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Sedimentary stylolite networks and connectivity in limestone: Large-scale field observations and implications for structure evolution

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ABSTRACT

Stylolites are rough surfaces, formed by localized rock dissolution, and prevalent in carbonates and other sedimentary rocks. Their impact on porosity and permeability, and capacity to accommodate compactive strain, are well documented. This paper presents a meso-scale field study on sedimentary stylolites in carbonates, characterizing large-scale distributions of stylolites, including measurements conducted on longer than kilometer-long stylolites. Our field study suggests that on large scales connections between stylolites become important. Since connectivity, and also lack of connectivity, are expected to play a significant role in strain accommodation and hydraulic rock properties, we suggest that large-scale analysis may require a new characterization scheme for "stylolite populations", based on their connectivity. We therefore divide sedimentary stylolite populations into three end-member types, which are correlated with the three possibilities for percolation of such systems: isolated stylolites (with zero percolation/connectivity), long-parallel stylolites (with 2-dimensional percolation/connectivity), and interconnected stylolite networks (with 3-dimensional percolation/connectivity). New statistical parameters and measures are devised and used to quantitatively characterize the different population types. Schematic mechanistic models are then offered to explain the evolution of the three end-member connectivity-classes. In addition we discuss the effect on fluid flow of the different population types.

1. Introduction

Stylolites are rough surfaces of dissolution, common in sedimentary rocks and especially prominent in carbonates. They are lined by a thin layer of relatively insoluble particles, mainly clay minerals, oxides, and organic matter, that are thought to accumulate while the major constituent of the rock, which is more soluble (e.g. carbonate, quartz) dissolves away (Stockdale, 1922; Park and Schot, 1968; Kaplan, 1976; Railsback, 1993). Stylolites are known to affect fluid flow in opposing ways: On the one hand, stylolites are often associated with reduced permeability – material that dissolves at the stylolite precipitates in adjacent pores, forming "tight" units (Wong and Oldershaw, 1981; Tada and Siever, 1989; Finkel and Wilkinson, 1990; Ehrenberg, 2006) that are important in management of hydrocarbon aquifers and reservoirs (Corwin et al., 1997). In other cases, stylolites may enhance porosity and permeability in their vicinity, in particular their tips (Carozzi and Vonbergen, 1987; Raynaud and Carrioschaffhauser, 1992) and sometimes fluid flow is observed along stylolitic surfaces (Wong and Oldershaw, 1981; Rye and Bradbury, 1988; Heap et al., 2014). In addition to their hydraulic role, stylolites are also known to accommodate large compactive strains (Tada and Siever, 1989), playing a key role in the evolution of mechanical rock properties, and the overall compactive strain of rocks.

Stylolite formation is attributed to localized Pressure Solution (PS). PS is broadly defined as dissolution and re-precipitation driven by spatial variations in chemical potential along grain

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surfaces: regions with high chemical potential dissolve, the dissolved material is transported through the fluid phase, and precipitates in regions where the chemical potential is lower. Variations in the chemical potential arise due to spatial variations in stress, plastic and elastic strain energies, crystal orientation and interface curvature (Deboer, 1977; Lehner, 1995; Paterson, 1995; Shimizu, 1995). The chemical potential can be extended to an electrochemical potential (Greene et al., 2009) where spatial variations in surface charge are considered as well. Clays and organic matter are also thought to play an important role in the PS process (Heald, 1956; Thomson, 1959; Sibley and Blatt, 1976; Gruzman, 1997), and their distribution and content are believed to affect the rate of PS (Hickman and Evans, 1995; Renard et al., 2001) and the degree of PS localization on stylolites (Heald, 1955, 1956; Engelder and Marshak, 1985; Marshak and Engelder, 1985). How clays, phyllosilicates, and organic matter enhance PS is not fully understood, and suggestions include purely physical (propping grain contacts) (Weyl, 1959), chemical (varying pH) (Thomson, 1959), electrochemical (solute gradients amplified by clay electric charge) (Walderhaug et al., 2006) effects, or a combination of the above.

Key models for stylolite formation view them as isolated and spatially limited surfaces (e.g. Fletcher and Pollard (1981); Stockdale (1922)). However, in the field they are rarely “isolated”, but rather appear to be closely related to other stylolites and structures (primarily Mode I and Mode II fractures) (Peacock and Sanderson, 1995; Smith, 2000). Perhaps because of the scarcity of isolated stylolites, and the difficulty in determining their terminations when not isolated, there is very limited literature on stylolites’ lateral extent. Stylolites were traced in limestone for over 50 m by Park and Schot (1968), and Safaricz (2002) followed single stylolites for 8.5 m and dissolution seams for over 800 m. An often-cited linear relationship between stylolite length and thickness (either amplitude or seam thickness), is thus based on a handful of field studies (Stockdale, 1922; Mardon, 1988; Benedicto and Schultz, 2010; Nenna and Aydin, 2011) though a theoretical rationale for it is fairly well understood (Aharonov and Katsman, 2009).

Most stylolites seem to have been studied on “small” outcrops or, in the case of the oil and gas industry, on cores. A few exceptions are the field-wide studies of Stockdale (1922), Railsback (1993), Andrews and Railsback (1997), Safaricz (2002), Safaricz and Davison (2005). Stylolites, like fractures, are “very large” in one dimension but “very small” in another dimension. Their thickness is of the order of centimeters at most, so they are impossible to resolve with standard seismic techniques. In order to determine the large-scale distribution of stylolites (needed to assess for example reservoir performance or compactive basin-scale strain) the geometry and hydraulic properties of the centimeter-scale observation made routinely on cores needs to be upscaled to the kilometer-scale structure, which is always a challenging task. To devise a robust upscaling methodology, the cm-scale structure needs to be linked to the km-scale structure through an adequate analog-outcrop, as is common in the petroleum industry. Only through such an analog can upscaling parameters and workflows be tested and confirmed. Such studies were previously done on fractures (Dawers et al., 1993; Main, 1996; Cello, 1997; Willemse, 1997; Bour and Davy, 1998; McLeod et al., 2000), and led to basic understanding regarding the relationship between aperture and length (Vermilye and Scholz, 1995) and the formation and connectivity of fractures (Segall and Pollard, 1980; Cartwright et al., 1995; Gupta and Scholz, 2000). The present work performs a similar multiscale study on sedimentary stylolite populations, aiming to quantify their distributions and connectivity and provide a step towards understanding their large-scale effects.

The connectivity of stylolites may be important both when they act as flow conduits, and in the opposite case, when they act as barriers. Their impact on large-scale flow properties can be understood using ideas from percolation theory (for a review on percolation see e.g. Bunde and Havlin (1991)). Percolation theory is a mathematical theory that addresses the question of the connectivity and conductivity within a composite material, composed of “black” defects placed within a “white” matrix. In the percolation, “game” the black defects are typically assigned a different conductivity than their host white matrix, and percolation theory predicts electrical conductivity and resistivity of the composite black-white material (e.g. McLachlan et al. (1990)). The black defects are said to “percolate” when one can trace along black parts only (without “stepping” into white parts) from any side of the matrix body to any other. When black defects are conductive, “percolation” is accompanied by abrupt enhancement of the conductivity of the matrix relative to a state of no percolation. The opposite game is just as simple – if black defects have high resistivity (low conductivity), percolation of conducting whites controls conductivity. Percolation of conductive whites is lost when there are enough black defects, or when blacks are distributed in such a way that whites are disconnected.

In line of the above percolation picture, we suggest to envision stylolites as “penny-shaped” surfaces with a different fluid conductivity (higher or lower) than their host rock. These surfaces can have different radii and can be oriented in different angles to each other. They can be envisioned as “black” defects in a “white” host rock.

Percolation or connectivity of the stylolite surfaces are then expected to occur in one of three end-member ways:

I Isolated surfaces – no percolation: If the radii of surfaces is small, and if there are not many surfaces within the region, then the surfaces may not cross each other and remain isolated from one another. In that case there is no percolation of surfaces from any side of the box to any other. This system is below the percolation threshold.

II Parallel surfaces – 2D percolation: if surfaces are virtually infinite and parallel, they create a layered structure. In this case both surfaces and host rock percolate in the direction parallel to the surfaces, but neither of them percolates in the direction perpendicular to the surfaces. If the surfaces have higher conductivity than the host rock they will enhance conductance in the surface-parallel direction and will not affect the perpendicular direction. Instead, if the surfaces have lower conductivity they will not affect the surface-parallel direction yet will act as barriers for conductance in the perpendicular direction. In this case percolation is anisotropic and so is conductance.

III Networks of interconnected surfaces – 3D percolation: when there are enough surfaces, and they have a distribution of orientations, they will connect to one another and allow percolation in all three dimensions.

In order to analyze the 3D connectivity of stylolites with the above framework in mind we devised new statistical characterization tools that quantify the morphology of stylolite populations. We use our new tools in three well-exposed localities, chosen from a collection of 17 field-sites (Table 1). These sites were chosen due to their good exposure, and also because they exemplify the 3 end-member surface-connectivity/percolation possibilities presented above. The provides location, geological setting and general description of stylolites exposed in the other 14 localities. Most of these are field-sites that we studied and a few are places described in the literature and studied by others.