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Impact of stylolites on the mechanical strength of limestone

Patrick Baud [a,*], Alexandra Rolland [a], Michael Heap [a], Tao Xu [b], Marion Nicolé [a], Thomas Ferrand [c], Thierry Reuschlé [a], Renaud Toussaint [a], Nathalie Conil [d]

[a] Institut de Physique du Globe de Strasbourg (UMR 7516 CNRS, Université de Strasbourg/EOST), 5 rue René Descartes, F-67084 Strasbourg Cedex, France
[b] College of Resources and Civil Engineering, Northeastern University, Shenyang, China
[c] Département de Géologie, Ecole Normale Supérieure, Paris, France
[d] Andra, Bure, France

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ABSTRACT

We performed a series of uniaxial compression tests on samples of microporous carbonates from the Paris Basin (Bure, France). Sedimentary stylolites are pervasive in these formations. We show that the porosity in the vicinity of the stylolites is always higher than that of the host rock. As a result, our new mechanical data reveal that samples with a stylolite are always measurably weaker with respect to the adjacent stylolite-free material. However, when present, the orientation of the stylolite (with respect to the direction of loading) does not result in any mechanical anisotropy. Numerical simulations using a 2D finite element code suggest that the weakening induced by the presence of a stylolite is mostly due to the higher porosity and the higher level of heterogeneity in and around the stylolite, while the absence of mechanical anisotropy is due to the roughness of the stylolite. While the presence of stylolites weakens carbonate rocks, stylolites only act as planes of weakness when their thickness exceeds a certain threshold (about 5 mm).

1. Introduction

Stylolites are the product of intergranular pressure-solution and are common in sedimentary formations. They have been described in carbonates (Stockdale, 1943; Park and Schot, 1968; Bathurst, 1971), sandstones (Heald, 1955; Baron and Parnell, 2007), and shales (Rutter, 1983). They appear as column-and-socket interdigitation features (Nenna and Aydin, 2011; Croizé et al., 2013) and are filled with insoluble elements such as organic matter, oxides, or clay particles (Nelson, 1981). Stylolites grow orthogonal to the major principal stress and are often divided in two groups: sedimentary stylolites oriented subparallel to bedding (i.e., those that form due to overburden stresses) and tectonic stylolites (perpendicular or oblique to bedding).

Stylolites have interested geoscientists for now almost a century primarily because, as compaction localization features, they could potentially impact fluid flow at various scales. Until recently, prevalent views on this matter were that stylolites were barriers to fluid flow (see for example Dunnington, 1967). Recent experimental studies revealed however that stylolites in limestones do not influence permeability when they are oriented perpendicular to fluid flow and, in some cases, can act as conduits when orientated parallel to flow (Lind et al., 1994; Heap et al., 2014a; Rustichelli et al., 2015). In the last decade, several studies also used stylolites as palaeostress gauges by linking their morphology to in situ stresses (e.g., Schmittbuhl et al., 2004; Rolland et al., 2012).

In situations where stylolites are abundant, another outstanding question important for reservoir/aquifer production (and a wide variety of geotechnical applications) is their impact on the mechanical strength and rheology of sedimentary formations. This question has received less attention from the scientific community perhaps because its answer appeared somehow obvious. The prevalent views are that the presence of stylolites significantly weakens rocks (Yates and Chakrabarti, 1998; Larbi, 2003; Özvan et al., 2011), that stylolites are natural planes of weakness in sedimentary formations (Nicholson and Nicholson, 2000; Pires et al., 2010), and that they induce a significant mechanical anisotropy (Rashed and Sediek, 1997). The fact that stylolites weaken a rock mass is supported by many observations in quarries. López-Buendía et al. (2013), for example, noted that more than 95% of cm-scale breakages within the quarried Crema Marfil marble (Alicante, Spain) were due to stylolites. Although very low strength was reported in Brazilian tests on the same material with open stylolites (López-Buendía et al., 2013), no study has, to our knowledge, systematically quantified the impact of stylolites on rock strength. One reason is probably that, in both field and laboratory contexts, the opening of the stylolites due to drilling, cutting, or depressurization, is a major issue and there is always some ambiguity whether the observed effect could in fact not primarily be due to some significant microcracking/fracturing associated to the stylolites and not to the structure itself. To what extent are stylolites planes of weakness if they are not open? Do they induce any mechanical anisotropy in that case, and is it possible to systematically quantify the weakening, if it exists at all? To answer these questions we performed a series of uniaxial compression tests on samples prepared from cores

* Corresponding author.

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taken from a borehole drilled in a limestone formation in the Paris Basin (France). Stylolites are abundant in this formation and Heap et al. (2014a) recently showed that it is possible to prepare samples in various orientations without opening the stylolites. We were therefore able to systematically compare the mechanical behaviour of these limestones with and without stylolites. Guided by new petrophysical measurements and microstructural observations, numerical modelling was used to interpret our mechanical data and clarify the role of stylolites on the brittle strength of carbonate rocks.

2. Material studied and experimental set-up

2.1. Material origin and preparation of the samples

In this study, we focused on Oxfordian limestones from the Eastern part of the Paris Basin. Several boreholes were drilled surrounding the Andra (French national radioactive waste management agency) Underground Research Laboratory (URL) near Bure, France. All the limestones studied here are allochemical (oolitic) limestones. They are all from the same borehole and belong to units located above the URL, which is built within a layer of claystone (see Rolland et al., 2014 for details). Stylolites are abundant in most of the retrieved cores (Fig. 1A). The larger stylolites (of cm thickness) were open in all cases, probably due to the depressurization upon retrieval. It is important to specify that the thickness to which we refer to in this study is the actual thickness of insoluble elements that can be seen by eye. For this study, we focused on sedimentary stylolites and selected zones presenting regularly spaced closed stylolites surrounded by sufficient reference stylolite-free material to be used for comparison. The typical distance between the studied stylolite and the stylolite-free material was about 10 cm. We avoided zones with large heterogeneities, anostomosing stylolites, and stylolites with tilted teeth. We also disregarded partially open stylolites that we could easily spot from the high resolution pictures of Rolland (2013). Because of these quite restrictive criteria, we could not sample the available cores at regular interval of depths. We focused on 6 different depths between 158 and 364 m. The geological and textural details of these layers, named for simplicity in this study O1 to O6, are given in Table 1 (based on the previous systematic study of André (2003)). The studied units are grainstones, wackestones, and packstones. The stylolites in these different layers show different morphologies, studied in detail by Rolland et al. (2014). In particular, the amplitude of the teeth was observed to be quite variable, from ~1 mm (Fig. 1B) to ~1 cm and sometimes more (Fig. 1C).

Cylindrical samples nominally 4 cm long and 2 cm in diameter with and without stylolites were prepared from the 10 cm diameter cores (Fig. 2A–B). For the samples containing stylolites, two orientations were cored: orthogonal and parallel to the stylolite plane. For simplicity, we will refer to these samples henceforth as orientation Z (samples cored orthogonal to the stylolite plane and stress also applied orthogonal to the stylolite plane) and orientation X (samples cored parallel to the stylolite plane and stress also applied parallel to the stylolite plane), respectively. Where possible, several samples at an oblique orientation (~60° to the core axis) were also prepared (Fig. 2C). At each selected depth, stylolites with different morphologies were encountered (Rolland et al., 2014). We grouped the stylolites that showed common morphological attributes and when possible obtained all the data from the same stylolite. This preparation phase was challenging and coring in three different orientations often minimized the number of cores we could prepare from a given length of core. Further, cutting and drilling into the cores occasionally revealed large heterogeneities, local

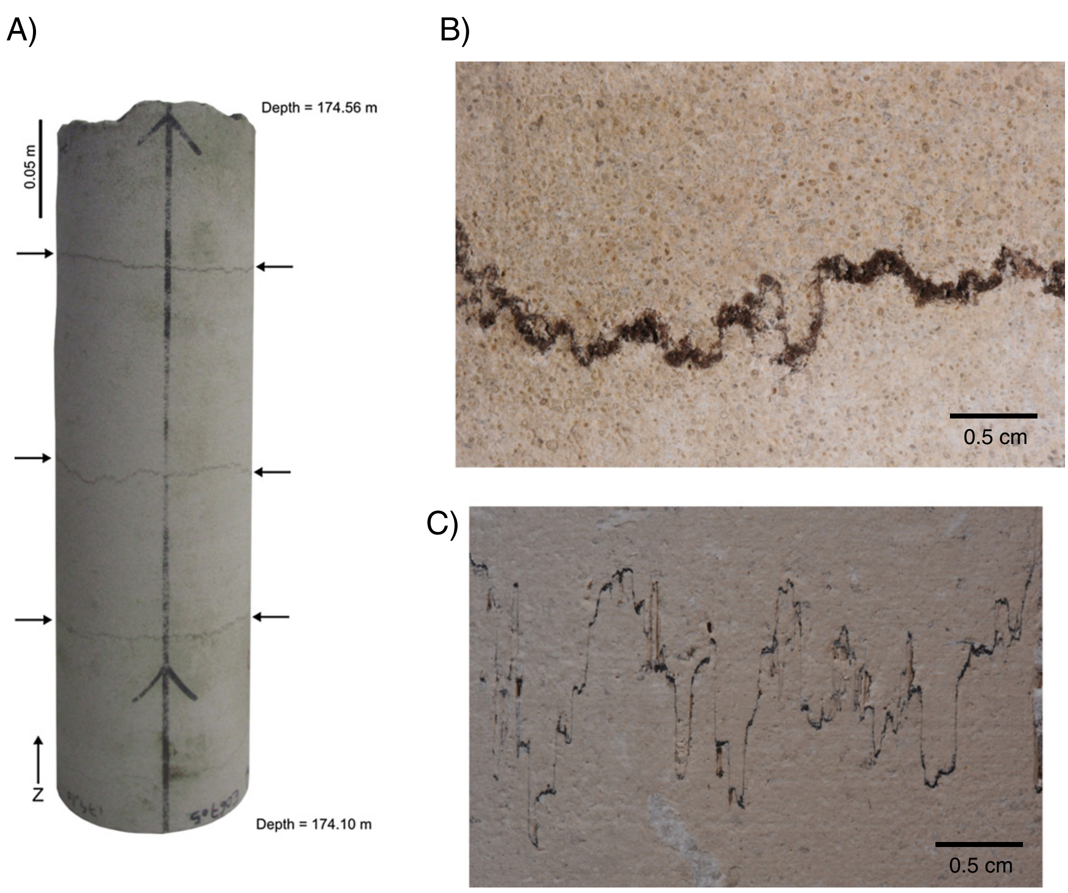

Fig. 1. (A) Photograph of a section of a core from the borehole EST205 from the ANDRA site in Bure, France. Three stylolites (indicated by arrows) are visible on the core of ~50 cm length. High resolution photographs showing the details of a stylolite in layers O3 (B) and O5 (C).