E07

Fault-controlled Carbonate Cementation along Leaking Faults - Implications for Diagenetic Fault Sealing

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SUMMARY

Carbonate fault cement can lead to effective sealing of faults that act as conduits for upward fluid flow. In conductive faults, fluid flow, and thus cementation, is typically focused along fault intersections, extensional steps, and fault terminations. Based on the analysis of four carbonate-cemented faults, I propose that carbonate fault cements form by 1. the microbial oxidation of hydrocarbons and 2. exsolution and degassing of CO2 during rapid upward fluid flow. Depending on the quantity and distribution of oil migration, microbial oxidation of oil can lead to discontinuous cements and thus ineffective seals. In contrast, oxidation of migrating methane is observed to lead to effective fault seal. Degassing of CO2 during upward flow can also lead to effective fault seal provided pressure gradients are steep in the flow direction. Under subsurface conditions, steep pressure gradients are expected for coseismic seal failure and rapid fluid flow.

The sealing behavior of faults has received wide attention in recent years, with most emphasis given to the effects of juxtaposition, shale smear geometry, and fault rock composition and texture on cross-fault flow. Diagenetic fault seals and fault-parallel fluid flow or leakage have received less attention. As a consequence, diagenetic seals and fault leakage behavior are not routinely considered in industry fault seal assessments. Carbonate cement is common along leaking faults in sedimentary basins and, given the right flow and reaction conditions, can lead to self-sealing of flow conduits. Seismic imaging of fault cements can provide an indication of fossil hydrocarbon migration pathways and reservoir spillways for trap integrity analysis.

This study compares four leaking faults and associated diagenetic sealing processes in different structural and depositional settings to assess mechanisms of fault sealing by carbonate cementation and their efficiency for fault seal. All four examples are paleo-flow systems that are exposed in surface outcrops. Key characteristics of these faults are summarized in Table 1.

The Moab fault in east-central Utah is a normal fault with extensive calcite cementation of the eolian sandstone sequence in the segmented central portion of the fault system (Chan et al., 2000; Foxford et al., 1996; Garden et al., 2001; Eichhubl et al., 2009). Calcite cementation is localized in the vicinity of fault segment intersections, fault steps with releasing geometry, and fault terminations. Calcite cement occurs as concretions and veins where the fault damage zone is composed of joints. The spatial association of calcite with dead oil ("bitumen") and carbon isotopic trends suggest that carbonate cementation resulted from microseepage of hydrocarbons into a meteoric aquifer and microbial hydrocarbon degradation. Carbonate cementation of the porous eolian sandstone is discontinuous providing an incomplete seal. While fault-parallel flow may be impeded within the brecciated and cemented fault core, flow would be enhanced relative to the host sandstone in the incompletely cemented fractured fault damage zone.

The Refugio-Carneros normal fault in the Santa Barbara basin, California, is extensively cemented with blocky and acicular calcite at the fault terminations, effectively sealing the fault core and damage zone. Layers of entrained detrital material in banded calcite cement indicate pulses of upward fluid flow. Carbon isotopic values as low as -41‰PDB are consistent with carbonate precipitation by oxidation of thermogenic methane under meteoric conditions (Boles et al., 2004).

The Jalama strike-slip fault in the western Santa Barbara basin is hosted in siliceous dolostone of the Miocene Monterey Formation. Layered botryoids of dolomite and minor quartz effectively cement the fault core and damage zone within an extensional fault step. Fluid inclusion and oxygen isotopic analyses suggest dolomite precipitation from rapidly upward moving formation water and exsolution and degassing of CO_2 (Eichhubl and Boles, 2000a, b; Martin and Rymerson, 2002).

The Little Grand Wash normal fault in east central Utah is locally cemented with calcite and aragonite cement around fossil and active CO_2 seeps. Calcite forms banded fault and fracture cement and pore cement in the adjacent host sandstone (Shipton et al., 2004) creating an effective fault seal in otherwise permeable host sandstone.

All four examples demonstrate that cementation is associated with upward fault-parallel fluid flow which is focused within structurally controlled flow conduits or fault pipes. Based on the source of carbonate, cementation reactions can be classified into two basic types: microbial degradation and oxidation of hydrocarbons in contact with meteoric water, and CO_2 exsolution and degassing of rapidly upward moving fluids. The Moab fault demonstrates that carbonate cementation by microbial degradation of oil is controlled by the quantity and distribution of oil in the fault core and damage zone, potentially leading to discontinuous cementation, and thus ineffective sealing. Methane oxidation, the inferred cementation reaction along the Refugio-Carneros fault, provides conditions for effective fault sealing where faults are connected to a source of methane. Both types of reactions require oxygenated conditions and are thus limited to areas of groundwater influx. CO_2 degassing, causing carbonate cementation at the Jalama and Little Grand Wash faults, is not limited to shallow meteoric environments but requires a steep pressure gradient for CO_2 exsolution for effective fault sealing. Under reservoir conditions, steep pressure gradients are expected for rapid, possibly co-seismic, upward fluid flow. On the other hand, carbonate fault cementation is expected to be ineffective where upward flow is slow and where chemical and pressure gradients are subtle in the flow direction.

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Table 1. Key characteristics of four carbonate fault seals.

	Moab fault, Utah Courthouse-Mill Canyon	Refugio-Carneros fault, California	Jalama fault, California	Little Grand Wash fault, Utah
Displacement	390 m normal	150 m normal	~100 m strike-slip	210 m normal
Mineralogy	Calcite (ankerite)	Calcite	Dolomite (quartz)	Calcite, aragonite
Structural control	Fault segment intersection, extensional step, terminations	Fault terminations	Extensional step	Segment boundaries
Precip. temperature	Up to 125°C	83-104°C	Up to 100°C	cold (?)
Carbonate $\delta^{13}C$	0 to -15‰ PDB	-10 to -42‰ PDB	-4 to -24‰ PDB	+4 to +6‰ PDB
Precipitation reaction	Microbial oil degradation	Oxidation of methane	Rapid upward flow CO_2 degassing	CO_2 degassing
Pore fluid chemical environment	Mixing of brine with meteoric water	Mixed saline formation water/ meteoric water	Saline formation water	Mixed brine/ meteoric water
Diagenetic fault sealing	Moderate to good in fault core, poor in damage zone; permeable host rock	Good in fault core and damage zone; permeable host rock	Very good in fault core and damage zone, tight host rock	Good in fault core and vicinity of fault, permeable host rock
Selected references	Chan et al. 2000; Foxford et al. 1996; Garden et al. 2001; Eichhubl et al. 2009	Boles et al. 2004; Appold et al. 2007	Eichhubl & Boles 2000a, b; Martin & Rymerson 2002	Shipton et al. 2004