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Geological control of the partitioning between seismic and aseismic sliding behaviours in active faults: Evidence from the Western Alps, France

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ABSTRACT

Given that active faults can slide either continuously by aseismic creep or episodically during earthquakes, and that the same fault zone may evolve laterally from seismic to aseismic deformation, an important issue is to know whether seismic to aseismic transition can be geologically controlled. This article presents examples of contrasted mechanical behaviour along active faults that cross cut limestone and marl units within the sedimentary cover of the French Alps. By matching seismic events along strike-slip and normal faults with the nature and structure of the rocks, it is demonstrated that the partition between seismic and aseismic sliding at depth is geologically controlled: earthquakes nucleate in the strongest rocks, mainly limestones, whereas marls accommodate at least part of the tectonic loading by aseismic creep. By looking at exhumed rocks deformed in the same context it is possible to identify the mechanism of creep, which is shown to be pressure solution creep either as a permanent or post-seismic creep. As earthquakes slip are seen to propagate through the whole upper crust, creep processes do not necessarily prevent an earthquake rupture from propagating through creeping units. However, creep relaxes stress and consequently reduces the available elastic potential energy at the origin of earthquakes in such creeping zones. The key parameters of pressure solution creep laws are presented and discussed. Using these laws, it is possible to infer why marl may creep more easily than limestone or why highly fractured limestone may creep more easily than intact rock. This approach also identifies other rocks that could creep by pressure solution in subduction zones and indicates how creeping zones may act as barriers for earthquake rupture propagation. Finally, the criteria possibly revealing geological control of the transition between seismic and aseismic sliding at depth are discussed with respect to subduction zones.

1. Introduction

The mechanical behaviour of active fault zones involves a variety of sliding modes, from continuous aseismic creep to sudden rupture during earthquakes. Such contrasting behaviour may be observed in various contexts, such as subduction zones where seismic patches are surrounded by aseismic deformation zones (Masson et al., 2005; Satyabala et al., 2012), collision zones (Masson et al., 2005; Satyabala et al., 2012), and strike-slip faults (Evans et al., 2012; Nadeau et al., 2004). Even in the so-called "seismic zone", afterslip creep may accommodate part of the displacement (Freed, 2007). Consequently, aseismic creep, which occurs either as a continuous process or as post-seismic afterslip deformation, could significantly relax tectonic stresses and therefore reduce the occurrence of major earthquakes in these zones. A major issue is to understand whether the transition between seismic and aseismic behaviours could be controlled by the geological characteristics of the deformed rocks: are some types of rocks more prone to seismic failure while others are more prone to aseismic creep? To answer such a question, it is necessary to identify the grain-scale mechanisms of aseismic creep and then to investigate how such mechanisms may be sensitive to the nature, structure or composition of the rocks. Finally, if such geological control does indeed govern the transition between seismic and aseismic slips, how can the key geological characteristics controlling the seismic to aseismic transitions be recognized at depth?

To answer these questions, several examples are presented of contrasted rock behaviours along active faults that cross cut layers of limestones and marls within the sedimentary cover of the French Alps. This area of moderate seismicity has been carefully monitored over the past thirty years through a network of short-period seismometers, providing accurate locations of small seismic events. In a first step, the seismicity distribution along active strike-slip and normal faults (Vuache and Clansayes faults) was matched with the nature, structure and composition of the rocks that can be seen on the geological cross-section. These data indicate a lithological control of the transition between seismic and aseismic slips at depth because most earthquakes nucleate in the strong limestone units and only few of them could be observed in the weak marl units. However, in

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most cases, it is not possible to observe directly the rocks at depth, and therefore to identify the creep mechanisms. A second step therefore had to be introduced to provide additional constraints based on the Cléry fault zone that formed in the same geological context as the Vuache and Clansayes faults, and which was recently exhumed.

Stratigraphically analogous limestone and marl units, outcropping at the surface near the same type of recent Alpine exhumed faults, were studied in order to establish the mechanisms of the creep processes associated with seismic and aseismic deformations: either as permanent or post-seismic creep. Various mechanisms of creep in crustal rocks could be at work: i) pressure solution creep (Rutter, 1976) involves coupling fluid–rock interactions with deformation; ii) brittle creep (Chester et al., 2007; Heap et al., 2009) involves the generation and slow propagation of microcracks that weaken the rocks, iii) frictional processes such as low-friction deformation with talc-bearing phyllonite for example (Smith et al., 2012), or the presence of weak phyllosilicates such as saponite (Lockner et al., 2011), or the effect of fault fabric as well-developed foliation (Collettini et al., 2009). Frictional-viscous creep involves the coupling between pressure solution and frictional sliding (Bos and Spiers, 2002; Bos et al., 2000). “Mixed mode” deformation, with fault creep in a foliated phyllosilicate-rich fault zone and a seismic event initiating in more rigid competent lenses as dolomite or mafic blocks, has been described for example by Collettini et al. (2011), Faulkner et al. (2003).

The main result of the present work is that both long-term seismological monitoring, with high-resolution locations of earthquake foci at depth, and outcrop observations provide evidence that earthquakes rupture nucleate and propagate in the strongest rocks, mainly limestone, whereas marl units accommodate tectonic loading, mainly by aseismic pressure solution creep. This clearly reflects lithological control of the seismic to aseismic transition. However, creeping in a given type of rock does not necessarily prevent earthquake rupture from propagating through it, either because the creeping process does not completely relax the stress or as a result of dynamic processes of seismic interactions from neighbouring earthquakes. Moreover, the so-called seismic zones may also show afterslip creep. For both permanent and transient creep processes, the stress is relaxed, which therefore lowers the probability of occurrence of a new earthquake in these zones. Finally, since the creep mechanism has been identified in this work as pressure solution creep, the manner in which this mechanism is sensitive to the nature, structure and composition of the rocks is discussed, together with ways of identifying at depth rocks that are more prone to failure and those more prone to creep. It is also shown that pressure solution needs specific conditions to develop (presence of a fluid that may dissolve some minerals, specific pressure and temperature conditions to favour the maximum solubility of the mineral in solution). As a consequence, the whole geological context, and not only the lithology, should be considered.

2. Seismicity distribution and geology: the Vuache fault (Jura massif)

The first example is the Vuache fault, located in the Jura massif, within the western part of the Alps (Gratier et al., 1989; Lemoine et al., 1986). In this area, E–W Alpine contraction led to folds, thrusts and strike-slip faults that can be seen both in geological cross-sections and on maps (Fig. 1). The Jura massif is a typical foreland fold–thrust belt within this part of the Alps, where deformation affects a relatively thin sedimentary cover deformed above a basal décollement in Triassic evaporites (Hindle and Burkhard, 1999). The Jura belt was formed during the latest stage of the Alpine orogeny between the Upper Miocene and Lower Pliocene ages. It developed into a mountain range with arcuate folds-and-thrusts and strike-slip movement (major N–S to NW–SE sinistral, and minor E–W dextral strike-slip faults) that are linked with the Alpine arc formation (Affolter and Gratier, 2004). Present-day active faults are indicative of the continuity of tectonic loading with an active thrust fault being observed at the front of the Jura: ML 5.1 (local magnitude) 2004, Roulans earthquake (Cara et al., 2007; Molliex et al., 2011), close to Besançon and an active strike-slip fault in the rear part where occurred the ML 5.2 1996 Epagny earthquake (Hoang-Trong and Cara, 1998; Thouvenot et al., 1998), near Annecy. This latter earthquake occurred on the Vuache fault, which is one of the main NW–SE left-lateral strike-slip faults that currently offset the NE–SW trending folds-and-thrusts at the rear part of the Jura.

2.1. Seismicity distribution

The so-called Epagny earthquake is the strongest event recorded in southern-eastern France since 1962. The hypocentre was located in a Mesozoic limestone formation at very shallow depths (1–3 km). The focal mechanism indicates left-lateral strike-slip motion on a N136°-E-striking plane dipping 70° to the NE. This earthquake was followed by several hundred aftershocks, the locations of which were accurately determined thanks to the rapid installation of a temporary 16-station seismic network (Thouvenot et al., 1998). All aftershocks (magnitude 0.5 to 4) occurred along the southernmost segment of the Vuache fault, defining a 5-km-long, 3.5-km-deep, 130°E-striking rupture zone dipping 73° to the NE as the mean value (Fig. 2). However, some aftershock alignments appeared to indicate a more complex structure with some parts of the fault possibly being vertical. Fault-plane solutions for the 60-recorded aftershocks were consistent with left-lateral slip on a NW–SE striking plane. The intersection of the aftershock cluster mean plane with the topographic surface is very near the inferred extension of the Vuache fault marked on the geological map (Fig. 2). Aftershocks selected here (174 events) were well recorded by the temporary network, with more than 8 arrival times available, with an azimuthal gap smaller than 180°, and with high location accuracy: uncertainties are 160 m for epicentres, and 200 m for focal depths. Conversely, the main-shock position computed from permanent stations, up to 150 km away, was not as accurate as that of the aftershocks. However, by comparing the location of some aftershocks obtained from the local network with those obtained from the permanent network, it was possible to evaluate the location of the main earthquake with a horizontal uncertainty of less than 700 m.

2.2. Geological cross-sections

In order to compare the location of earthquakes at depth with the lithological characteristics of the sedimentary cover, geological cross-sections were constructed using both outcrops and drill hole data (Fig. 3). The balanced cross-section technique (Dahlstrom, 1969) was used to constrain the structures at depth as accurately as possible. This technique is based on the idea that a valid cross-section must be restorable to its initial state. This is achieved by assuming that the cross-sectional area is conserved during deformation above a single detachment fault and that at least some layers (competent layers) keep the same length over the entire deformation. In such case, a simple relation relates the transferred surface area (excess area above a reference layer) to the shortening (present length minus the initial length of a reference competent folded layer) multiplied by the depth of the detachment below the reference layer (Dahlstrom, 1969; Elliott, 1983; Hossack, 1979). The assumption of cross-sectional area conservation is supported by the observation of cylindrical folds perpendicular to the finite displacement with no evidence of strain extension parallel to the fold axis (except some fractures that account for no more than a few percent of deformation, which is considered here to be negligible). The balance between the excess area and the two other parameters (shortening and depth of the detachment) is based on a good knowledge of both the fold structure and the lithological section (Hossack, 1979; Ménard and