tips in tabular concretions
F	Spherical	0.1 - 0.8*	Bedding-parallel spherical-shaped bodies
G	Nodular	0.1 - 2.5	Irregularly-shaped bodies
H	Elongate bodies along faults	0.5 - 1.5	Fault-parallel elongate bodies

4. Diagenetic bodies: Diagenetic concretions comprise tabular, laterally-extensive and m-thick concretions, which are affected by joints and deformation bands.

Single to coalescent elongate concretions developed parallel to sandstone bedding, with length from 10 cm up to ~100 m.

Spherical concretions with diameters up to 30-60 cm occur, while nodules form irregular masses composed of several merged single elements.

Nearby deformation bands and faults, elongate concretions show elongation directions parallel to the fault dip direction and are no longer sub-horizontal.

5. Petrophysical properties: Selective cementation operated by calcite precipitation produced a diminishing of primary porosity down to 1-2%, a drop of permeability up to 3-4 orders of magnitude compared to the host sandstone, with a marked increase in sandstone stiffness (45-75 Q-value) as indicated by relative rock strength measurements.

Concretionary bodies preferentially developed in very coarse-grained sandstone beds with fine gravel content up to 25% of total sample volume.

6. Diagenetic cement textures: The loss of primary porosity is given by the precipitation of non-ferroan calcite.
Considering all concretions, four different cement types can be recognized:
(1) Circum-granular and isopachous rims of equant-shaped, pore-lining, calcite crystals with 20-30 µm size. Along siliciclastic grains, the crystal rims are often incomplete, while are more developed around bioclasts. This is the most common cement type in weakly cemented concretions.
(2) Sparitic granular pore-filling calcite with 100-120 µm crystal size found in tabular and elongate concretions.
(3) Sparitic granular pore-filling calcite with drusy texture and crystal size up to 200-250 µm with dusty appearance given by solid inclusions characterizing tightly cemented concretions.
(4) Sparitic blocky-granular pore-filling calcite with crystal size up to 400 µm documented in elongate and tabular tightly cemented concretions.

All cement types are characterized by bright yellow to orange color under cold cathodoluminescence and the fourth cementation stage shows subtle zonation rims.

Within deformation bands and secondary faults, porosity drop is also related to the mechanical comminution imparted by granular flow and cataclastic deformation processes.

7. Cement stable isotope geochemistry: Calcite C-O isotopes show a shift from a mixing between meteoric and marine fluids with contributions of CO_2 from percolation through soils, towards more shallow marine fluids with methane signature likely related to biogenic activity. Spherical concretions display symmetrical (center to edge) isotopic variations, while elongate bodies display asymmetrical isotopic patterns.

8. Concretion nucleation and growth: Concretions started to develop from cementation nuclei (bioclast, detrital calcite grains). The final shape of concretions is the result of areal distribution of cementation nuclei and fluid flow dynamics through the porous host sandstone. Tabular and elongate bodies can be related to laterally extensive advective fluid flow, while spherical and nodular concretions formed under diffusive flow.

9. Discussion and conclusions: The selective cementation affecting the studied siliciclastic sequence is related to sustained fluid flow with evolving chemical composition through time.
Cementing fluids shifted from meteoric to marine ones with a gradual increase of low-temperature methane. The origin of methane can be traced in the biogenic activity within the sulphate-rich (gypsum and anhydrite) Evaporite formation underneath the studied siliciclastic sequence.

The differential overburden promoted the migration of fluids towards the basin margin where fluids were vertically channellized along basin boundary fault system which provided the hydraulic gradient needed to drive fluids through the porous sandstone.

Concretions developed according to the outward growth model and could be used as proxy to trace fossil surficial fluid flow in high-porosity reservoir analogues.

Selective cementation led to strong modifications of the petrophysical properties of the host rocks. We documented a decrease of porosity down to 1-2%, a drop of permeability of 4 orders of magnitude compared to the host rocks, and an increase in sandstone cohesion. The increase of cohesion is testified by the different deformation mechanism documented in the concretions (brittle jointing) compared to the host rock (deformation banding).

Further readings:

Balsamo, F., Storti, F., and Gröcke, D., 2012, Fault-related fluid flow history in shallow marine sediments from carbonate concretions, Crotone basin, south Italy: Journal of the Geological Society, London, v.169, p. 613–626.

Pizzati, M., Balsamo, F., Storti, F., Mozafari, M., Iacumin, P., Tinterri, R., and Swennen, R., 2018, From axial parallel to orthogonal groundwater flow during fold amplification: insights from carbonate concretion development during the growth of the Quattro Castella Anticline, Northern Apennines, Italy: Journal of the Geological Society, London, v. 175, p. 806–819.