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Modelling the heat pulses generated on a fault plane during coseismic slip: Inferences from the pseudotachylites of the Copanello cliffs (Calabria, Italy)

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Abstract

A pseudotachylite vein network crosscutting late Hercynian foliated tonalites can be observed along the Copanello cliffs (Calabria, Southern Italy). Pseudotachylites formed during the Oligocene–Miocene at intermediate crustal levels (ca. 10 km). They show variable thickness ranging from few mm up to 10 cm, as observed in injection veins branching from the fault plane. Microscopic observations indicate that pseudotachylite matrix mainly consists of plagioclase (An_{46}–An_{58}) and biotite microlites. Rounded clasts of quartz, plagioclase or of plagioclase–quartz lithic fragments are disseminated in the matrix. Intergranular, flow and spherulitic textures are commonly observed. Microstructural features are consistent with rapid crystallisation from melt. EDS analyses of rare and tiny glass veins indicated a trachyandesite or An_{50} plagioclase melt composition.

The conditions for pseudotachylite formation were reproduced by an analytical model taking into account the heat released by friction along a horizontal fault plane during a seismic event. The model is based on a three-stage rupture history that includes nucleation, propagation and stopping. In addition, by means of a numerical approach, the model reproduces cooling that follows the stopping stage.

According to previous studies, the thermal perturbation induced by fault displacement is very intense. In fact, temperatures exceeding the tonalite and even An_{50} plagioclase liquidus (1470 °C) are reproduced by small amount of slip (≤6 cm) in suprahydrostatic regime. On the other hand, the thermal perturbation is strongly localised and of short duration. Peak temperatures abruptly decrease at a short distance from the fault plane (typically in few millimetres). In these conditions a thin film of melt can be produced. Therefore, the presence of cm-scale pseudotachylite veins can be only explained assuming an efficient and fast melt migration towards dilatant sites, such as pull-apart structures and

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injections veins. Results of the model may be useful to predict the thermal disturbance produced by earthquakes of low intensity.

Keywords: Pseudotachylite; Frictional heating; Slip time function; Tonalite; Calabria

1. Introduction

Pseudotachylites, though first defined in impact structures (Shand, 1916), have been recognized in several fault zones developed at different crustal depths (i.e., Passchier, 1982; Swanson, 1992; Camacho et al., 1995; Wenk et al., 2000). The presence of tectonic pseudotachylites has been related to high-velocity frictional slip episodes along fault planes indicative of ancient seismic events (Sibson, 1975). Shear heating is capable of generating a short-lived and localized thermal anomaly, with temperatures exceeding 1000 °C in the vicinity of the fault plane (Spray, 1995).

Several numerical and analytical models (e.g. McKenzie and Brune, 1972; Cardwell et al., 1978; Lachenbruch, 1980; Killick and Roering, 1998; Fialko, 2004) have been proposed to reproduce the temperature rise consequent on frictional sliding along a fault plane. They differ either for the approach (kinematical vs. dynamical) used in simulating the rupture process or the assumption on the initial thickness of the fault zone. Laboratory studies (e.g. Spray, 1995; Hirose and Shimamoto, 2003; Di Toro et al., 2004) have been performed to evaluate the physical conditions required to produce frictional melting. The finite difference method has been adopted by Di Toro and Pennacchioni (2004) to model the subsequent cooling.

In this paper we present a new model for the heat pulse generated by frictional heating on a fault plane. The model is based on seismic source kinematics (e.g. Haskell, 1964; Sato and Hirasawa, 1973; Sato, 1994; Deichmann, 1997) and includes the three stages of the slip evolution process: nucleation, propagation and stopping of the rupture. This is in agreement with worldwide experimental evidence for the existence of nucleation (Iio, 1995; Beroza and Ellsworth, 1996) and stopping phases (Madariaga, 1976; Brustle and Muller, 1997).

Sudden temperature increase is responsible for the production of small amounts of melt that can be found along the fault plane in the so-called fault veins, or as accumulations in dilatant fractures to form injection veins (Sibson, 1975; Magloughlin and Spray, 1992). Melt production has been proven in experiments (Spray, 1995), and in some glassy natural pseudotachylites associated to recent faults (Lin, 1994a). However, glass is generally rare in pseudotachylites, largely because of subsequent devitrification and alteration processes. For this reason some authors emphasized the connection between pseudotachylites and cataclasites, pointing out that intense comminution processes are responsible for the glassy appearance of some veins (Wenk, 1978; Wenk et al., 2000). On the other hand, the microstructure of several pseudotachylites, characterized by dendritic and spherulitic microlites, clearly implies a rapid crystallization from a melt (Camacho et al., 1995).

Widespread evidence of melting with formation of a pseudotachylite vein network is found in a fault zone crosscutting late Hercynian foliated tonalites, exposed along the Copanello cliffs (Calabria, Italy; Fig. 1a). Pseudotachylites occur as spectacular cm- to dm-thick injection veins branching from fault planes. The fault zone is located near the southern shoulder of the Catanzaro Graben, an E–W oriented trough offsetting the Calabria–Peloritani terrane (Bonardi et al., 2001) from the Ionian to the Tyrrhenian sea (Fig. 1a).

Field observations and petrological features of pseudotachylites from Calabria were used to obtain constraints on the frictional heating model.

2. Geological setting

The Calabria–Peloritani terrane (Bonardi et al., 2001) is characterized by the presence of pre-Mesozoic basement units lacking in the adjoining chains: the NW–SE trending Southern Apennines and the E–W trending Maghrebides of Sicily. The basement underwent contractional tectonics related to the for-