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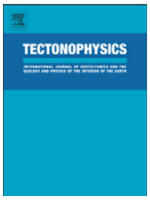

Evolution of fault permeability during episodic fluid circulation: Evidence for the effects of fluid–rock interactions from travertine studies (Utah–USA)

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ABSTRACT

Faults are known to be important pathways for fluid circulation within the crust. The transfer properties along faults can evolve over time and space. The Little Grand Wash and Salt Wash normal faults, located on the Colorado Plateau, are well known examples of natural CO_2 leakage systems from depth to surface. Previous studies dated and established a chronology of CO_2-enriched fluid source migration along the fault traces and linked the aragonite veins observed close to Crystal Geyser to CO_2-pulses. However, multiple circulation events recorded along a given fault segment deserve to be studied in minute detail in order to unravel the chronology of these events, precipitation processes and associated mechanisms. A combination of structural geology, petrography, U/Th dating, oxygen and carbon isotope analysis were used to study the fault related CO_2-enriched paleo-circulations in order to build a conceptual model of CO_2-circulation along the faults. This study resulted in the precise descriptions of the features attesting CO_2-enriched fluid circulation by a characterization of their relationship and architecture at the outcrop scale. These features are witnesses of a large range of circulation/sealing mechanisms, as well as changes in fluid chemistry and thermodynamic state of the system, providing evidence for (i) the evolution of the fluid through a pathway from depth to the surface and (ii) different cycles of fault opening and sealing. Large circulation events linked with fault opening/sealing are observed and calibrated in nature with millennial circulation and sealing time-lapses. Numerical modelling indicates that such sealing time-scale can be explained by the introduction of a fault sealing factor that allows modifying permeability with time and that is calibrated by the natural observations.

1. Introduction

Fluid advection (Cox and Etheridge, 1989), channelled along crustal faults, regularly occurs in the Earth's crust (Marques et al., 2010; McCaig, 1988). Faults represent main pathways for fluid flow from deep reservoirs up to the surface, but faults can also act locally as impermeable barriers (Person, 2007). Consequently, faults may successively act as open or closed pathways. Their opening can be triggered by earthquakes, fluid overpressures or localized dissolution (Gratier and Gueydan, 2007). Their closure can be linked to progressive sealing due to mechanical (Eichhubl et al., 2000; Hancock, 1999; Solum et al., 2010), and chemical processes (Renard et al., 2009). Consequently, the relative fluid transfer properties change in space and time within natural faults, i.e. porosity and permeability variations may occur (Kopf et al., 2000). These are crucial controlling parameters in relation to earthquake chronology and frequency (Fitzenz and Miller, 2001; Gratier, 2011; Micklethwaite and Cox, 2004).

Exhumed examples of such systems are located in the Colorado Plateau, namely the Little Grand Wash (LGW) and Salt Wash (SW) normal faults. These sites provide a way of observing the natural CO_2 circulation along faults and the leakage at the surface that has taken place over thousands of years. The investigated area provides a unique opportunity to collect direct data to calibrate fault-related discharge. The leakage of CO_2 along faults has been identified and documented in previous studies showing a spatio-temporal migration of CO_2-enriched fluid

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leakage zones along the faults (Burnside et al., 2013; Dockrill, 2005; Dockrill and Shipton, 2010; Kampman et al., 2012; Shipton et al., 2004). This leakage has been evidenced to start at least 400 ka ago and the U–Th dating of aragonite veins indicates that the recorded CO_2 pulses can be related to glacial cycles (Kampman et al., 2014). However important questions remain to be addressed: i.e. (i) Can the structure and the processes of the circulation pathways from depth to the surface be unravelled by a close analysis of the different features attesting paleo-fluid flows observed in the fault zones? (ii) What are the fault opening and sealing mechanisms and their evolution with time?

The partially exhumed LGW and SW faults offer the possibility to examine the link between the fault activity and the fluid flow history recorded along a given fault segment. In order to unravel the precipitation conditions, this study focuses on a close study and classification of observations of paleo and modern circulation made along the faults, from structural field observations to thin-section petrographic analyses. In addition, the opening and sealing time-lapses of selected compact veins has been constrained by precise U/Th dating and stable isotope analyses. Finally, the influence of the fault sealing on the duration and rate of fluid flow circulation is numerically tested. A post-seismic sealing process of the fault is incremented in a numerical model of Darcy flow in order to understand the reasons why and how the circulation decreases and stops along a fault, depending on the relative value of various parameters such as the fault structure and the fluid flow properties (Faulkner et al., 2010; Miller, 2013). Using an exponentially decreased evolution of the permeability with time, we finally discuss our results which explain the sealing time-lapses observed in nature and provide an evaluation of the fault sealing factor.

2. Geological settings

LGW and SW faults are located in Utah within the northern part of the Paradox Basin (Fig. 1A). This study area is located at the front of the extensive Sevier Fold-and-Thrust Belt that borders the western and northern part of the Colorado Plateau. The structure of the Paradox Basin results from a complex structural history well summarized by Peterson (1989), Hintze (1993), Barbeau (2003) and Trudgill (2011). The NW–SE Paradox Basin developed as a foreland basin with the Uncompaghre Uplift. High subsidence rates made the basin filled with thick Paleozoic sediments reflecting alternation of deep marine and very shallow water restricted depositional environments (Barbeau, 2003). Since Permo-Triassic times, these ductile evaporitic layers largely influenced the tectonic style in the Basin, by salt diapirs and development of large roll-overs (Hintze, 1993). From Cretaceous to Oligocene, the NE/SW Sevier and Laramide orogenies reactivate the fault system formed by the Permian the Basin elongation, such as the Moab fault, Lisbon Fault, Little Grand Wash and Salt Wash faults (Pevear et al., 1997; Solum et al., 2010). The Laramide thick deformation also resulted in basement inversions such as the San Raphael Swell and Monument uplift (Fig. 1.A). Finally, the current rising of the Colorado plateau and E/W Basin and Range tectonics keep the zone under an active extensional regional stress.

Ten Mile graben and Crystal Geyser areas (Fig. 1B, C) constitute the main CO_2 leakage zones along the LGW and SW faults respectively. Modern and paleo-leakages of CO_2-enriched water are documented by the occurrence of active and fossil travertines (Fig. 1B, C, D). In this article, we follow and extend the travertine designation adopted in the Dockrill thesis (2005). For that reason, the classification begins in Crystal Geyser area, labelling the active travertine T0 and the 4 ancient travertine mounds T1, T2, T3 and T4 (Fig. 1C, D, E), incrementing from the east to the west. In Ten Mile graben, two ancient travertine mounds are located close by the modern bubbling sources (Ten Mile Geyser and Ten Mile spring) and are called T5 and T6 (Fig. 1B, E). Toward the east, other ancient travertines have also been spotted along SW fault; we called T7 the major outcrop of this series (Fig. 1B).

Travertine is a term used to qualify carbonate precipitations under near ambient conditions in continental areas (Crossey et al., 2006; De Filippis et al., 2011, 2013b,c; Pentecost, 2005). In the study zone, modern travertines are currently formed by CO_2 bubbling springs and geysers. The fossil travertines, where CO_2 sourcing stopped some while ago, have been formed from less than 1 ka to 400 ka BP (Burnside, 2010). These endogenic travertines are characterized by a complex structure but overall two main features can be distinguished, i.e.: "surface travertines" and "travertine veins" (Altunel and Hancock, 1993; De Filippis and Billi, 2012; De Filippis et al., 2013a). The term "surface travertine" is used for the layered carbonate deposition that formed at the surface, whereas the term "travertine veins" corresponds to the travertines formed in fractures at shallow depth (Hancock et al., 1999) (Figs. 2 & 3). The travertine veins are mainly formed from aragonite and have a heavy $\delta^{13}C$ composition ranging from $+4.4‰$ to $+7.2‰$ (Burnside, 2010; Dockrill and Shipton, 2010; Heath, 2004; Kampman et al., 2012) indicating a thermogenic origin based on Pentecost's definition (2005). The term "thermogenic" here relates to the deep underground CO_2-enriched water supply rather than the current water temperature as usually referred to in many travertine studies (Bargar, 1978; Curewitz and Karson, 1997; De Filippis et al., 2012; Sella et al., 2014; Uysal et al., 2007, 2009; Vignaroli et al., 2014). For instance, in Crystal Geyser area the leaky bubbling water temperature is about 17 °C. At depth, the CO_2 is dissolved in the water and the exsolution takes place within the 100 uppermost meters below the surface (Assayag et al., 2009) and the CO_2 arrives at the surface in two phases, namely dissolved in the water and as free gas. At present day, the gas sampled in the Geyser bubbles contains more that 98% of CO_2, with a $\delta^{13}C$ (CO_2) ranging from -7.6 to $-5.7‰$ (Gilfillan et al., 2008, 2009; Jandel, 2008; Jandel et al., 2010) indicating an inorganic origin of the $CO_{2,}$ probably resulting from reactions within the crust or mantle. This $\delta^{13}C$ range likely indicates an overlap between "crustal" and "mantle" CO_2 (Wycherley et al., 1999). Stable oxygen and hydrogen isotope data demonstrated that about 90% of Crystal Geyser water comes from a shadow groundwater (Kampman et al., 2009). However, the chemical and isotopic analyses of the water of Green River area, and of the pore water from an oil field (Greater Aneth) located some 150 km to the SE of Green River, suggest a mix origin from the regional Jurassic Navajo aquifer and the Paradox Basin brine (Heath, 2004; Shipton et al., 2004).

3. Methods and sampling

This study integrates structural geology, petrography, oxygen and carbon stable isotope geochemistry and U/Th dating in order to develop a conceptual model of the spatiotemporal variations of fluid flow along faults and to calibrate the CO_2 leakage dynamics.

3.1. Structural geology and petrography

The first step of our study consisted in a structural investigation of modern and paleo-fluid flow architecture through the fault zones. This investigation is based on field work and petrographic analyses grouping observations from outcrop to thin-section scale. More than 300 samples were collected and analysed. In order to differentiate the distinct phases of carbonate precipitation, samples were stained using alizarine. Subsequently, to differentiate calcite from aragonite, the Feigl staining at room temperature was used on polished samples and thin sections (Kato et al., 2003). The solution was prepared according to the original recipe (Feigl and Leitmeier, 1933). Surface areas composed of aragonite immersed in this stain changed gradually from white to black over a 10-minute period.

3.2. U/Th dating and stable isotopes

An accurate chronology of the building of T1 travertine was established by absolute U–Th dating. Nine veins were collected along