In: Structural Geology: New Research
Editor: S. J. Landowe and G. M. Hammler, pp.
ISBN 978-1-60456-827-1

Chapter 4

FAULT-RELATED CARBONATE ROCKS AND EARTHQUAKE INDICATORS: RECENT ADVANCES AND FUTURE TRENDS

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ABSTRACT

A major problem in seismology and structural geology is the lack, at least apparently, of clear records of seismic fault slip. Some geologists even suggested that, except for pseudotachylytes, earthquakes do not leave detectable geological indicators along faults. Discovering new geological indicators of seismic fault slip is therefore a challenging but also a very important target to advance the knowledge of how, where, when, and why earthquakes occur along faults.

High-velocity weakening of faults may drive fault motion during large earthquakes. Laboratory experiments on simulated faults in Carrara marble performed at seismic slip rates (about 1 m/s) showed that thermal decomposition of calcite due to frictional heating induces pronounced fault weakening with very low friction coefficients (about 0.1 instead of a typical rock friction coefficient of 0.7). The ultra-low friction appears to be associated with the flash heating on the ultrafine products of calcite decomposition. It follows that thermal decomposition may be an important process for the dynamic weakening of carbonate-bearing faults and the products of calcite thermal decomposition (i.e. ultrafine particles and decomposition-related minerals) may be clear indicators of seismic slip in exhumed faults. Energy budget calculations predict seismic slip to be localized in ultra-thin slipping zones, compared to crystalline rocks. This research field is

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among the most promising ones in seismology and structural geology and recent results from laboratory simulations require proper validation in natural examples.

Other likely seismic slip indicators are fault zone-related pulverized rocks, consisting of mechanically-pulverized rocks lacking in significant shear and preserving most of their original fabric. Pulverized rocks such as those recently found in the damage zone of active faults (i.e., the Hartebeestfontein mine in South Africa and the San Andreas Fault in California) are still poorly documented and studied. Further field and experimental studies are, therefore, required to establish the diffusion of these fault zone rocks, the mechanism of production, and whether they can be commonly considered as indicators of ancient earthquakes.

Carbonate rocks usually occur in the upper portion of the crust and are often known as hypocenters of shallow earthquakes. For this reason, exposures of exhumed faults in carbonate rocks are a promising target to study earthquake rupture dynamics in the shallow crust. Faults exposed in carbonate rocks from three sites of central Italy (i.e. Mattinata, Sperlonga, and Venere sites) and one site in northwestern England (i.e. the Dent Fault) are here indicated as potentially suitable to research earthquake indicators similar to those mentioned above (i.e. mineralogical thermal decomposition and pulverized rocks).

INTRODUCTION

Since the studies of H.F. Reid on the 1906 San Francisco great earthquake [Reid, 1908; 1910], research on the mechanics and geology of earthquakes has strikingly advanced; however, despite a wealth of published data and studies, clear geological records of earthquakes along faults are still very limited. At present, in fact, only tectonic pseudotachylytes [i.e. solidified melts produced by frictional heating due to the interaction of the opposite fault surfaces during seismic slip, e.g. Jeffreys, 1942; McKenzie and Brune, 1973; Sibson, 1975; Di Toro et al., 2005a, 2005b; Lin, 2008] are unambiguously recognized by geologists and geophysicists as the signature of ancient earthquakes in exhumed faults [Cowan, 1999]. However, pseudotachylyte occurrences are not as widespread as the seismic activity in the Earth's crust are [Sibson and Toy, 2006]. Although recent studies indicate that pseudotachylytes are more common than usually assumed, at least at nucleation depths of destructive earthquakes (10-15 km) [e.g., Griffith et al., 2007; Kirkpatrick and Shipton, 2008], pseudotachylytes are absent in fault-zones hosted in carbonate-bearing rocks, where, in contrast, fault rock assemblages such as cataclasites, pulverized rocks, or fluidized gouges occur rather frequently. The interpretation of these rock assemblages remains enigmatic. Can they be produced during earthquakes? What microstructural features, if any, can unequivocally signal the occurrence of seismic slip?

These unanswered questions have, hitherto, inhibited significant advances in the understanding of earthquake mechanics. Preliminary experimental studies suggest that, together with pseudotachylytes, other stable mineral assemblages and microstructures can be produced during the high temperature pulses achieved during seismic slip and may be preserved in the geological record. These results are of outstanding importance because they suggest that the study of exhumed faults may reveal the ancient seismicity of a fault, thus yielding a wealth of information about earthquake mechanics (rupture dynamics, earthquake energy budgets, etc.) only by means of field and microstructural studies. A further advantage of field studies is that important information can be obtained at low costs compared, for instance, to that achieved by drilling seismically-active faults (e.g., see the San Andreas Fault Observatory at Depth and the Taiwan Chelungpu-Fault Drilling Project). Though, of course, fault drilling has several advantages (e.g. the possibility to monitor in situ seismic activity), the structural information is limited. The well crosses the fault zone only in a few places (and for a few tens of centimeters in diameter) and at a depth of a few kilometers (< 3 km) at most, whereas big earthquakes involve large structures and nucleate and propagate at larger depths. Field investigation of large exposures of exhumed seismogenic faults may yield information that is complementary to that gained from fault drilling and at a much lower cost.

Earthquakes are the result of ruptures that nucleate, grow, and terminate often along pre-existing faults [Gilbert, 1884; Scholz, 2002]. Earthquakes propagate because fault strength decreases with increasing slip (slip-weakening materials) and slip-rate (velocity-weakening material) at a more rapid rate than the release of tectonic stress driving the fault motion [Marone, 1998; Scholz, 1998, 2002]. It follows that understanding the factors that control slip- and velocity-weakening in nature is fundamental to comprehend earthquake mechanics [Wibberley and Shimamoto, 2005]. Understanding these factors, however, is severely limited because, with the exception of pseudotachylytes, detectable traces of earthquakes along faults are nearly unknown at present.

This problem has been tackled by conducting theoretical [Jeffreys, 1942; McKenzie and Brune, 1972; Melosh, 1996; Kato, 2001; Kato et al., 2003; Fialko, 2004; Kanamori and Brodsky, 2004; Fialko and Khazan, 2005; Rice, 2006; Bizzarri and Cocco, 2006; Rempel, 2006; Nielsen et al., 2008; Beeler et al., 2008] and, more recently, experimental studies [Weeks and Tullis, 1985; Spray, 1987; 1995; 2005; Tsutsumi and Shimamoto, 1997; Hirose and Shimamoto, 2005a, 2005b; Di Toro et al., 2004; 2006a; 2006b; Beeler, 2006; Han et al., 2007a, 2007b; Hirose and Bystricky, 2007; Mair et al., 2007; Mizoguchi et al., 2007; Brantut et al., 2008; Boutareaud et al., 2008]. A main advantage of experimental studies is the possibility to study the evolution of the friction coefficient with slip and slip-rate and to recover artificial fault materials produced under controlled conditions to be compared to samples retrieved from exhumed faults. Deformation conditions during earthquakes are extreme: slip rates of m s^{-1} [Heaton, 1990], displacements up to 20 m, and stresses up to several hundreds of MPa. Though the current experimental apparatuses [see Hirose and Shimamoto 2005a for a description] reproduce the slip rates and displacements typical of large earthquakes, technical limitations impede to apply the large stress typical of earthquakes [the maximum applied normal stress is 20 MPa, e.g., Di Toro et al, 2006a]. Even with the experimental limitations described above, this intense experimental work conducted to the discovery of several thermally-activated fault weakening mechanisms other than melt lubrication [Hirose and Shimamoto, 2005a; Spray, 2005; Di Toro et al., 2006b], including, among others, weakening in the presence of clay-rich gouges [Mizoguchi et al.,, 2007], water pressurization and vaporization [e.g., Boutareaud et al., 2008], dehydration [Hirose and Bistricky, 2007; Brantut et al., 2008] and decarbonation reactions [Han et al., 2007a], gelification of silica-bearing rocks [Goldsby and Tullis, 2002; Di Toro et al., 2004; Roig-Silva et al., 2004], local (flash) heating, and melting of the asperity contacts [Goldsby and Tullis, 2003]. Moreover, experiments conducted in fault clay-rich gouges [Brantut et al., 2008; Boutareaud et al., 2008] and calcite rocks [Han et al., 2007a, 2007b] produced dehydrated and decarbonated layers and new mineral assemblages that might be preserved in the geological record. These fault rock assemblages, if found in nature, might be the evidence of seismic slip in ancient exhumed faults.

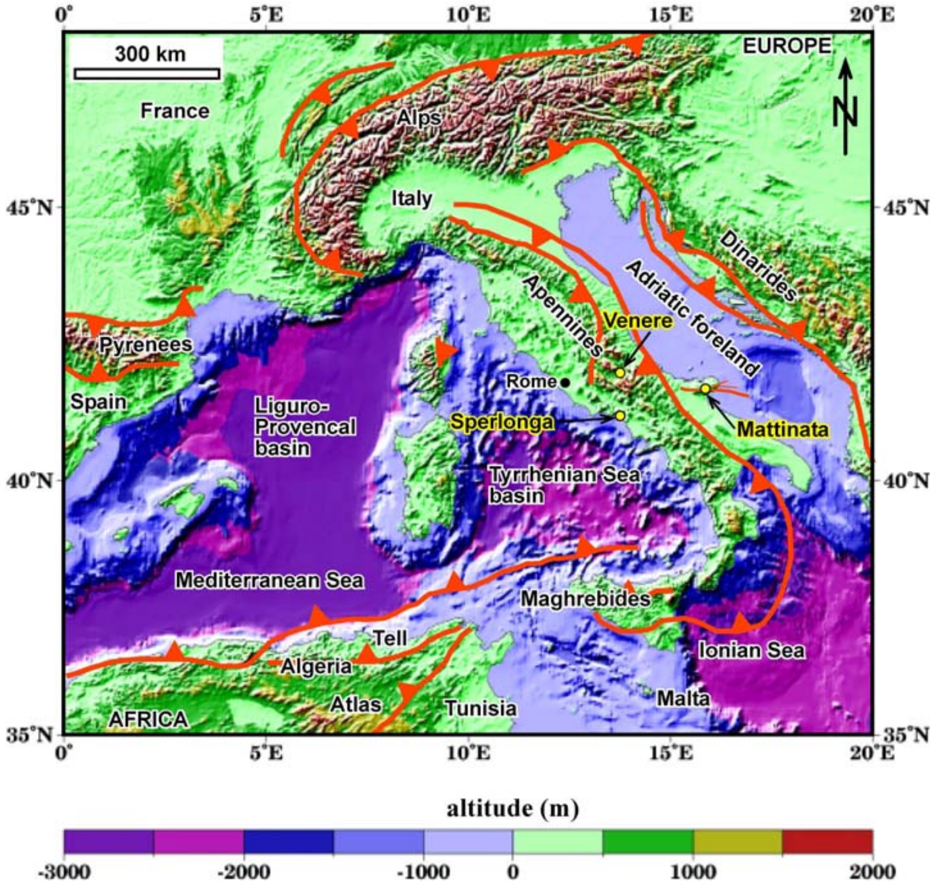


Figure 1. Elevation model and schematic tectonic map of Italy and adjoining areas. Main fold-thrust belts and thrust fronts are displayed in red. Location of the Mattinata, Sperlonga, and Venere sites mentioned in the text is shown. Related coordinates are as follows. Mattinata site: Lat. 41°43'12''N, Long. 15°52'05''E; Sperlonga site: Lat. 41°15'33''N, Long. 13°26'23''E; Venere site: Lat. 41°58'26"N, Long. 13°29'27''E.

In addition to the above-mentioned evidence or clues of ancient earthquakes, recent field studies on particular fault zone-related rocks named as pulverized rocks [Reches and Dewers, 2005; Wilson et al., 2005; Dor et al., 2006a; 2006b] suggested that these structures may represent another indicator of seismic ruptures.

In this chapter, we will discuss the effects of the heat pulses associated to seismic slip and critically comment the latest advances from studies on geological indicators of seismic fault slip in carbonate rocks. Geological evidence from three sites in Italy (Figure 1) and one site in England, where geological indicators of seismic fault slip may occur, is then considered. Eventually, recommendations are given and future trends are drawn. This chapter is mostly devoted to carbonate rocks, which are known as potential hypocenters for earthquakes in several tectonic environments [e.g. Amato et al., 1998; Di Bucci and Mazzoli, 2003; Miller et al., 2004; Milano et al., 2005;], are particularly diffuse in Italy [e.g. Micarelli et al., 2006; Billi et al., 2007], and are present in several other countries [e.g. Marshak and Engelder, 1985; Petit and Mattauer, 1995; Willemse et al., 1997; Kirschner and Kennedy, 2001; Kim et al., 2003; Mancini et al., 2004; Dumurdzanov, et al., 2005].

FAULT ZONE ARCHITECTURE

In the literature, conceptual models of large-displacement fault zones (Figure 2) are mostly coincident and usually include a meter-scale-thick fault core (where most slip is accommodated through individual centimeter-scale-thick slipping zones) bounded by a hundreds-of-meters-thick damage zone, which is where rock fractures occur without significant shear [e.g., Chester et al., 1993; Caine et al., 1996]. This structural architecture is well represented by the Punchbowl Fault in the San Andreas Fault system, California. The Punchbowl Fault exhumed from a depth of 2-5 km and accommodated about 30 km of slip [Chester and Chester, 1988]. Some active strands of the San Andreas Fault near Parkfield are characterized by several creeping sub-parallel fault cores, which cut through a wide damage zone [Hickman, 2007].

A spectacular example of the complexity of a mature plate-boundary fault zones exhumed from a depth of 1.5-4 km is the Carboneras Fault in Spain [Faulkner et al., 2003]. This fault accommodated a maximum displacement of about 40 km. The fault includes a 1-km-thick fault zone consisting of continuous and anastomosing strands of phyllosilicate-rich fault gouge bounding hundreds-of-meters-long lenses of dolostone.

With increasing depth, the fault zone architecture seems to vary with the grade of maturity (i.e. displacement) of the fault. For instance, long-lasting active faults exhumed from a depth of about 10-15 km and characterized by hundreds of kilometers of slip (e.g. the Median Tectonic Line in Japan), may show complex fault cores with mylonites and foliated-cataclasites (representative of the deeper activity of the fault) cut by phyllosilicate-rich foliated gouges and clay-rich cores, this latter being produced during the latest stages of exhumation [Wibberley and Shimamoto, 2003].

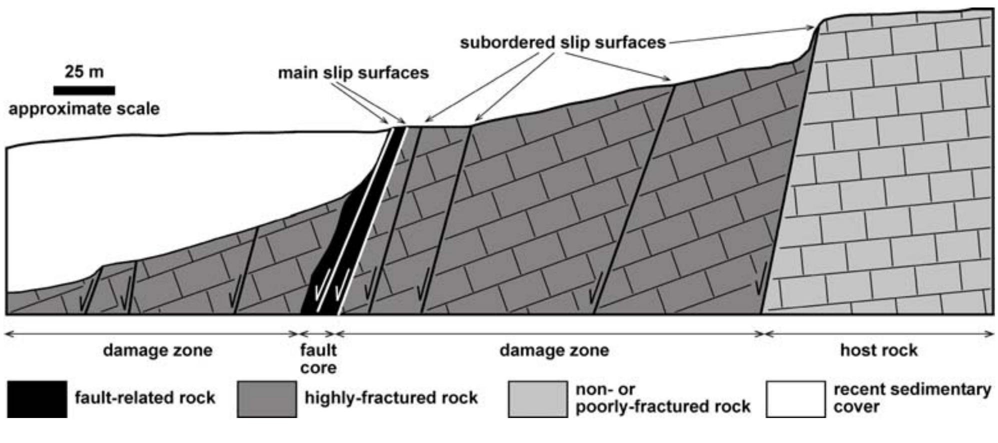


Figure 2. Conceptual model for the architecture of a typical fault zone in carbonate rocks [modified after Agosta and Aydin, 2006]. The fault zone includes a fault core, where most slip is accommodated, and a damage zone, where the carbonate strata are intensely fractured. The host rock is usually non- or poorly-fractured.

Instead, less mature fault zones exhumed from similar depth (9-11 km), but with cumulated displacements of several km at most, may consist of hundreds of centimeter-thick cataclastic horizons cutting a poorly developed damage zone (e.g., Gole Larghe Fault, Italy, Di Toro and Pennacchioni, 2005; Fort Foster Brittle Zone, Maine, Swanson, 1988; Ikertoq Brittle Fault Zone, Greenland, Grocott, 1980). In this latter case, the fault zone may host abundant pseudotachylytes, which, instead, are rarely found in more mature faults. This evidence provides preliminary insights into the complexity of natural fault zones and is symptomatic of how difficult is to determine and infer the fault structure at depth.

In carbonate rocks, the architecture of exhumed large-displacement fault zones has been recently depicted and analyzed [e.g. Salvini et al., 1999; Billi and Storti, 2004; Agosta and Aydin, 2006]. These fault zones usually include a fault core where cataclastic rocks occur and pristine sedimentary or tectonic fabrics are totally obliterated (Figure 2). The fault core may be several meters thick and it is usually bounded on one side by a major slip surface. Secondary faults may also cut through the fault core. The bulk of the fault core is constituted by a cataclastic breccia, whereas a very narrow (even less than 1 mm) layer of gouge usually occurs along the major slip surface. The fault core is included in a larger damage zone (up to hundreds of meters thick) where intensely fractured strata occur and the pristine sedimentary fabrics (e.g. bedding) are still visible. In the damage zone, pulverized rocks may occur [Agosta and Aydin, 2006] and the brittle deformation usually intensifies with approaching the fault core [Billi et al., 2003].

HEAT PULSES AND SLIPPING ZONE THICKNESS DURING EARTHQUAKES

During an earthquake, the release of the elastic strain energy stored in the wall rocks drives the propagation of the rupture and is converted into mechanical work in the fault zone [Scholz, 2002]. In particular, assuming that the energy adsorbed by plastic deformation in the damage zone and in the fault core is negligible [a reasonable assumption, e.g., Chester et al., 2005; Pittarello et al., 2008; Brantut et al., 2008], most mechanical work occurs in the slipping zone and is converted into heat (see below). Since thermal diffusivity κ in rocks is low ($\kappa = 10^{-6}$ m^2 s^{-1}, see Table 1) and the slip duration t at a point of a fault is between 1 and 10 s [Heaton, 1990], the heat penetration depth $z = (\kappa\ t)^{0.5}$ is limited to a few millimeters at most. It follows that heat pulses are localized in narrow bands (i.e., almost corresponding to the thickness of the slipping zone, see below) and, therefore, earthquake mechanics is mainly controlled by heat [Rice, 2006].

If heat losses by advection, radiation and diffusion are negligible [e.g., Di Toro et al., 2006b], energy budget considerations constrain the thickness of the slipping zone during earthquakes. The mechanical work $\tau\, d$ (where τ is the shear stress and d is the seismic slip) on the fault surface of area A is (1) converted into heat (E_{heat}) and (2) adsorbed in several energy sinks including dehydration (E_{dehyd}) of H_2O-bearing minerals (clays, micas, gypsum, etc.), decarbonation (E_{decarb}) of CO_2-bearing minerals (calcite, dolomite, etc.), amorphization (E_{amorph}) and melting (E_{melt}) of the fault rock assemblage, and fracturing (E_{surf}) or formation of new grain surface during sliding.

Table 1. Thermal properties (specific heat capacity), and energies adsorbed for melting, decarbonation, and amorphization in limestone, dolostone, and tonalite. Given the small amount of hydrated minerals in tonalite (less than 15% in the studied rocks, Di Toro et al., 2005), we did not report the dehydration energy. Data are from Brantut et al. 2008 [Br], Bruce and Walsh 1962 [B], Clauser and Hunges 1995 [C], Di Toro et al. 2005 [D], Holland and Powell 1990 [H], Samtani et al. 2002 [S], Xiao et al. 1997 [X], and Wright et al. 2001 [W]

Rock type	ρ $kg\ m^{-3}$	c_p at 473 K $J\ kg^{-1}K^{-1}$	κ $10^{-6}\ m^2\ s^{-1}$	Energy adsorbed for melting $J\ kg^{-1}$	Energy adsorbed for decarbonation $J\ kg^{-1}$	Energy adsorbed for amorphization $J\ kg^{-1}$	Specific surface energy $J\ m^{-2}$
Limestone	2710	962 [H]	1.3 [C]	n.n.	1783600 [X]	?	0.3 [W]
Dolostone	2900	943 [H]	1.7 [C]	n.n.	950000 [S]	?	0.3 [W]
Tonalite	2795 [D]	944 [D]	1.8 [D]	332000 [D]	n.n.	100000 [Br]	3 [B]

This energy partitioning is summarized as follows [modified from Kostrov and Das, 1988; Di Toro et al., 2005a]:

$$\tau\ d\ A = E_{\mathrm{heat}} + E_{\mathrm{dehy}} + E_{\mathrm{decar}} + E_{\mathrm{amor}} + E_{\mathrm{melt}} + E_{\mathrm{surf}} \qquad \text{(Eq. 1)}$$

where

$$E_{\mathrm{heat}} = c_{\mathrm{p}}\Delta T(\rho A w)$$

$$E_{\mathrm{amorph}} = E_{\mathrm{sp\ \ amor}}(\rho A w)$$

$$E_{\mathrm{dehyd}} = E_{\mathrm{sp\ \ dehy}}(\rho A w)$$

$$E_{\mathrm{decarb}} = E_{\mathrm{sp\ \ decarb}}(\rho A w)$$

$$E_{\mathrm{melt}} = E_{\mathrm{sp\ \ melt}}(\rho A w)$$

$$E_{\mathrm{surf}} = \gamma \frac{6w}{r} A$$

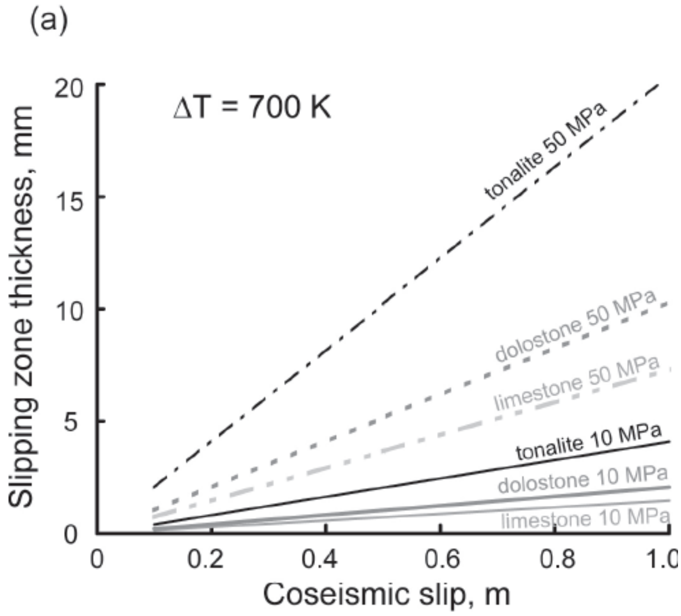
In the above equations, c_p is the specific heat capacity, ΔT is the difference between the maximum temperature achieved in the slipping zone and the ambient temperature, w is the slipping zone thickness, ρ is the rock density, and r is the average particle radius of the rock fragmented during seismic slip [a few nanometers, Chester et al., 2005; Ma et al., 2006; Pittarello et al., 2008]. $E_{\mathrm{sp\ amor}}$, $E_{\mathrm{sp\ dehy}}$, $E_{\mathrm{sp\ decarb}}$, and $E_{\mathrm{sp\ melt}}$ are energies adsorbed, for unit of mass (J kg^{-1}), during amorphization, dehydration, decarbonation, and melting, respectively. The specific surface energy is γ (in J m^{-2}). For sake of simplicity, in Eq. 1, we did not consider the mass fraction of each mineral in the fault rock assemblage. If the temperature achieved in the slipping zone is, for instance 1000 ^{o}C, biotite (melting temperature 700 ^{o}C) melts, whereas quartz (melting point 1700 ^{o}C) does not. It follows that only a fraction of the mechanical work will be adsorbed as E_{melt} (melting of biotite) whereas the remnant frictional work will be expended to further heat the quartz grains and the biotitic melt. From the equations above:

$$\tau\ d = w\left[\rho\ \left(c_{\mathrm{p}}\Delta T + E_{\mathrm{sp\,dehy}} + E_{\mathrm{sp\,decar}} + E_{\mathrm{sp\,amor}} + E_{\mathrm{melt}}\right) + \gamma\frac{6}{r}\right] \quad \text{(Eq. 2)}$$

and, rearranging, the thickness of the slipping zone is:

$$w = \frac{\tau\ d}{\rho\ \left(c_{\mathrm{p}}\Delta T + E_{\mathrm{sp\,dehy}} + E_{\mathrm{sp\,decar}} + E_{\mathrm{sp\,amor}} + E_{\mathrm{melt}}\right) + \gamma\frac{6}{r}} \quad \text{(Eq. 3)}$$

Energy budget considerations suggest that slipping zone thickness increases with shear stress and slip, but decreases with the temperature achieved in the slipping zone (Figures 3a and 3b). If we consider thermal and energetic values typical for carbonates (limestones and dolostones) and crystalline rocks (Table 1), we can predict that for given shear stress, seismic slip, and grain size (say r = 10 nm), the thickness of the slipping zone in carbonates is thinner than in crystalline rocks. In particular, assuming an ambient temperature of 200 ^{o}C, a temperature increase (ΔT) of 700 ^{o}C, which allows the rapid thermal decomposition of calcite and dolomite (850° and 750^{o} C, respectively), results in a slipping zone three and two times, respectively, thinner than that expected in the case of tonalite (Figure 3a).



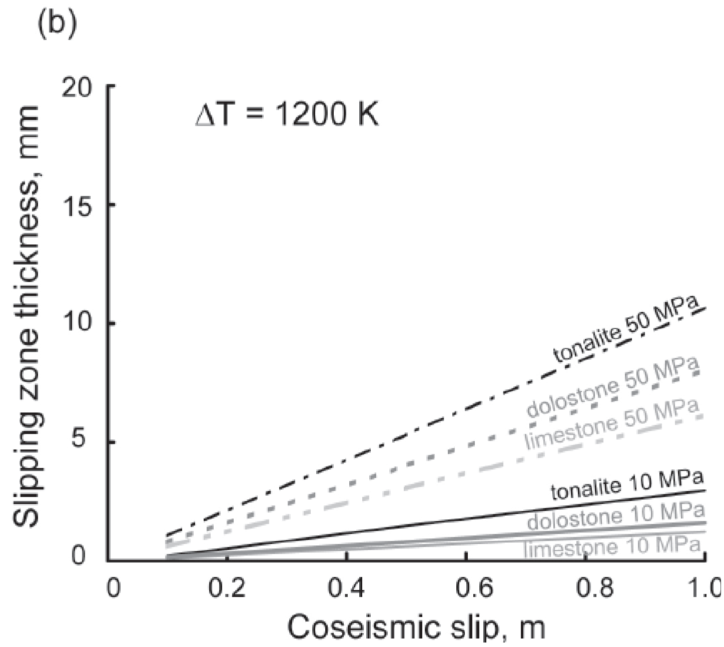


Figure 3. Plots of slipping zone thickness versus coseismic slip according to Eq. 3 and the thermal properties described in Table 1. In the computations, we neglected the energy adsorbed by amorphization. Ambient temperature is 200° C, average grain size in the slipping zone is 20 nm (r = 10 nm), and shear stress is between 10 and 50 MPa (reasonable values for shear stresses acting on faults at depths of 1-5 km). (a) Plot drawn for a temperature increase of 700 K. (b) Plot drawn for a temperature increase of 1200 K. Note that (1) with increasing temperature in the slipping zone, the thickness of the slipping zone decreases (compare b with a); (2) with increasing shear stress, the thickness of the slipping zone increases (compare the 10 MPa curve with the 50 MPa curve).

This is caused by the large heat adsorption due to calcite and dolomite decomposition (about 2 and 1 MJ kg^{-1}, respectively, Table 1). If the temperature in the slipping zone increases up to 1200 ^{o}C, allowing frictional melting of most of the tonalite, the difference in thickness between carbonate- and tonalite-bearing slipping zones decreases, though carbonate-bearing slipping zones remain significantly thinner than tonalite-bearing slipping zones. Preliminary studies in exhumed fault zones confirm the presence of mm-thick slipping zones cutting meters- to tens-of-meters-thick fault cores in dolomitic rocks (e.g., Figure 4). From the above considerations, we infer that ultra-thin slipping zones in carbonate rocks could be the result of seismic slip. Further microstructural and mineralogical studies (e.g., presence of periclase, see next section) are needed to test and validate this hypothesis.

MINERALOGICAL RECORD OF EARTHQUAKES IN CARBONATE ROCKS

Han et al. [2007b] conducted forty-two laboratory simulations of fault slip in specimens of Carrara marble (i.e. consisting of about 99% of calcite, $CaCO_3$) at room temperature and humidity. Simulations were done by using a rotary-shear apparatus at fault-normal stresses of 1.1 to 13.4 MPa and slip rates of 0.03 to 1.3 m s^{-1}.

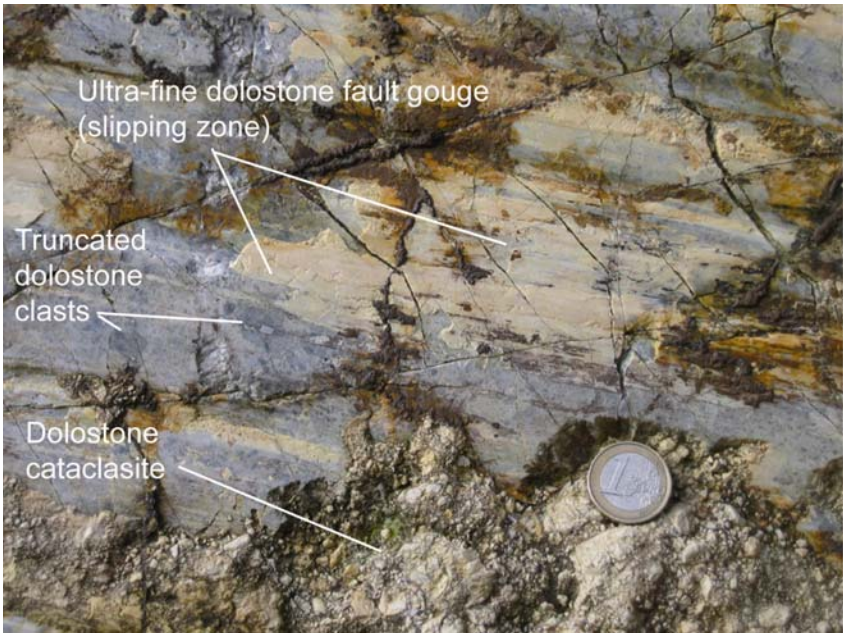


Figure 4. Slipping zone cutting through a dolostone cataclasite. The ultra-thin layer (< 1 mm) of dolostone fault gouge corresponds to the slipping zone. The striated slip surface truncates the dolostone cataclasites (note the dark gray clasts of dolomite). The fault surface was exhumed from a depth of less than 4 km depth [Zampieri et al., 2003]. The photograph is from Passo della Borcola, Schio-Vicenza Fault, Southern Alps, Italy. See coin (2 cm in diameter) for scale.

At seismic slip rates (> 0.4 m s^{-1}), the simulated faults showed pronounced slip weakening and concurrent thermal decomposition of calcite. In particular, by SEM and TEM observations, x-ray diffraction, and gas sensors, it was detected that calcite thermally decomposed into ultrafine particles (i.e. a few tens of nanometers in diameter) of lime (CaO) and hydrated lime [$Ca(OH)_2$] and into CO_2 gas. No thermal decomposition of calcite was detected at subseismic slip rates (i.e. 0.08 m s^{-1}). In all experiments, no frictional melting was observed. Fault weakening is attributed to the low frictional properties of ultrafine lime and hydrated lime particles formed during thermal decomposition of calcite, specifically to the flash heating on the ultrafine material. In contrast, the contribution of the CO_2 gas pressure on the fault friction [e.g. Miller et al., 2004] could be clearly ruled out by running a decisive simulation, in which significant fault weakening was still observed also after complete decomposition of calcite, i.e. meaning when no further emissions of CO_2 gas occurred.

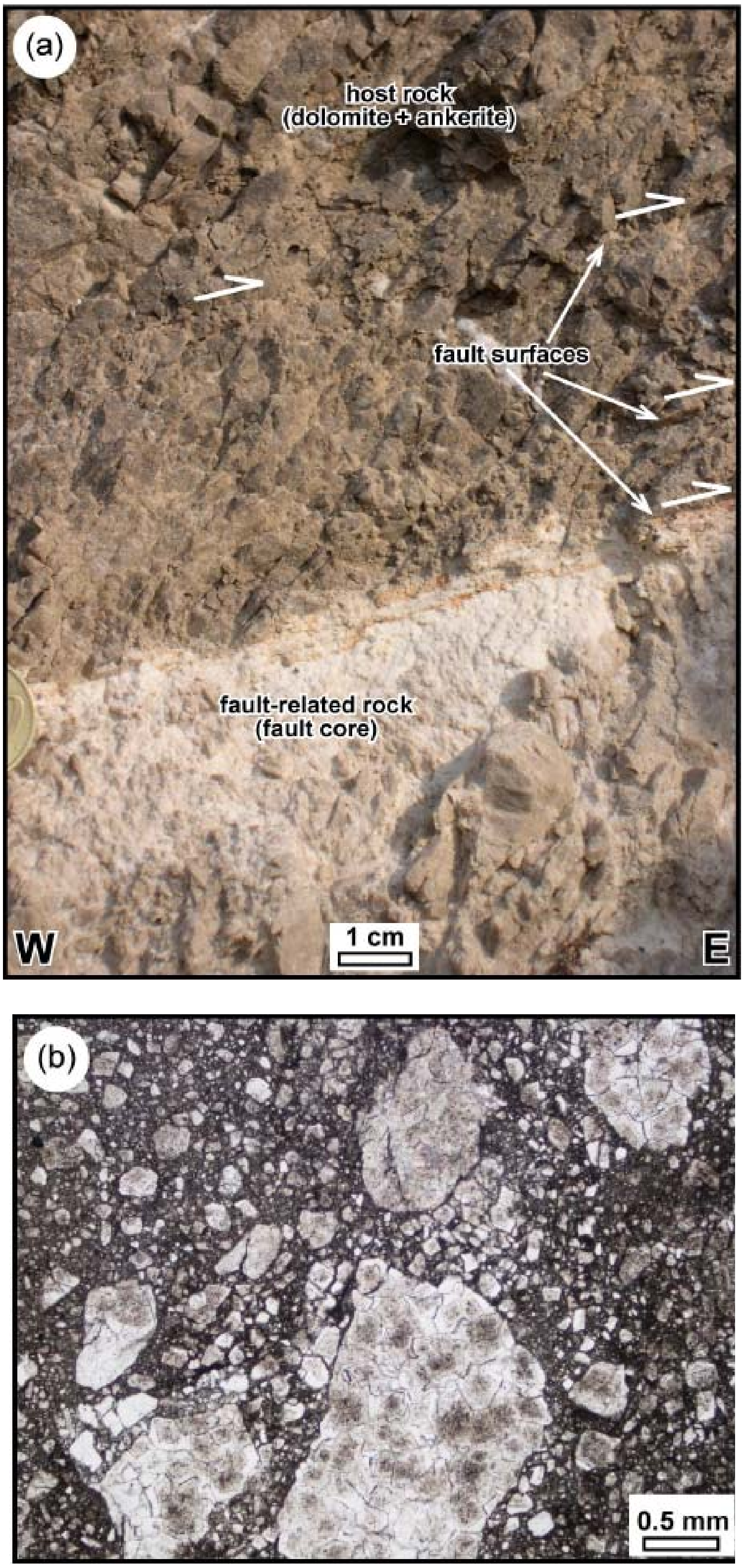
The experiments conducted by Han et al. [2007b] show that the products of calcite thermal decomposition (i.e. ultrafine particles of lime and hydrated lime) are potentially suitable indicators of seismic fault slip in carbonate rocks; however, the very low stability of lime and hydrated lime, which rapidly transform into calcite by contact with CO_2-bearing fluids under room conditions, makes these substances very poor indicators of seismic fault slip in natural examples. In contrast, ultrafine particles of calcite may be a reliable indicator of seismic fault slip also in nature. These particles, in fact, may be the final product of calcite thermal decomposition during seismic slip (i.e. producing ultrafine particles of lime or hydrated lime) and subsequent transformation of lime and hydrated lime into calcite again by contact with CO_2-bearing fluids. This inference should be properly validated in natural examples.

Han et al. [2007a] conducted a new set of fault slip simulations in siderite ($FeCO_3$)-rich carbonates instead of marble (mostly $CaCO_3$). In terms of stability of the earthquake record, these experiments are more promising and useful than those conducted in the Carrara marble. It was, in fact, found that, under seismogenic conditions, by shear heating, siderite thermally decomposed into CO_2 gas and magnetite (Fe_3O_4), which is much more stable than lime and hydrated lime under room conditions. It follows that a significant concentration of magnetite along natural faults affecting siderite-rich carbonate rocks may be a clear indicator of seismic fault slip. It should be considered, however, that also magnetite may undergo reactions in a geological time scale.

Simulations of seismic fault slip in marble and siderite-rich carbonates [Han et al., 2007a, 2007b] indicate future promising trends in the study and discovery of earthquake indicators along faults in nature. In addition to calcite and siderite, in fact, other metal-bearing carbonates affected by faults may reveal as sites bearing reliable and detectable indicators of seismic fault slip. For instance, it is known that dolomite [$MgCa(CO_3)_2$] and ankerite [$Ca(Fe, Mg, Mn)(CO_3)_2$] may undergo thermal decomposition producing substances more stable than lime and hydrated lime, including periclase (MgO), magnetite (Fe_3O_4), magnesioferrite ($MgFe_2O_4$), and calcite ($CaCO_3$), whose presence along faults could be easily detected by x-ray diffraction on appropriately collected samples. The kinetics of the thermal decomposition reactions and, therefore, the possibility that these reactions can truly occur in nature along faults under seismogenic conditions should be, of course, properly considered and verified [e.g. Milodowski et al., 1989; Fazeli and Tareen, 1992; Samtani et al., 2002; Gunasekaran and Anbalagan, 2007]. Ree et al. [2006], for instance, have already conducted laboratory simulations of seismic fault slip in dolomite and found that, under seismogenic conditions, this mineral undergoes a thermal decomposition reaction similar to that observed for calcite and siderite [Han et al., 2007a, 2007b].

It should be also considered that, in addition to the products of mineralogical decomposition [e.g. Han et al., 2007a, 2007b], other promising indicators of past heating along faults are being studied [O'Hara, 2004; Fukuchi et al., 2005; Mishima et al., 2006; Ujiie et al., 2008] and may soon provide interesting results in terms of paleoearthquake detection.

The above-reported results from laboratory replications of seismic fault slip necessitate appropriate validation in natural examples. Natural examples possibly suitable for the study of earthquake-related thermal decomposition of carbonate minerals along faults occur near Sperlonga (Figure 1), in a site recently studied by Billi et al. [2008]. This site is located in the inner portion of the Neogene Apennines fold-thrust belt, central Italy. Reverse and transpressional faults are exposed across Jurassic dolomitic strata and are usually bordered by a band of carbonate cataclastic rocks including gouges and breccias, which are collectively named as fault core (Figures 5a and 5b). In the Sperlonga area, contractional deformation occurred mostly during Tortonian time. Afterward, faults exhumed from less than about 3-4 km [Cipollari and Cosentino, 1995; Cosentino et al., 2002; Rossi et al., 2002]. The fault-perpendicular thickness of the analyzed fault cores is usually less than about 1 m and the fault displacement is estimated in as much as a few decameters. Mineralogical analyses showed that the host rock mainly consists of dolomite with a minor content of ankerite (Figure 5c).


(a)
host rock
(dolomite + ankerite)
fault surfaces
fault-related rock
(fault core)
W
1 cm
E
(b)
0.5 mm

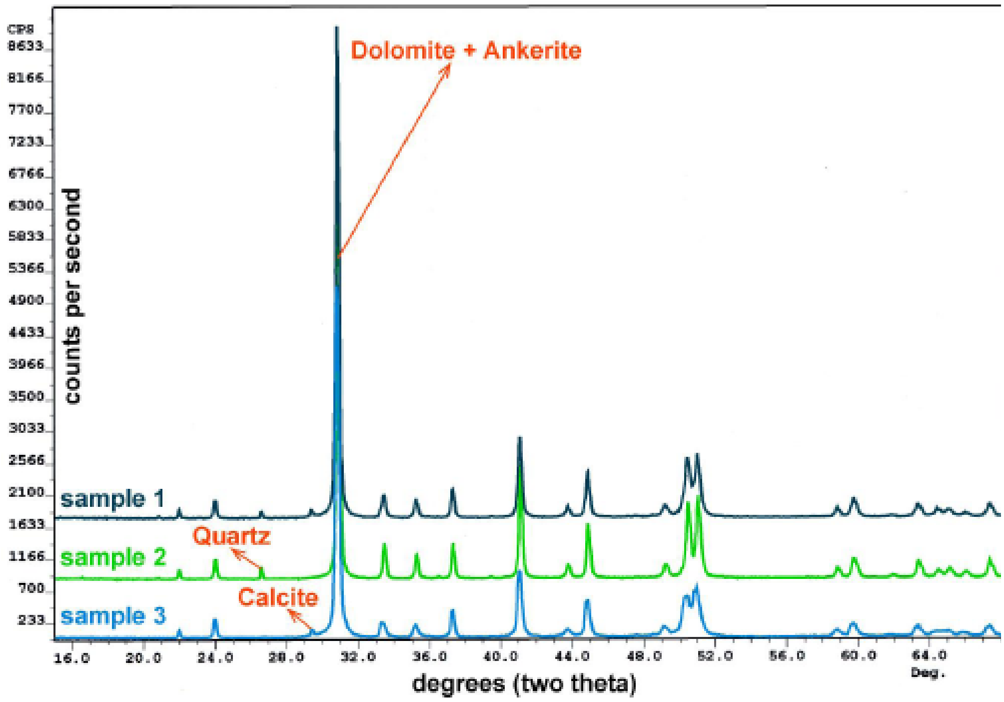


Figure 5. (a) Photograph of reverse (i.e. top block moved toward the east) fault-related rocks developed across metal-bearing dolomitic strata from the Sperlonga site (Fig. 1). The light brown-reddish color of the dolomitic host rock may be induced by some Fe-bearing carbonate minerals. (b) Microscope photograph of reverse fault-related rocks from the Sperlonga site. Note the overall cataclastic fabric consisting of some large survivor grains almost entirely surrounded by a fine matrix. (c) Results from x-ray diffraction analysis on three samples of host rock (samples 1, 2, and 3) from the Sperlonga site. A comparison of these results with the database of the International Center for Diffraction Data (ICDD; data set codes: 36-0426 and 41-0586) shows that the analyzed samples mostly consist of dolomite with a minor content of ankerite. Traces of calcite and quartz are also present. Analyses were done with a Scintag X1 diffractometer. This figure is reproduced after Billi et al. [2008] by kind permission of AGU.

Traces of calcite and quartz are also present. No mineralogical analyses were done on the fault core rocks, whose grain size distribution was determined only for the grains larger than 0.063 mm in diameter [Billi et al., 2008]. It follows that studying the mineralogy and size distribution of fine and ultrafine particles forming the fault cores exposed at the Sperlonga site may reveal the presence of earthquake indicators similar to those documented by Ree et al. [2006] and Han et al. [2007a, 2007b].

PULVERIZED ROCKS AS EARTHQUAKE RECORD

In the last few years, a group of researchers has concentrated its studies on a particular type of fault-related rocks named pulverized fault zone rocks or, simply, pulverized rocks [Brune, 2001; Reches and Dewers, 2005; Wilson et al., 2005; Dor et al., 2006a, 2006b]. This term mainly refers to crystalline plutonic and metamorphic rocks but also to sedimentary rocks [e.g. Agosta and Aydin, 2006], which were mechanically pulverized up to the micron scale or even finer despite the fact that they preserve most of their pristine fabrics (i.e. igneous, metamorphic, or sedimentary fabrics) and are not affected by significant shear deformation. Exposures of these rocks are well known along the San Andreas Fault in California, where they form a circa 70-100 m wide damage zone in the vicinity of the master slip surface [Wilson et al., 2005; Dor et al., 2006a]. At least in two cases, namely the Hartebeestfontein mine, South Africa, and the San Andreas Fault, California, it was ascertained (Hartebeestfontein mine) or inferred (San Andreas Fault) that the pulverized rocks developed under an impulsive tensional load (dynamic rock pulverization) such as that generated by an earthquake occurring within the tip region of a fast propagating fault [Reches and Dewers, 2005; Wilson et al., 2005] at crustal depths of a few kilometers at most [Ben-Zion and Shi, 2005; Rice et al., 2005]. As such, pulverized rocks are important candidates to become widely-recognized indicators of shallow earthquakes along faults. Further field studies are required to validate this hypothesis and to know the worldwide distribution of pulverized rocks. Rock fragmentation processes similar to those inferred for the pulverized rocks from California and South Africa were previously studied and reported [e.g. Sibson, 1986; Grady and Kipp, 1987].

A suitable site for the study of pulverized rocks is the Venere Fault (Figure 1) in the Apennines fold-thrust belt, central Italy [Cavinato et al., 2002; Agosta and Aydin, 2006; Agosta et al., 2006]. This fault is presently well exposed in Mesozoic platform carbonates within the Santilli Quarry (see site coordinates in Figure 1) and exhumed from more than 1 km [Ghisetti and Vezzani, 1999]. The Venere Fault is a segment of a post-orogenic system of normal faults several kilometers long, which accommodated as much as 0.6 km of throw since the Pliocene time at least [Cavinato et al., 2002]. This system of faults is seismically active and was the causative structure of the 1915, magnitude 7.0, Avezzano earthquake [Gasparini et al., 1985; Michetti et al., 1996]. Agosta and Aydin [2006] and Agosta et al. [2006] thoroughly documented and analyzed the pulverized rocks occurring in the damage zone of the Venere Fault (Figure 1). They found that these rocks are broken into small and very small fragments. In particular, the grain size distribution is power law over the 16.0-0.063 mm size range with a fractal dimension, *D*, of 2.95. Grain size under 0.063 mm was not analyzed, whereas rock porosity and permeability were estimated as 15% or higher and about 10^{-15}-10^{-14} m^2, respectively.

An additional site potentially of interest for the study of pulverized or intensely fractured carbonate rocks is the Mattinata Fault in the Adriatic foreland, central Italy (Figure 1). This structure is a regional strike-slip fault active since the Miocene time. At present, the Mattinata Fault is seismically active and was the causative structure of historical destructive earthquakes [Salvi et al., 1999; Patacca and Scandone, 2004; Billi et al., 2007; Del Gaudio et al., 2007]. The fault cuts across a 4-5 km thick succession of Mesozoic platform-to-basin carbonates and exhumed from a depth of less than about 2-3 km. Large exposures of fault-related rocks occur in the San Simeone Quarries (see coordinates in Figure 1), in the vicinity of the master slip surface of the Mattinata Fault [Salvini et al., 1999; Billi and Storti, 2004]. In the easternmost quarry, intensely fractured carbonates occur (Figure 6). Despite the severe damage, these rocks preserve most of the original sedimentary fabric (e.g. bedding and compaction stylolites).

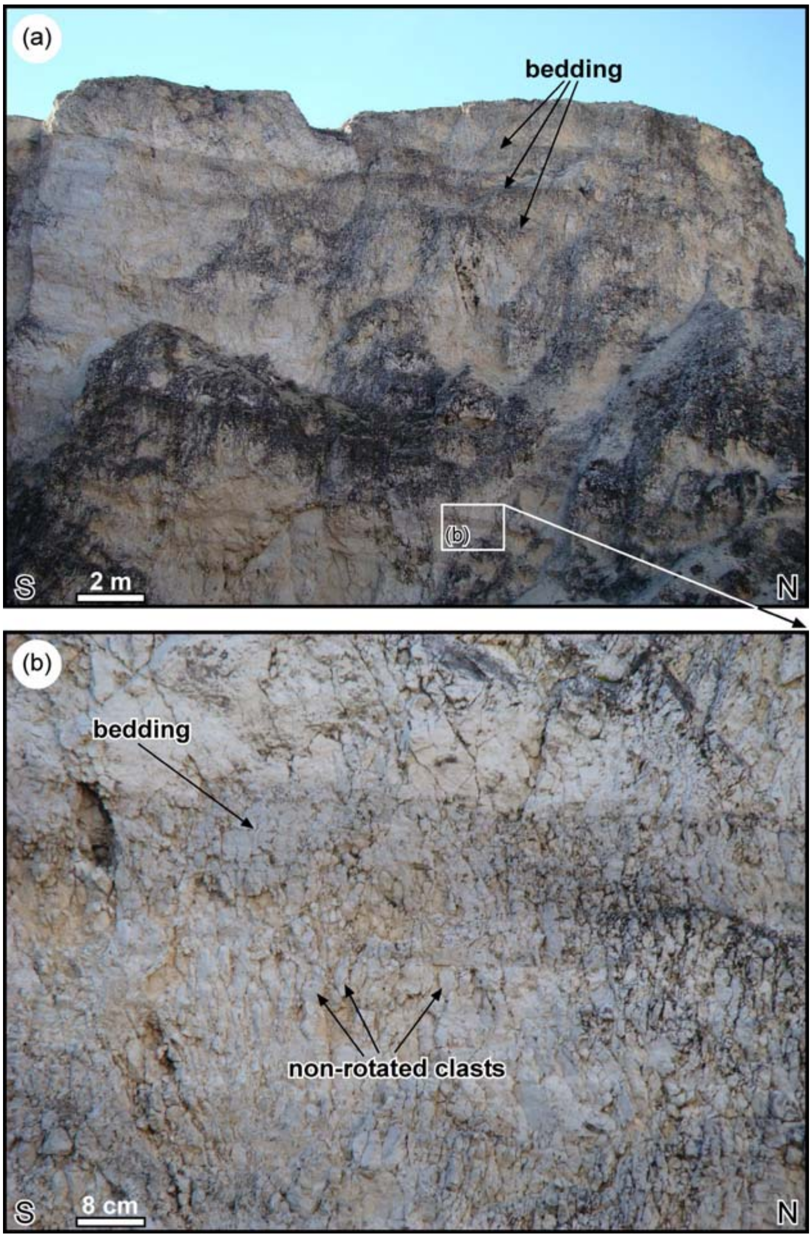


Figure 6. (a) Exposure of intensely fractured carbonate strata in one of the San Simeone Quarries along the Mattinata Fault in the Adriatic foreland, central Italy. (b) Enlargement from (a). Note that the carbonate rocks are intensely fractured despite the fact that they preserve most of their pristine fabrics (e.g. bedding) and are not affected by significant shear deformation.

Although these rocks cannot be properly classified as pulverized rocks because fractures are mostly in the centimeter scale (i.e. Dor et al., 2006a named a similar class of fault-related damage as "fragmentation"), a preliminary inspection of their exposures (Figure 6) suggests that these rocks may have undergone fragmentation under a unique and impulsive tensile load without considerable shear. Detailed study of these rocks and related computation of the energy and energy-release rate necessary to produce them [e.g. Chester et al., 2005; Reches and Dewers, 2005] may thus reveal that they are the effect of a single seismic fault slip [Li, 1987].

For some features, the intensely fractured carbonates observed in one of the San Simeone Quarries along the Mattinata Fault are very similar to the carbonate dilation breccias exposed along the reverse Dent Fault in the foreland to the Variscan orogen, northwestern England. Structural evidence suggests that these carbonate breccias were most likely produced at process zones ahead of advancing fault tips or at fault jogs during a single-phase fragmentation [Tarasewicz et al., 2005]. As such, analogously to the pulverized rocks observed in the Hartebeestfontein mine and along the San Andreas Fault [Wilson et al., 2005], also the Dent Fault breccias also may be the record of a fault seismic slip. In the case of the Dent Fault, proper energy computations are required to confirm whether the observed fault-related breccias may truly be the record of a seismic fault slip.

CONCLUSION

To make significant advances in the knowledge of earthquake mechanics, geophysicists and structural geologists should find natural records of earthquakes in addition to pseudotachylytes, which develop only in crystalline rocks. We provided analytical evidence suggesting that, in carbonate rocks, very narrow layers of cataclastic material along fault surfaces (e.g. Figure 4) can develop under seismogenic conditions. Field and laboratory studies of these layers are recommended to test the analytical evidence. Also, mineralogical evidence of seismic fault slip, such as that found in recent laboratory simulations on carbonate rocks [Han et al., 2007a, 2007b] and pulverized rocks like those studied along the San Andreas Fault and in a South African mine [Reches and Dewers, 2005; Wilson et al., 2005; Dor et al., 2006a], are very promising scientific targets in the near future to improve the comprehension of earthquake mechanics. More field, laboratory, and theoretical work should be done to know the worldwide diffusion of the above-mentioned evidence (i.e. thermal decomposition-related minerals and pulverized rocks) along faults and to understand whether this evidence is commonly an earthquake indicator. Three sites in central Italy, namely the Mattinata, Sperlonga, and Venere sites (Figure 1), are potentially promising for the discovery of earthquake indicators in fault-related carbonate rocks. In the Mattinata and Venere sites, carbonate pulverized or intensely fractured rocks may be the evidence of seismic fault slip [Billi and Storti, 2004; Agosta and Aydin, 2006]. In the Sperlonga site, carbonate minerals formed by thermal decomposition during fault seismic slip may be found along reverse and transpressional faults affecting strata of metal-bearing carbonates [Billi et al., 2008]. In addition to these sites, as well as the Dent Fault in northwestern England, where a fault-related dilation breccia occurs [Tarasewicz et al., 2005], may reveal as a promising site for the discovery of earthquake indicators in carbonate rocks.

ACKNOWLEDGMENTS

F. Agosta, M. Cocco, C. Giampaolo, T. Hirose, and S. Nielsen are thanked for fruitful discussions about fault-related rocks and earthquake indicators. AGU is thanked for the permission to reproduce Figure 5(c). AB acknowledges funding provided by a FIRB grant supervised by F. Barberi and C. Faccenna at Università Roma Tre. GDT acknowledges that the costs of his research were covered by grants from the Università degli Studi di Padova (Progetto di Ateneo 2007) and CARIPARO.

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