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The Central Southern Alps (N. Italy) paleoseismic zone: a comparison between field observations and predictions of fault mechanics

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Abstract

The internal sectors of the Orobic Alps (Northern Italy) are characterised by Alpine age regional shortening showing a transition, through time, from plastic to brittle deformation. Thrust faults cut Alpine ductile folds and are marked by cataclasites and, locally, by pseudotachylytes, suggesting that motion was accommodated by seismic frictional slip. In the Eastern Orobic Alps the thrusting initiated at depths deeper than 10 km (the emplacement depth of the Adamello pluton) and possibly continued at shallower depths. This demonstrates that thrust motion occurred between 10 km depth and the brittle-ductile transition, i.e., at mid-crustal depths. The Orobic Alps exhumed paleoseismic zone shows different geometries along strike. In the central sectors of the Orobic Alps, thrust faults, associated with pseudotachylytes, have average dips around 40° and show no pervasive veining. Much steeper thrusts (dips up to about 85°) occur in the eastern Orobic Alps. In this area, faults are not associated with pervasive veining, i.e., fluid circulation was relatively scarce. This suggests that faulting did not occur with supralithostatic fluid pressure conditions. These reverse faults are severely misoriented (far too steep) for fault reactivation in a sublithostatic fluid pressure regime. We suggest that thrust motion likely started when the faults were less steep and that the faults were progressively rotated up to the present day dips. Domino tilting is probably responsible for this subsequent fault steepening, as suggested by a decrease of the steepness of thrust faults from north to south and by systematic rotations of previous structures consistently with tilting of thrust blocks. When the faults became inclined beyond the fault lock-up angle, no further thrusting was accommodated along them. At later stages regional shortening was accommodated by newly formed lower angle shear planes (dipping around 30–40°), consistently with predictions from fault mechanics.

Keywords: Thrust faulting; Fault mechanics; Southern Alps; Pseudotachylyte; Paleoseismicity

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1. Introduction

The understanding of the mechanics of brittle-frictional faults has greatly advanced in the last decades. The coupling of information from laboratory experiments on rock failure (Byerlee, 1978; Jaeger and Cook, 1979) with the knowledge of the state of stress within the shallow seismogenic crust from theoretical considerations (e.g., Anderson, 1951) and from in situ stress measurements (e.g., McGarr and Gay, 1978; Townend and Zoback, 2000) has led to the development of a widely accepted theory of fault mechanics (e.g., Sibson, 1998). This theory is based on rock failure data and stress distributions typical of the shallowmost crust. The understanding of the mechanical behaviour of the deep seismogenic zones (i.e., close to the bottom of the seismogenic zone) is, however, particularly important because it has been suggested that large earthquakes tend to nucleate near the base of the brittle layer (Das and Scholz, 1983; Sibson, 1983). At such depths, confirmation of the validity of the theory of fault mechanics comes mainly from seismological observations rather than from field studies.

Deep paleoseismogenic zones are well investigated from a structural geology point of view both in the field and in laboratory (e.g., Wenk et al., 2000; Di Toro and Pennacchioni, 2004 and references therein). However, comparisons between field and laboratory observations and predictions of the theory of fault mechanics are less frequent. Such a comparison is the aim of our work. We present structural observations from the Central Southern Alps (Italy), a fold and thrust belt that exposes, in its innermost portions, thrust faults that developed at the bottom of the seismogenic zone and were later exhumed. In this area the dips of thrust faults increase from west to east, where reverse faults as steep as 85° occur. In the easternmost parts of the belt, a second generation of reverse faults, cutting previous steep thrusts, is observed. The east–west variation of fault dips and the occurrence of a second generation of reverse faults in the east are discussed within the framework of the theory of fault mechanics, which proved to be efficient to explain seismological observations from deep seismic zones. We infer that the frictional reactivation of the faults and domino tilting of fault planes can explain the geometry of thrust faults in this area.

2. Geology of the Orobic Alps

The Southern Alps are the south vergent retro-belt of the north vergent Alpine orogen. The metamorphic pro-belt and the anchimetamorphic to non metamorphic retro-belt are, at present, separated by the Periadriatic Line, a dextral transpressive fault active mainly since the Oligocene (Schmid et al., 1989).

The Orobic Alps are the portion of the Southern Alps bounded by the Como Lake to the west and by the Giudicarie Line to the east and consist of a south vergent fold-and-thrust belt (e.g., De Sitter and De Sitter-Koomans, 1949; Gaetani and Jadoul, 1979; Brack, 1981; Castellarin et al., 1992; Forcella, 1988; Schönborn, 1992; Roeder, 1992). This belt developed during Cretaceous-Paleocene oceanic subduction and subsequent continental collision (e.g, Doglioni and Bosellini, 1987; Bernoulli and Winkler, 1990; Zanchi et al., 1990; Carminati et al., 1997). The Orobic system of stacked thrust sheets is limited at its base by a décollement, which deepens from about 5 km under the Po plain to about 16 km in the vicinity of the Periadriatic Line as shown by commercial and deep seismic lines (CROP-project) and by borehole stratigraphies (e.g., Pieri and Groppi, 1981; Montrasio et al., 1994; Carminati and Siletto, 1997; Scrocca et al., 2003). The polyphase Alpine shortening involved, in the Orobic fold-and-thrust belt, Variscan metamorphic basement (e.g., Siletto et al., 1993; Spalla and Gosso, 1999) in its northern portions and, more to the south, Permian to Cainozoic sedimentary cover deposited during the Alpine cycle (e.g., Forcella, 1988). A quasi-systematic younging of both deformation age and stratigraphic age of the rocks takes place toward the south (Schönborn, 1992). The pre-shortening geometry of the sedimentary basins strongly influenced the location and geometry of Alpine thrusts and of transverse zones dissecting the general E–W trend of folds and thrusts (e.g., Laubscher, 1985; Schönborn, 1992). The north-eastern part of the Orobic Alps was intruded, in the middle Eocene–early Oligocene by the Adamello pluton, which cut and deformed the Alpine contractional structures (folds and faults) and caused contact metamorphism in both basement and cover (Cornelius, 1928; Brack, 1981). The pluton consists of several magmatic bodies that were emplaced between 43 and 30 Ma BP, with a general younging of the intrusion from south to north (Del