Geological Society, London, Special Publications

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Geological Society, London, Special Publications 2006; v. 262; p. 245-258
doi:10.1144/GSL.SP.2006.262.01.15

Miocene to present major fault linkages through the Adriatic indenter and the Austroalpine–Penninic collisional wedge (Alps of NE Italy)

M. MASSIRONI[1], D. ZAMPIERI[1,2] & A. CAPORALI[1]

[1]*Dipartimento di Geologia, Paleontologia e Geofisica, Università di Padova, Via Giotto 1, 35137 Padova, Italy (e-mail: matteo.massironi@unipd.it)*

[2]*CNR, Istituto di Geoscienze e Georisorse, Sezione di Padova, Corso Garibaldi 37, 35137 Padova, Italy*

Abstract: From the Miocene onwards, the Alpine and South Alpine domains have been closely coupled within the framework of fault kinematics and geodynamic processes related to the continuing indentation of the Adria plate against Europe. In this study, the post-Oligocene evolution of a wide sector of the North Adriatic indenter border and nearby areas is re-examined in an extensive regional context by means of structural, geochronological and seismotectonic data. The Adria northern edge roughly corresponds to the Periadriatic lineament which is characterized in the central–eastern Alps by an abrupt change of orientation from east–west to NNE–SSW at the North Giudicarie line. Several strike-slip fault linkages have developed along the northern and southern sections of this major fault since the Miocene. In the Alpine domain, fault connections facilitated tectonic unroofing of the deeper nappes (Penninic units) in the Tauern window and a westward crustal stretching of the upper nappes (Austroalpine units) in the Brenner detachment hanging wall. In the Southern Alps, several fault linkages are observed, which are related to reactivation of inherited faults by the indentation process. These processes began during the early Miocene, were fully developed in the latest Miocene–early Pliocene, and are very probably still continuing. The final result is a complex shear zone of 250 km length, that in the southern part is considered as an incipient divide between the nearly stationary westernmost part of the North Adriatic indenter and the still northward-pushing main body of the Adria plate.

The Alps are composed of a Europe-vergent collisional wedge (Alpine domain *sensu stricto*) and a south-propagating fold-and-thrust belt (South Alpine domain). The Alpine domain is the product of a complex subduction–collisional history between the lower European plate and the upper Adria (Africa) plate, whereas the Southern Alps developed during the last stages of the collision. Interpretations of seismic reflection and refraction data across the Alps indicate that a rigid wedge of Adriatic lower crust, named the North Adriatic indenter, was pushed into the Austroalpine–Penninic wedge in Neogene time (Nicolas *et al.* 1990; Fantoni *et al.* 1993; Pfiffner & Hitz 1997; Schmid *et al.* 1997; Lammerer & Weger 1998). The aim of this paper is to re-examine the strike-slip fault system extending from the North Giudicarie line to the Schio–Vicenza line in an extensive regional context, partly corresponding to the boundary of the North Adriatic indenter in the Italian Alps. This revision is based on structural, geochronological, geophysical and seismological data provided by decades of detailed studies in the Alps. The relationships between the tectonic evolution of the Southern Alps and the Austroalpine–Penninic collisional wedge during the last stages of the Alpine orogenesis are closely examined, as well as their interactions with the accreting Apennine orogen. In addition, particular emphasis is placed on the role of the inherited Mesozoic structures in creating tectonic linkages between major strike-slip faults in the boundary zone of the Adriatic indenter.

The Alpine orogenic wedge and the South Alpine fold-and-thrust belt

The Alpine orogenic belt originated from the Cretaceous–present convergence between the Adriatic upper plate and the subducting European lower plate, including the Mesozoic Tethyan ocean (e.g. Dewey *et al.* 1989; Kurz *et al.* 1998; Dal Piaz *et al.* 2003). It is composed of a Europe-vergent collisional wedge (Alpine domain *sensu stricto*) and a south-propagating fold-and-thrust belt (South Alpine domain) separated by a major fault system called the Periadriatic lineament (Fig. 1).

The collisional wedge of the eastern Alps is composed of the Adria-derived Austroalpine continental basement and cover system, and the Penninic unit of the Tauern window, which includes the ophiolite-bearing Glockner nappe and the underlying Europe-derived continental basement (Central

From: MORATTI, G. & CHALOUAN, A. (eds) 2006. *Tectonics of the Western Mediterranean and North Africa*. Geological Society, London, Special Publications, **262**, 245–258.
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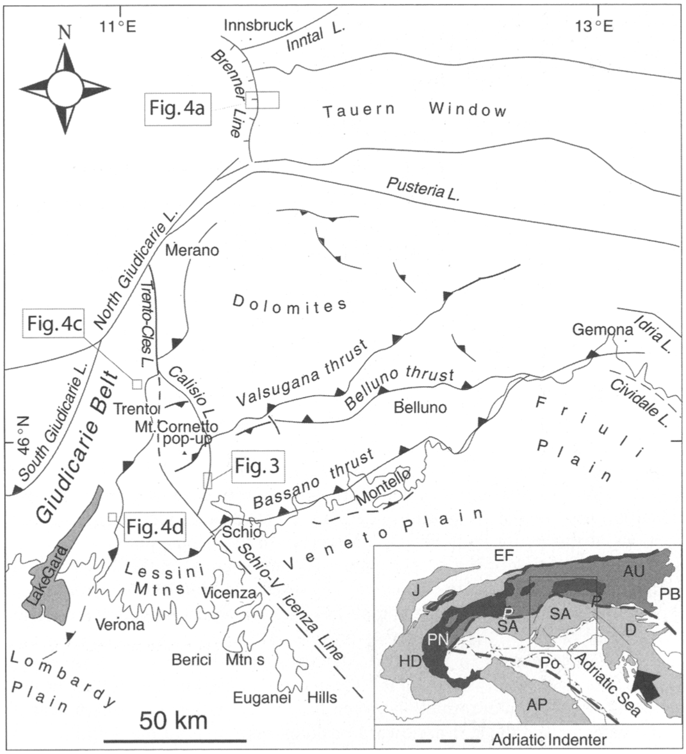

Fig. 1. Structural map of central–eastern Southern Alps. Inset: northern part of Adriatic indenter and main units. EF, European Foreland; J, Jura; HD, Helvetic–Dauphinois; PN, Penninic; AU, Austroalpine; SA, Southern Alps; Po, Po Plain; AP, Apennines; D, Dinarides; PB, Pannonian Basin; P, Periadriatic lineament.

Gneiss) and cover units (Fig. 2). During the subduction–collisional wedge development, the Periadriatic lineament was the active tectonic boundary between the Alpine exhuming wedge and the South Alpine rigid lithosphere, of which the frontal part (Austroalpine) was involved in the collisional wedge. The nappe stack was affected by subduction-related eclogite- to blueschist-facies metamorphism (scattered relics) of Eocene age (Penninic zone, Zimmermann *et al.* 1994) and a pervasive Barrovian (amphibolite- to greenschist-facies) overprint of Oligocene age (Tauern crystallization of Sander 1912; Christensen *et al.* 1994). In Oligocene time, during the continuing Adria–Europe convergence, rapid uplift took place together with magmatism along or near the Periadriatic lineament (von Blackenburg & Davies 1995; Dal Piaz 1999; Rosenberg 2004). Only the post-Oligocene evolution of the Alpine domain is of paramount importance for our purpose. From this time onward, the rigid Southern Alpine lithosphere indented the inner sector of the orogenic wedge, causing the rapid tectonic extrusion and cooling of the Penninic nappes previously softened by the Barrovian metamorphism. Consequently, the continuing north–south shortening caused the vertical exhumation of the Penninic units at the Tauern window (facilitated by erosion), tectonic unroofing along the Brenner detachment, and orogen-parallel escape of the Brenner footwall toward the opening Pannonian basin (Selverstone 1988; Ratschbacher *et al.* 1991*a*,*b*; Frisch *et al.* 2000). In the mean time, the upper part of the indenter, detached from the underlying lithosphere, was involved in the antithetic South Alpine fold-and-thrust belt propagating towards the Po Plain. From the Miocene onward, the tectonic histories of the Alpine collisional nappe stack and the Southern Alps may be considered together because both are concurrently deformed under the same regional stress field.

The Southern Alps and the Austroalpine domain preserve the original Mesozoic northwestern passive margin of the Adria plate (e.g. Bertotti *et al.* 1993). During the first stages of the Alpine orogeny (Late Cretaceous–Early Paleocene), the central and western Southern Alps constituted the slightly deformed hinterland of the Europe-vergent Austroalpine–Penninic collisional wedge.

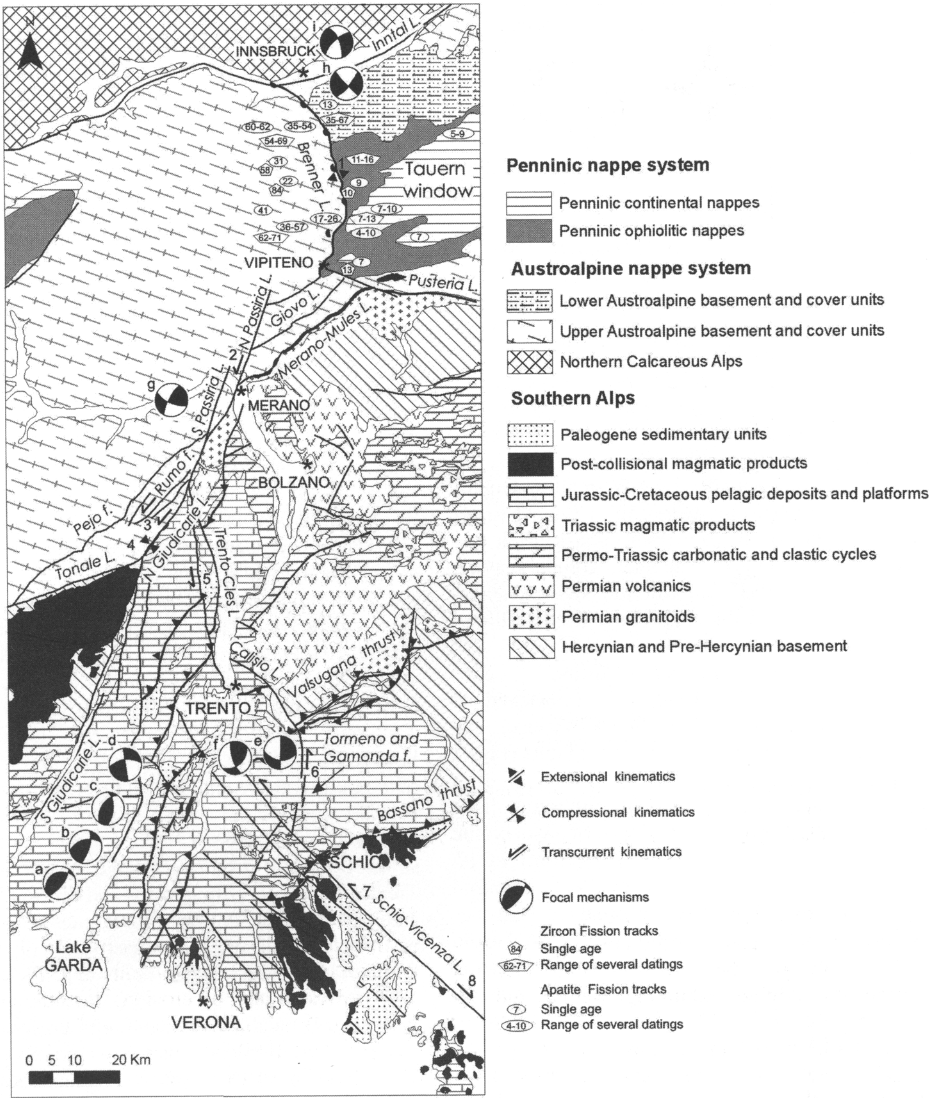

Fig. 2. Geological map of Innsbruck–Verona transect, showing Neogene fault kinematics and focal mechanisms. Fission-track dating shows the Early Miocene onset of the Brenner detachment (from Grundman & Morteani 1985; Fügenschuh *et al.* 1997, 2000). Fault kinematics: 1, Early Miocene to Pliocene (at least until 3 Ma) Brenner detachment kinematics (Behrmann 1988; Selverstone 1988, 1993; Fügenschuh *et al.* 1997; Bistacchi *et al.* 2003); 2, Mid-Miocene (*c.* 17 Ma) to Pliocene Passiria fault kinematics (Müller *et al.* 2001; Spiess *et al.* 2001; Viola *et al.* 2001); 3, Mid-Miocene to Pliocene kinematics of fault at North Giudicarie hanging wall (Fellin *et al.* 2002); 4, Mid-Miocene (*c.* 13 Ma) to Pliocene kinematics of North Giudicarie line and faults near its hanging wall (Prosser 2000; Fellin *et al.* 2002; Viola *et al.* 2004); 5, Mid-Miocene (*c.* 13 Ma) to Pliocene Trento–Cles system kinematics (Prosser 2000; Viola *et al.* 2004); 6, Mid-Miocene (*c.* 13 Ma) to Pliocene kinematics of Tormeno–Gamonda fault arrays (Zampieri *et al.* 2003); 7, Messinian (*c.* 8 Ma) to Pliocene Schio–Vicenza fault kinematics (Castellarin & Cantelli 2000; Zampieri *et al.* 2003); 8, Presumed Mid-Miocene Schio–Vicenza fault kinematics. Focal mechanisms: a, 2004.11.24, 45°54′N, 10°83′E, $h = 18$ km, Mi = 5.2, Salò (www.ingv.it/seismoglo/RCMT/); b, 1975.01.11, 45°39′N, 10°36′E, $h = 12$ km, M = 4, Gardone (Slejko *et al.* 1987); c, 1986.04.15, 45°46′N, 10°44′E, $h = 15$ km, M = 3.2, Tremosine (Slejko *et al.* 1987); d, 1976.12.13, 45°55′N, 10°50′E, $h = 2$ km, M = 4.5, Riva (Slejko *et al.* 1987); e, 1968.06.22, 45°48′N, 11°13′E, $h = 24$ km, M = 4.5 Pasubio (Slejko *et al.* 1987); f, 1968.06.22, 45°45′N, 11°14′E, $h = 23$ km, M = 4.1 Pasubio (Slejko *et al.* 1987); g, 2001.07.17, 46°39′N, 11°08′E, $h = 1.6$ km, M = 5.1 Merano (Pondrelli *et al.* 2004; Caporali *et al.* 2005); h, 1982.05.01, 47°17′N, 47°16′E, $h = 7$ km, M = 3.8 Innsbruck (Slejko *et al.* 1987); i, 1965.07.08, 47°18′N, 11°24′E, $h = 5$ km, M = 3.3 Mittenwald (Slejko *et al.* 1987).

In detail, pre-Mid-Eocene south-vergent structures cut by the Adamello intrusion are recorded only in the central sector of the Southern Alps (Brack 1981). In the Eocene–Early Oligocene phase, the easternmost sector was deformed by Dinaric SW-vergent thrusts. Later, from the Miocene onward (Neoalpine phase), the whole of the Southern Alps was shortened as a south-vergent fold-and-thrust belt, which developed as a retro-wedge (Doglioni & Bosellini 1987; Castellarin & Cantelli 2000).

The Southern Alps are subdivided into two main sectors by the NNE–SSW-trending Giudicarie belt (Fig. 1). The western sector exposes a complete crustal section, from the classic Ivrea lower crust to the post-Variscan Permian–Mesozoic cover. The eastern sector exposes low-grade basement and Permo-Mesozoic cover sequences, well represented in the Dolomites (Bigi *et al.* 1990). To the east, the Southern Alps are bounded by NW-trending Dinaric Palaeogene thrust fronts (Idria and Cividale lines), reactivated during the Neoalpine phase as dextral strike-slip faults (Fig. 1). The main tectonic features of the eastern Southern Alps are the Neogene south-vergent thrusts, i.e. the Valsugana (Serravallian–Tortonian), Belluno (Tortonian–Messinian?) and Bassano (Messinian–Pliocene) thrusts (Venzo 1941; Castellarin *et al.* 1992; Selli 1998) and, to the west, the NW-trending Schio–Vicenza and north-trending Trento–Cles strike-slip faults (Figs 1 and 2).

Many pre-Alpine extensional structures have been recognized from the analysis of syntectonic sediments (e.g. Castellarin 1972; Bertotti *et al.* 1993) and structures that crop out (e.g. Doglioni 1992; Zampieri 1995*b*). These normal faults, trending north–south to NNE–SSW, are derived from multiple tectonic phases, i.e. the early Permian and Mid-Triassic tectonomagmatic events (Cassinis & Perotti 1993; Dal Piaz & Martin 1998), Jurassic extension of the passive margin of the Apulian microplate (Bertotti *et al.* 1993), and Palaeogene rifting coupled with magmatism (Zampieri 1995*a*). The major map-view undulations of the Neogene SSE-vergent thrusts have been explained by inversion of these inherited normal faults (Doglioni 1992). The Giudicarie belt itself is the main example of a transpressive fault zone controlled by pre-existing Jurassic normal faults (Castellarin *et al.* 1993; Prosser 1998, and references therein).

The Giudicarie boundary of the Adriatic indenter and related fault systems in the South Alpine and Alpine domains

The western edge of the corner of the Adriatic indenter is marked by the North Giudicarie fault and a complex network of faults with dominant transcurrent kinematics, at a high angle to the east–west general trend of the chain (Figs 1 and 2). This crustal-scale shear zone includes the major strike-slip faults of the Southern Alps and the main faults of the Alpine domain *sensu stricto* involved in differential exhumation of nappes during the last stage of Alpine orogenesis.

The Schio–Vicenza line and its tectonic linkage with the Trento–Cles system

Within the Southern Alps fold-and-thrust belt, the Lombardian and Veneto–Friuli sectors and related forelands (i.e. the Po and Veneto–Friuli Plains) are separated by the Euganeo–Berico–Lessinian wedge, which is a morphological and structural divide. This high ('Adige embayment' of Laubscher 1996) is bounded to the east by the NW-trending Schio–Vicenza line and to the west by the frontal sector of the Giudicarie belt. The Schio–Vicenza fault probably originated as a Palaeogene extensional structure on the Dinaric foreland bulge (Doglioni & Bosellini 1987). South of Schio this fault shows a southward-decreasing top down-to-the-east throw connected to the development of the eastern Southern Alps foredeep (Finetti 1972; Pellegrini 1988). Many researchers have suggested that the post-Tortonian kinematics of the Schio–Vicenza line was sinistral (Semenza 1974; Zanferrari *et al.* 1982; De Vecchi *et al.* 1986; Castellarin & Cantelli 2000; Zampieri *et al.* 2003). On the other side of the Adige embayment, the Giudicarie belt is composed of a series of late Miocene ESE-vergent thrust sheets and NNE–SSW to north–south strike-slip faults, involving a large area between the Trento–Cles strike-slip systems and the South Giudicarie line (Fig. 2). All these structures are totally or partly the result of strike-slip reactivation on inherited Permian–Mesozoic normal faults (e.g. Picotti *et al.* 1995; Prosser 1998).

It is well established that faults are commonly composed of numerous discrete segments overlapping in en echelon geometry. Their mechanical linkage occurred by ductile strain structures (soft linkage), which may evolve into breaking faults connecting the initial segments (hard linkage) (e.g. Peacock & Sanderson 1991). In the area between Schio and Trento (Fig. 2), the processes of strike-slip reactivation and linkage of various fault segments are clearcut. A north–south-trending fault zone connects the Schio–Vicenza line with the Trento–Cles line via the Calisio line. These fault segments formed during earlier extensional events (Permian for the Calisio fault; Jurassic for the others), but they also were reactivated as normal faults in the Palaeogene. Finally, they were reactivated as sinistral strike-slip faults in the Neogene, when the eastern Southern Alps shortened (Zampieri *et al.* 2003). Pre-existing structures are an important mechanical anisotropy, which may be responsible for strain partitioning into strike-slip and dip-slip displacements along different structures (e.g. Tikoff & Teyssier 1994). Consequently, the inherited normal faults, oblique to the direction of shortening, played a key role in adsorbing the strike-slip component of the transpression. In the stepovers between fault segments, restraining and releasing structures developed at various scales.

At the kilometre scale, the most impressive evidence of soft linkage between fault segments is observed at the right step between the two conjugate Gamonda and Tormeno faults (Figs 2 and 3). In the overlap zone, Jurassic to Early Cretaceous sediments, filling a narrow graben, were shortened in a direction nearly parallel to the strike of the normal faults. The shortening has been accommodated by the development of an array of east- to ENE-trending folds associated with thrusts and reverse faults (Fig. 3).

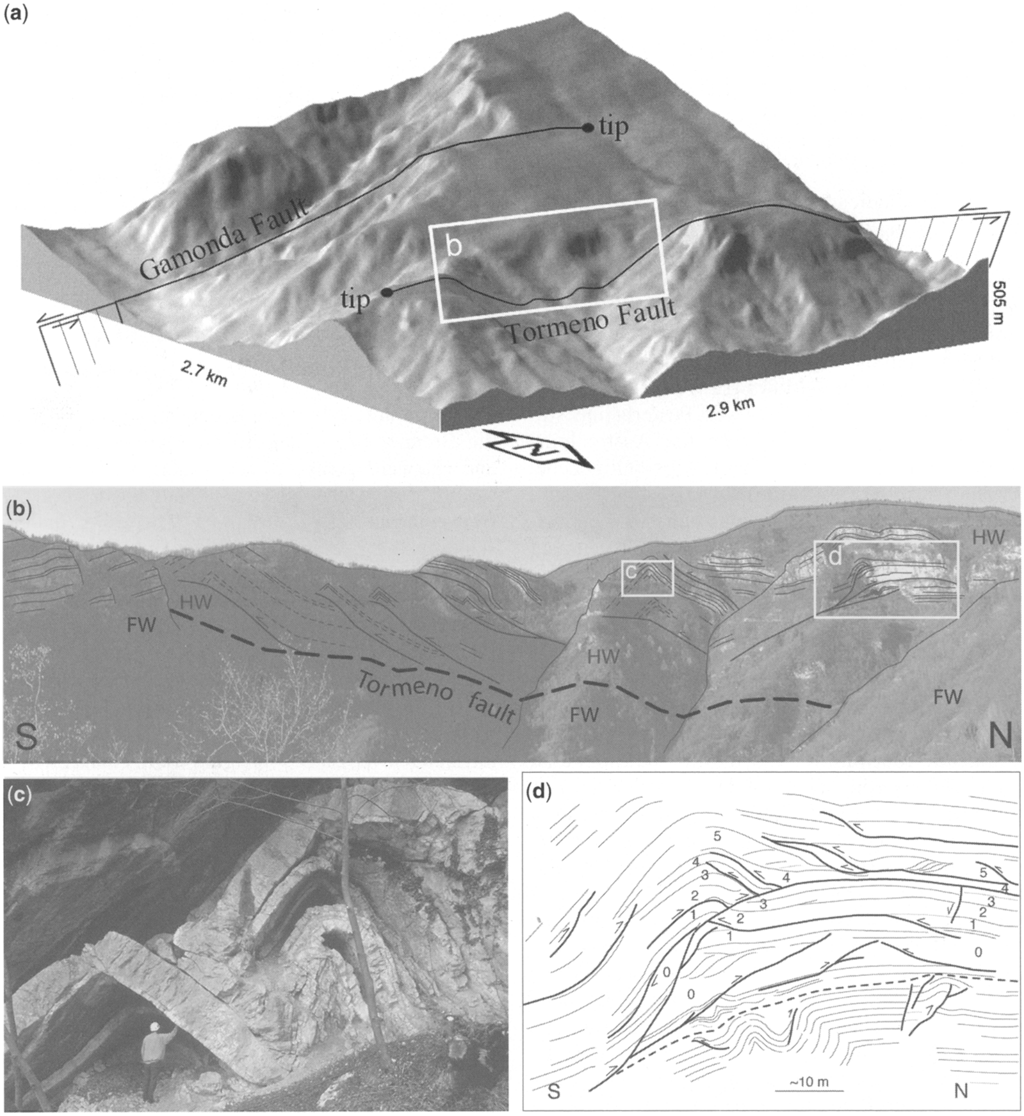

Fig. 3. Contractional stepover between Tormeno and Gamonda faults (location of the stepover structure is shown in Fig. 1). (**a**) Digital terrain model (DTM) perspective view looking NW. (**b**) Detail of fold-and-thrust structures inside stepover area (looking W). HW, hanging wall of the west-dipping Tormeno fault; FW, footwall of the west-dipping Tormeno fault. (**c**) Core of a major anticline (axis trending east–west), showing space accommodation structures (location shown in (b)). (**d**) Line drawing of contractional structures in core of the major box fold (location shown in (b)) (after Zampieri *et al.* 2003).

At a regional scale, the Schio–Vicenza line may be directly connected with the north-trending Trento–Cles line along the Adige valley, as suggested by Semenza (1974). If this hypothesis is correct, then the Trento–Cles–Schio–Vicenza fault system is a regional structure displaying a prominent right bend (Figs 1 and 2). Alternatively, the linkage between the Trento–Cles and the Schio–Vicenza strike-slip faults has been accomplished through the development of a restraining stepover limited to the east by the Calisio–Tormeno–Gamonda fault array (Monte Cornetto di Folgaria pop-up) (Zampieri *et al.* 2003) (Figs 1 and 2).

The North Giudicarie line and the related footwall and hanging-wall fault systems

The North Giudicarie fault is the moderately (45°) WNW-dipping tectonic boundary between the Austroalpine nappe-stack and the Southern Alps (low-grade pre-Alpine basement, Permian–Mesozoic sedimentary cover and scattered Oligocene intrusions). The North Giudicarie line had two distinct northern sections (Fig. 2) of different ages: (1) the NE-trending Merano–Mules fault, which is the kinematic linkage with the east–west Pusteria line, still the tectonic boundary between the Austroalpine nappe stack and the Southern Alps (Oligocene; Müller *et al.* 2001); (2) the NNE-trending Passiria fault, dissecting the Austroalpine units and connecting the Giudicarie line to the Brenner detachment through the NE-trending Giovo line (Miocene to present, Viola *et al.* 2001; Caporali *et al.* 2005). Several Alpine faults, dismembering the high-grade pre-Alpine basement of the Austroalpine nappes, are present in the hanging wall of the North Giudicarie fault and show the same average trend (e.g. the Pejo and Rumo faults). In the North Giudicarie footwall, a major north–south-trending fault system (the Trento–Cles fault system) is present. All these faults, together with some minor ones, constitute the North Giudicarie system, which underwent three main post-nappe deformational phases. The first was Late Cretaceous–Early Paleocene extension, recorded only in some faults (Pejo and Rumo mylonitic horizons) (Martin *et al.* 1991, 1998; Müller *et al.* 2001; Viola *et al.* 2003). The second involved Oligocene dextral activity along the North Giudicarie and Merano Mules faults, and is well constrained by radiometric ages on mylonites, pseodotachylytes and cross-cutting relationships with the Oligocene intrusive rocks (Prosser 1998; Müller *et al.* 2001). Only since the Early Miocene, during the third deformational phase, has the North Giudicarie system kinematics been closely related to the Southern Alpine strike-slip systems on one side and to the Brenner detachment on the other. In this period, NNW compression reactivated the North Giudicarie fault as an ESE-vergent thrust (Martin *et al.* 1991), and the sinistral strike-slip component was accommodated in its footwall by the inherited Mesozoic Trento–Cles fault system (Figs 2 and 4c,d) (Prosser 1998; Viola *et al.* 2004). An Early Miocene (21–17 Ma) nucleation and sinistral strike-slip kinematics has been demonstrated for the Passiria fault by fission-track dating and by the 20 km displacement of the older Giovo deformation belt and minor Oligocene intrusive bodies (Müller *et al.* 2001; Spiess *et al.* 2001; Viola *et al.* 2001). Similarly, the north to NNE faults in the North Giudicarie hanging wall also underwent sinistral kinematics in the same period, as demonstrated by ductile to brittle kinematic indicators (Fellin *et al.* 2002). Therefore, during the Miocene, the connection between the Giudicarie and Brenner faults was accomplished through the Passiria and Giovo faults (Fig. 2).

The Brenner low-angle detachment and tectonic exhumation in the Tauern window

At the mountain-belt scale, detachment activity at the Brenner line is due to the tectonic unroofing and eastward escape of the Tauern window units toward the extensional Pannonian basin (Fig. 1) (Ratschbacher *et al.* 1991*a*,*b*). Therefore, understanding the Brenner fault kinematics is of paramount importance in constraining the onset of differential tectonic denudation in the Eastern Alps and the activity of Alpine *sensu stricto* and South Alpine faults.

The Brenner west-dipping low-angle detachment (Fig. 4a and b) is the western tectonic boundary of the Tauern window and brings the Austrolpine basement and cover nappes (hanging wall), characterized by Cretaceous Alpine metamorphism, into contact with deeper Penninic units of the window (footwall), which record a dominant greenschist- to amphibolite-facies Alpine metamorphic imprint of Oligocene age. Its extensional activity is therefore consistent with a considerable gap in radiometric age: mica ages in the Austroalpine hanging wall go back to the Late Cretaceous (Frank *et al.* 1987, and references therein), whereas Oligocene to Miocene Rb/Sr ages in phengite and garnet are recorded inside the Tauern window (Frank *et al.* 1987; von Blackenburg *et al.* 1989; Christensen *et al.* 1994). Similarly, the Late Cretaceous–Early Miocene zircon and apatite fission-track ages in the Austroalpine nappe contrast with the Mid- to Late Miocene ages at the Brenner detachment footwall (Fig. 2) (Grundman & Morteani 1985; Fügenschuh *et al.* 1997, 2000). In addition, numerous ductile to brittle kinematic

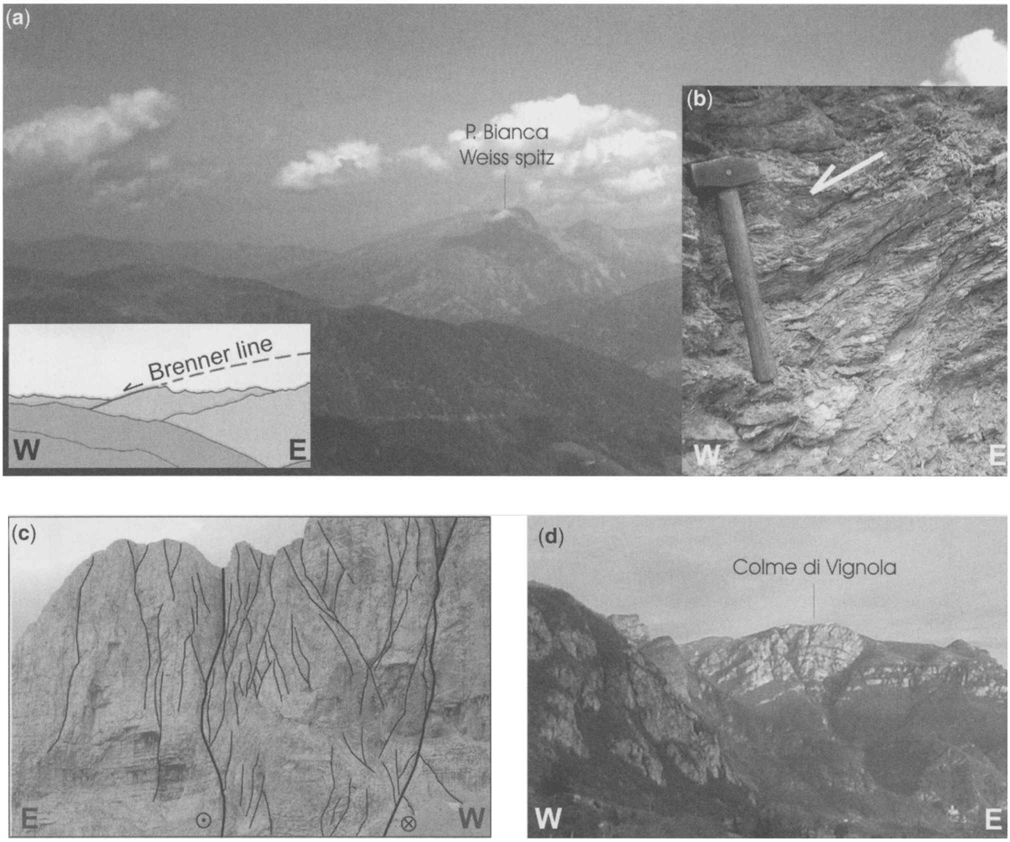

Fig. 4. Fault examples from Brenner area to Adige valley (locations shown in Fig. 1). (**a**) Panoramic view of Brenner detachment area (looking north). (**b**) Brenner detachment SC′ structures in the Penninic calcschists showing top-to-the-west movement. (**c**) NNE-trending strike-slip fault zone in Jurassic carbonates of Doss di Dalum (Brenta group, South Giudicarie system). Cliff face is *c*. 300 m high. (**d**) Panoramic view of Colme di Vignola positive flower structure (a few kilometres south of Ala) related to a NNE strike-slip fault of the Giudicarie Belt.

indicators constrain the top-to-the-west sense of shear of the Brenner detachment (Fig. 4b) (Behrmann 1988; Selverstone 1988, 1993; Fügenschuh *et al.* 2000; Bistacchi *et al.* 2003). All these data indicate that denudation of the Tauern window along the Brenner low-angle detachment began in the Early Miocene (Behrmann 1988; Selverstone 1988, 1993; von Blackenburg *et al.* 1989). The onset of lateral escape is further constrained by the dextral strike-slip deformations along the Pustertal fault system, which are coeval with or postdate the Late Oligocene intrusive bodies (Mancktelow *et al.* 2001). Nevertheless, in the light of the amount of displacement and regional tectonic influence, some workers believe that this process became important only after the Mid-Miocene (von Blackenburg *et al.* 1989; Fügenschuh *et al.* 1997; Frisch *et al.* 2000).

Present tectonic activity from the Brenner detachment to the Schio–Vicenza system

The South Alpine front between Schio and Gemona (Fig. 1) is the site of active thrusting related to the Neogene collisional convergence between Adria and Europe. The northeastern part of the Adriatic plate moved approximately toward the NNW, bordered to the NE by NW-trending dextral strike-slip faults (Idria and Cividale lines) and to the SW by the NW-trending sinistral Schio–Vicenza line (Figs 1 and 2).

In the eastern Alps the present regional velocity and strain fields, derived from global positioning system (GPS) data, *in situ* stress measurements (borehole break-outs) and seismotectonic data, indicate the maintenance of a compression running

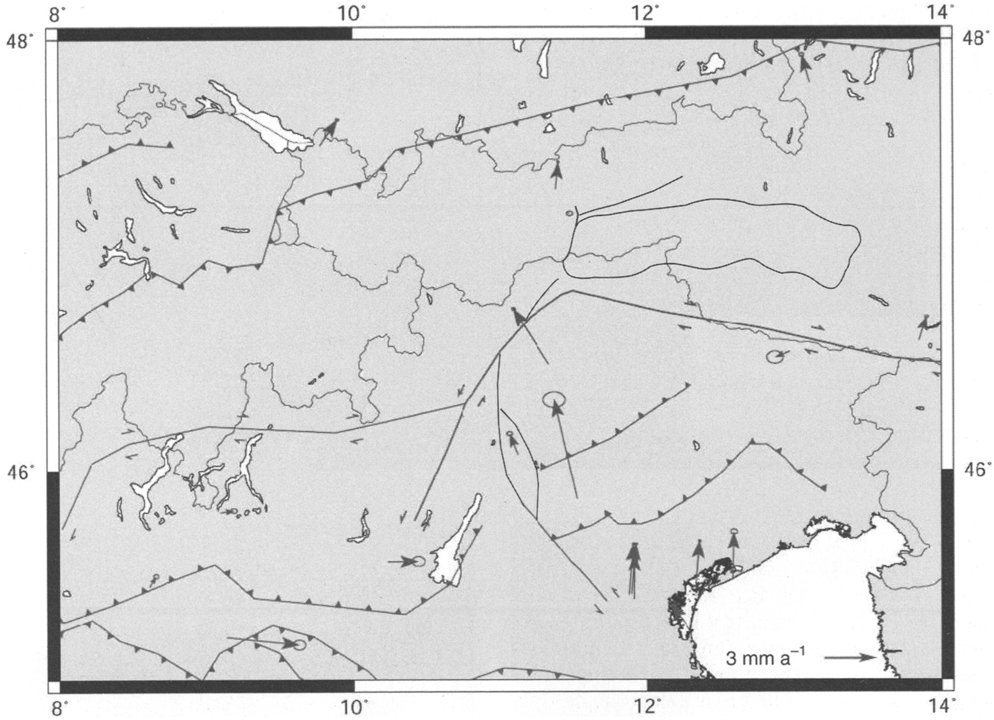

Fig. 5. Horizontal velocities of permanent GPS stations computed in ITRF2000 reference system (Altamimi *et al.* 2002), as interpreted by Caporali *et al.* (2003, 2005). Error ellipses are 1σ. Velocities are defined with respect to values predicted by Nuvel 1 A NNR (De Mets *et al.* 1994) Eulerian pole for Eurasia and, in this sense, are relative to a rigid Eurasian plate.

approximately NW–SE to NNW–SSE as in the Miocene (Müller *et al.* 1992; Zoback 1992; Bressan *et al.* 1998; Caporali *et al.* 2002, 2003; Oldow *et al.* 2002; Pondrelli *et al.* 2002, 2004; Battaglia *et al.* 2004) (http://www.ingv.it/seismoglo/RCMT/). The velocities reported by Caporali *et al.* (2002) have been improved with additional data up to November 2004 and are shown in Figure 5 with respect to a stable Eurasian plate. The velocities of permanent GPS stations east of the Schio–Vicenza fault and near the Adriatic Sea coastline, i.e. within the eastern sector of the North Adriatic indenter, are directed northwards. The velocities of the permanent stations north of the Pusteria line, i.e. within the stable Eurasian plate, are much lower. This decrease in horizontal velocity north of the Pusteria line is clear evidence of continuing compressional strain in the Friuli area, and sinistral shear strain along the Giudicarie and Schio–Vicenza fault systems. The eastward pattern of a few permanent GPS stations between longitudes of 8°E and 10.5°E in Figure 5 needs further investigation, as it may indicate a new scenario for the present-day tectonic flow in the Po Plain. This structural setting is consistent with the concept of an active northward indentation of the Adria plate against Europe (Renner & Slejko 1994; Regenauer-Lieb & Petit 1997; Bressan *et al.* 1998), whereas its westernmost part is nearly stationary (Oldow *et al.* 2002; Battaglia *et al.* 2004) or migrating eastward (Fig. 5).

According to the historical catalogue of the Istituto Nazionale di Geofisica e Vulcanologia (Valensise & Pantosti 2001; http://80.117.141.2/cft/ and http://emidius.mi.ingv.it/CPTI/), an earthquake of estimated magnitude 4.9 was recorded near Vipiteno in 1924. Based on the historical data of Schorn (1902), Lenhardt (2002) reported large earthquakes (up to M *c.* 7) in the Innsbruck area, related to the active Inntal line (Fig. 2, Reiter *et al.* 2002). Toward the Giudicarie system, the seismicity tends to be mostly at instrumental level except for the 2001 Merano earthquake (M = 4.8), and becomes stronger further south, between Verona and Vicenza (e.g. Verona 1117, M *c.* 6.4; Vicenza 1303, M *c.* 5; Lake Garda 2004, M = 5.5). Here it is associated with north–south strike-slip splays of the Giudicarie line, thrusts of the Giudicarie belt and the Schio–Vicenza strike-slip system (Slejko *et al.* 1989; Valensise & Pantosti 2001; (http://80.117.141.2/cft/ and http://www.ingv.it/seismoglo/RCMT/). The Schio–Vicenza line itself has been classified as a potential source for earthquakes exceeding M 5.5 (Valensise & Pantosti 2001; Galadini *et al.* 2002).

From the kinematic viewpoint, focal mechanisms along the Inntal line show clear sinistral kinematics, indicating the continuing eastward lateral escape of the Tauern window block (Slejko *et al.* 1987, 1989), whereas in the Southern Alps all focal mechanisms point to regional NNW–SSE compression and more complex fault kinematics (both compressional and strike-slip) (Slejko *et al.* 1987, 1989; Pondrelli *et al.* 2004; http://www.ingv.it/seismoglo/RCMT) (Fig. 2). In addition, the recent event at Merano (M = 4.8, 17 July 2001) fits the sinistral strike-slip activity along the Passiria line (Pondrelli *et al.* 2004; Caporali *et al.* 2005), clearly indicating the northward indentation of the Adria plate into the Eurasian plate (Renner & Slejko 1994; Regenauer-Lieb & Petit 1997; Bressan *et al.* 1998). Hence, it is conceivable that the seismicity follows fault arrays connecting the Inn valley at Innsbruck to the Adige valley across the Brenner Pass, continuing south along the Passiria–Giudicarie system through Vipiteno and Merano, and to the Schio–Vicenza system.

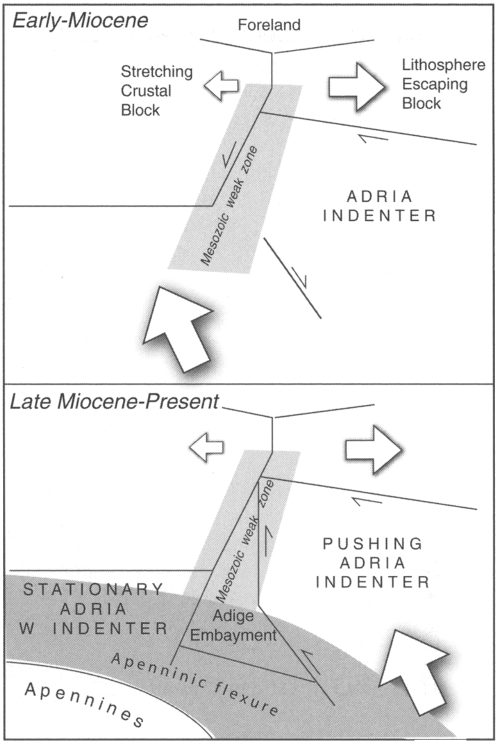

Fig. 6. Geodynamic sketch of evolution of the northern Adriatic indenter.

Discussion

Tectonic linkage from the Brenner detachment to the Schio–Vicenza system

As previously emphasized, the North Giudicarie system is closely related to the post-nappe evolution of the orogenic wedge, whereas the block bounded by the South Giudicarie and Schio–Vicenza–Trento–Cles fault systems (‘Adige embayment’ of Laubscher 1996) as a whole separates the Veneto–Friuli from the Lombardian Southern Alps.

During the Serravallian–Tortonian NNW–SSE contraction, the Giudicarie belt acted as an oblique ramp for the south-vergent Lombardian thrusts (Trevisan 1938; Castellarin *et al.* 1986; Picotti *et al.* 1995). Therefore, the deformation was partitioned inside the belt into sinistral north–south-trending strike-slip faults and several SSE-vergent thrusts. This kinematics completely fits the coeval strike-slip activity of the North Giudicarie–Passiria and Trento–Cles lines, which are in turn connected to the Brenner extensional activity. In fact, on the basis of the attitude and kinematics of the North Giudicarie–Passiria fault system, it is very probable that, from the Mid-Miocene onward, the lateral extrusion of the Penninic nappe stack in the Tauern window toward the Pannonian basin has also been coupled with a shallower westward crustal stretching of the Brenner fault hanging wall, both developing under the same regional stress pattern (NNW–SSE compression) (Fig. 6). This hypothesis is strongly supported by the coeval nucleation of the Brenner detachment and the onset of the sinistral kinematics along the Giudicarie–Passiria fault array. In addition, it is very unlikely that during the lateral escape of the Penninic units of the Tauern window toward the east, the hanging wall of the Brenner detachment has remained static, as it should has been affected by a westward movement related to tectonic unroofing process. In this framework, the deformation along the North Giudicarie–Passiria faults has been kinematically transferred to the Lombardian frontal thrusts through the Giudicarie belt. Furthermore, the 30 km of shortening in the Giudicarie belt and the eastern side of the Lombardian thrusts during the Mid–Late Miocene (balanced cross-sections by Picotti *et al.* 1995) reflects comparable deformation further north in the same period, as proven by recent studies on the Giudicarie–Passiria and Trento–Cles systems (Prosser 1998; Viola *et. al.* 2001). Therefore, the

North Giudicarie–Passiria system represents the SE boundary of a great estward crustal stretching block at the Brenner detachment hanging wall. At the same time, given its NW–SE trend, the Schio–Vicenza line probably acted as a right-lateral strike-slip fault (Fig. 6).

From the Messinian onward, the northern sector of the Schio–Vicenza fault inverted its kinematics and acted as a sinistral transfer fault, connecting the Bassano and Montello frontal thrusts (Fig. 1) with the Giudicarie transpressional belt, where post-Tortonian out-of-sequence reactivation occurred (Semenza 1974; Zanferrari *et al.* 1982; Picotti *et al.* 1995; Castellarin & Cantelli 2000). Therefore, from the latest Miocene onward there was kinematic linkage between the Schio–Vicenza and Trento–Cles lines and this complex fault system became a major crustal shear zone bounding to the west the Veneto–Friuli block, which is moving toward the NW to NNW (Fig. 6). This model approaches the conclusion of Boccaletti *et al.* (2005), who interpreted this shear zone as a lithospheric structure separating the Adria plate into two blocks in the context of the post-Pliocene Apennine evolution.

The Adige embayment high

The triangle between the southern sectors of Giudicarie belt and the Schio–Vicenza line includes the Lessini and Berici Mountains and the Euganean Hills (Fig. 1). This structural high, called the 'Adige embayment' by Laubscher (1996), was only slightly affected by the Neogene Alpine compression (Cantelli & Castellarin 1994). Consequently, the Palaeogene intracontinental rifting and related magmatism are well preserved (Zampieri 1995*a*, 2000). The high structural position of this embayment separates the central and eastern Southern Alps (and their foreland basins). It may be interpreted as a flexural outer rise of the Apennine foredeep basin, controlled by subsurface loads acting on the Adriatic subducted slab (Royden *et al.* 1987) or by a thicker crust (or lithosphere) with minor eastward rollback (Doglioni 1993). The Late Miocene–Pliocene uplift of the Adige embayment partly prevented the contemporaneous development of south-propagating frontal thrusts in this sector. Therefore, the prominent extensional evidence in the southern part of the Schio–Vicenza line, revealed by morphostructural (Pellegrini 1988) and geological (Zanferrari *et al.* 1982) analysis and seismic profiles (Finetti 1972), may be interpreted as the concurrent effect of subsidence caused by the load of the South Alpine thrust sheets and of uplift of the hinge zone of the Apennine flexure (Fig. 6).

A steady-state fault kinematics from the Miocene to the present

According to Dewey *et al.* (1989) and Mazzoli & Helman (1994), Africa and Europe changed their convergence direction from NNW to NW during the Messinian. Nevertheless, the relations between Africa and Adria are still a matter of debate and the change in Africa–Europe convergence direction through time does not necessarily imply an equivalent change in Adria–Europe motion. According to the kinematic data collected by Platt *et al.* (1989) in the Alpine orogenic wedge, Adria–Europe convergence remained roughly NW-directed from the Late Cretaceous to the present. In contrast, some workers have highlighted an overall change in regional compression from NNW to NW along the Giudicarie belt in the latest Miocene and have related it directly to the equivalent variation of Africa–Europe convergence at the Miocene–Pliocene transition (the 'Adria phase' of Castellarin & Cantelli 2000). Actually, the seismotectonic and GPS data agree with the Miocene fault kinematics and NW to NNW convergence between the northeastern part of the Adria plate and Europe, suggesting that no major changes happened from the Miocene to the present. In addition, Bressan *et al.* (1998) showed how the present deformation inside the Friuli area may be partitioned according to 'a cone in cone' model, which accounts for the NNW–SSE compression along the reactivated south-vergent frontal thrusts, the dextral transpression reactivating the Dinaric structures to the east, and the NW–SE compression recorded in the central and western sector of the Veneto–Friuli South Alpine belt. In this view the palaeostress changes recorded during the Messinian along the Giudicarie belt could be explained by local stress reorientation unrelated to Africa–Europe relative movements. Therefore, in our opinion, from the Miocene to the present the Alpine collisional wedge and South Alpine fold-and-thrust belt underwent the same tectonic process driven by NW migration of Adria towards Europe; faults should have kept the same overall kinematics through time, except for changes caused by the onset of linkages (e.g. inversion of Schio–Vicenza kinematics from dextral to sinistral in the Late Miocene).

Conclusions

From Miocene time, the Alpine collisional wedge and South Alpine fold-and-thrust belt have been welded together, and the fault kinematics in the two domains has been closely linked. In particular, several linkage systems between the major faults developed, mainly in the South Alpine domains, as a result of strike-slip reactivation of inherited normal faults. From the Early Miocene onward, the Brenner detachment was connected through the Giovo and Passiria faults to the North Giudicarie line, and its splays in the South Alpine domain are represented by the Trento–Cles system. In turn, during the Late Miocene (Messinian), the linkage between the latter fault system and the Schio–Vicenza fault was completed, via the Permian Calisio line and several Mesozoic north–south fault segments (e.g. Gamonda and Tormeno faults; Fig. 6). As a whole, these complex fault systems may be viewed as a single sinistral transcurrent shear zone 250 km long and 25 km wide. The southern sector of this crustal structure may be considered as an incipient separation zone between the westernmost part of the Adriatic indenter, almost completely involved in the lithospheric flexure of the Apennine subduction (Lombardian sector), and the main body of the Adriatic plate. The northeastern portion of the Adria plate (Friuli area) was less influenced by the lithospheric flexure, the hinge zone of which probably corresponds to the rising Adige embayment. To the south (Adriatic Sea sector) the space available for the flexure of the Adriatic lithosphere is wider, as the central Apennine and Dinaric fronts are more distant than those of the northern Apennines and Southern Alps. Consequently, a sharp discontinuity (the Schio–Vicenza line) has developed between the Friuli and Lombardian sectors, whereas a wider deformation zone can be envisaged further south in the Adriatic offshore (the Middle Adriatic Ridge of Argnani *et al.* 1993). This conclusion is supported by GPS velocity fields, GPS-derived strain rates and focal mechanisms, which show continuous active migration of the Adriatic plate toward Europe, whereas its westernmost part remains nearly stationary. From the Miocene onward, the Alpine collisional nappe stack has been involved in the concurrent processes of northward propagation of this separation zone of the Adria plate and the westward stretching of the Brenner fault hanging wall related to the tectonic unroofing of the Tauern window.

This work was supported by MIUR (Cofin 2002, no. 2002043912_002 to D.Z.) and CNR (Istituto di Geoscienze e Georisorse, Sezione di Padova). The paper has benefited from the recommendations made by G. V. Dal Piaz and the comments of the reviewers G. Prosser and M. Lukesch. We thank F. De Giusti for drawing the base of Figure 2, S. Castelli for helping in electronic assemblage of the composite figures, and G. Walton and P. Ferretti for the revision of the English text.

References

ALTAMIMI, Z., SILLARD, P. & BOUCHER, C. 2002. ITRF2000: a new release of the International Terrestrial Reference Frame for earth science applications. *Journal of Geophysical Research*, **107**(B10), 2214, DOI: 10.1029/2001JB000561.

ARGNANI, A., FAVALLI, P., FRUGONI, F., *ET AL.* 1993. Foreland deformational pattern in the Southern Adriatic Sea. *Annali di Geofisica*, **36**, 212–224.

BATTAGLIA, M., MURRAY, M. H., SERPELLONI, E. & BÜRGMANN, R. 2004. The Adriatic region: an independent microplate within the Africa–Eurasia collision zone. *Geophysical Research Letters*, **31**, L09605, DOI: 10.1029/2004GL019723.

BEHRMANN, J. H. 1988. Crustal-scale extension in a convergent orogen: the Sterzing–Steinach mylonite zone in the Eastern Alps. *Geodinamica Acta*, **2**, 63–73.

BERTOTTI, G., PICOTTI, V., BERNOULLI, D. & CASTELLARIN, A. 1993. From rifting to drifting: tectonic evolution in the South-Alpine upper crust from the Triassic to the Early Cretaceous. *Sedimentary Geology*, **86**, 53–76.

BIGI, G., COSENTINO, D., PAROTTO, M., SARTORI, R. & SCANDONE, P. 1990. Structural model of Italy. Sheet no. 1. *In*: CASTELLARIN, A., COLI, M., DAL PIAZ, G. V., SARTORI, R., SCANDONE, P. & VAI, G. B. (eds) *Progetto Finalizzato Geodinamica*. CNR, Rome.

BISTACCHI, A., DAL PIAZ, G. V., DAL PIAZ, G., MARTINOTTI, G., MASSIRONI, M., MONOPOLI, B. & SCHIAVO, A. 2003. Carta geologica e note illustrative del transetto val di Vizze–Fortezza (Alpi Orientali). *Memorie di Scienze Geologiche*, **55**, 169–188.

BOCCALETTI, M., CALAMITA, F. & VIANDANTE, M. G. 2005. La Neo-Catena litosferica appenninica nata a partire dal Pliocene inferiore come espressione della convergenza Africa–Europa. *Bollettino della Società Geologica Italiana*, **124**, 87–105.

BRACK, P. 1981. Structures in the southwestern border of the Adamello intrusion (Alpi Bresciane, Italy). *Schweitzeásche Mineralogische und Petrographische Mitteilungen*, **61**, 37–50.

BRESSAN, G., SNIDARCIG, A. & VENTURINI, C. 1998. Present state of tectonic stress of the Friuli area (Eastern Southern Alps). *Tectonophysics*, **292**, 211–227.

CANTELLI, L. & CASTELLARIN, A. 1994. Analisi e inquadramento strutturale del sistema Schio–Vicenza. *Atti Ticinensi di Scienze della Terra, Serie Speciale*, **1**, 231–245.

CAPORALI, A., MARTIN, S. & MASSIRONI, M. 2002. The present day strain rate field in Italy and surrounding countries as inferred from geodetic data. *Bollettino di Geofisica Teorica ed Applicata*, **43**(1–2), 3–21.

CAPORALI, A., MARTIN, S. & MASSIRONI, M. 2003. Average strain rate in the Italian crust inferred from a permanent GPS network—II. Strain rate versus seismicity and structural geology. *Geophysical Journal International*, **155**, 254–268.

CAPORALI, A., BRAITENBERG, C. & MASSIRONI, M. 2005. Geodetic and hydrological aspects of the Merano earthquake of July 17, 2001. *Journal of Geodynamics*, **39**, 317–336.

CASSINIS, G. & PEROTTI, C. R. 1993. Interazione strutturale permiana tra la Linea delle Giudicarie ed i bacini di Collio, Tione e Tregiovo (Sudalpino centrale, N Italia). *Bollettino della Società Geologica Italiana*, **112**, 1021–1036.

Castellarin, A. 1972. Evoluzione paleotettonica sinsedimentaria del limite tra Piattaforma veneta e Bacino lombardo a nord di Riva del Garda. *Giornale di Geologia*, **38**, 11–212.

Castellarin, A. & Cantelli, L. 2000. Neo-Alpine evolution of the Southern Eastern Alps. *Journal of Geodynamics*, **30**, 251–274.

Castellarin, A., Fesce, A. M., Picotti, V., *et al.* 1986. Structural and kinematics analysis of the Giudicarie deformation belt. Implications for compressional tectonics of Southern Alps. *Mineralogica et Petrographica Acta*, **30**, 286–310.

Castellarin, A., Cantelli, L., Fesce, A. M., *et al.* 1992. Alpine compressional tectonics in the Southern Alps. Relationships with the N Apennines. *Annales Tectonicae*, **6**, 62–94.

Castellarin, A., Piccioni, S., Prosser, G., Sanguinetti, E., Sartori, R. & Selli, L. 1993. Mesozoic continental rifting and Neogene inversion along south Giudicarie line (Northwestern Brenta Dolomites). *Memorie della Società Geologica Italiana*, **49**, 125–144.

Christensen, J. N., Selverstone, J., Rosenfeld, J. L. & De Paolo, D. J. 1994. Correlation by Rb–Sr geochronology of garnet growth histories from different structural levels within the Tauern window, Eastern Alps. *Contributions to Mineralogy and Petrology*, **118**, 1–12.

Dal Piaz, G. V. 1999. The Austroalpine–Piemonte nappe stack and the puzzle of alpine Tethys. *Memorie di Scienze Geologiche*, **51**, 155–176.

Dal Piaz, G. V. & Martin, S. 1998. Evoluzione litosferica e magmatismo nel dominio austro-sudalpino dall'orogenesi varisica al rifting mesozoico. *Memorie di Scienze Geologiche*, **53**, 43–62.

Dal Piaz, G., Bistacchi, A. & Massironi, M. 2003. Geological outline of the Alps. *Episodes*, **26**, 175–180.

De Mets, C., Gordon, R. G., Argus, D. F. & Stein, S. 1994. Effect of recent revisions to the geomagnetic reversal time scale on estimates of current plate motions. *Geophysical Research Letters*, **21**, 2191–2194.

De Vecchi, G. P., Di Lallo, E. & Sedea, R. 1986. Note illustrative della Carta geologica dell'area di Valli del Pasubio–Posina–Laghi, alla scala 1 : 20.000. *Memorie di Scienze Geologiche*, **38**, 187–205.

Dewey, J. F., Helman, M. L., Turco, E., Hutton, D. H. W. & Knott, S. D. 1989. Kinematics of the Western Mediterranean. *In*: Coward, M. P., Dietrich, D. & Park, R. G. (eds) *Alpine Tectonics*. Geological Society of London, Special Publications, **45**, 265–284.

Doglioni, C. 1992. Relationships between Mesozoic extensional tectonics, stratigraphy and Alpine inversion in the Southern Alps. *Eclogae Geologicae Helvetiae*, **85**, 105–126.

Doglioni, C. 1993. Some remarks on the origin of foredeeps. *Tectonophysics*, **228**, 1–20.

Doglioni, C. & Bosellini, A. 1987. Eoalpine and mesoalpine tectonics in the Southern Alps. *Geologcische Rundschau*, **76**, 735–754.

Fantoni, E., Pellini, S., Perdiceni, S. & Scarascia, S. 1993. Alpi Orientali: una sezione crostale dall'avampaese europeo all'avampaese adriatico. *Studi Geologici Camerti, CROP 1-1A Special Volume*, 27–34.

Fellin, M. G., Martin, S. & Massironi, M. 2002. Polyphase Tertiary kinematics and Quaternary fault reactivation in the central-eastern Alps (Western Trentino). *Journal of Geodynamics*, **34**, 31–46.

Finetti, I. 1972. Le condizioni geologiche della regione di Venezia alla luce di recenti indagini sismiche. *Bollettino di Geofisica Teorica ed Applicata*, **14**, 275–290.

Frank, W., Kralik, M., Scharbert, S. & Thöni, M. 1987. Geochronological data from the Eastern Alps. *In*: Flügel, H. W. & Faupl, P. (eds) *Geodynamics of the Eastern Alps. Deuticke, Vienna*, 272–281.

Frisch, W., Dunkl, I. & Kuhlemann, J. 2000. Postcollisional orogen-parallel large-scale extension in the Eastern Alps. *Tectonophysics*, **327**, 239–265.

Fügenschuh, B., Seward, D. & Mancktelow, N. 1997. Exhumation in a convergent orogen: the western Tauern window. *Terra Nova*, **9**, 213–217.

Fügenschuh, B., Mancktelow, N. S. & Seward, D. 2000. Cretaceous to Neogene cooling and exhumation history of the Oetztal–Stubai basement complex, Eastern Alps: a structural and fission track study. *Tectonics*, **19**, 905–918.

Galadini, F., Poli, E. & Zanferrari, A. 2002. Sorgenti sismogenetiche responsabili di terremoti distruttivi nell'Italia nord-orientale. 21° *Convegno Nazionale Gruppo Nazionale di Geofisica della Terra Solida, Abstract Volume*, 27–30.

Grundman, G. & Morteani, G. 1985. The young uplift and thermal history of the central Eastern Alps (Austria/Italy). Evidence from apatite fission track ages. *Jahrbuch der Geologischen Bundesanstalt*, **128**, 197–216.

Kurz, W., Neubauer, F., Genser, J. & Dachs, E. 1998. Alpine geodynamic evolution of passive and active continental margin sequences in the Tauern Window (Eastern Alps, Austria, Italy); a review. *Geologische Rundschau*, **87**, 225–242.

Lammerer, B. & Weger, M. 1998. Footwall uplift in an orogenic wedge: the Tauern Window in the Eastern Alps of Europe. *Tectonophysics*, **285**, 213–230.

Laubscher, H. P. 1996. Shallow and deep rotations in the Miocene Alps. *Tectonics*, **15**, 1022–1035.

Lenhardt, W. A. 2002. Seismicity in Tyrol in relation to the TRANSALP transect. *Memorie di Scienze Geologiche*, **54**, 49–52.

Mancktelow, N., Stöckli, D. F., Grollimund, B., *et al.* 2001. The DAV and Periadriatic fault system in the Eastern Alps south of the Tauern window. *International Journal of Earth Science*, **90**, 593–622.

Martin, S., Prosser, G. & Santini, L. 1991. Alpine deformation along the Periadriatic lineament in the

Italian Eastern Alps. *Annales Tectonicae*, **5**(2), 118–140.

MARTIN, S., GODARD, G., PROSSER, G., SCHIAVO, A., BERNOUILLI, D. & RANALLI, G. 1998. Evolution of the deep crust at the junction Australpine/Southalpine: the Tanale nappe. *Memorie di Scienze Geologiche*, **50**, 1–50.

MAZZOLI, S. & HELMAN, M. 1994. Neogene patterns of relative plate motion for Africa–Europe: some implications for recent Central Mediterranean tectonics. *Geologische Rundschau*, **83**, 464–468.

MÜLLER, B., ZOBACK, M. L., FUCHS, K., ET AL. 1992. Regional patterns of tectonics stress in Europe. *Journal Geophysical Research*, **97**, 11783–11803.

MÜLLER, W., PROSSER, G., MANCKTELOW, N., VILLA, I. M., KELLEY, P. S., VIOLA, G. & OBERLI, F. 2001. Geochronological constraints on the evolution of the Periadriatic Fault System (Alps). *International Journal of Earth Sciences (Geologische Rundschau)*, **90**(3), 623–653.

NICOLAS, A., HIRN, A., NICOLICH, R., POLINO, R. & Ecors-Crop working group 1990. Lithospheric wedging in the western Alps inferred from the Ecors-Crop traverse. *Geology*, **18**, 587–590.

OLDOW, J. S., FERRANTI, L., LEWIS, D. S., ET AL. 2002. Active fragmentation of the Adria, the north African promontory, central Mediterranean orogen. *Geology*, **30**, 779–782.

PEACOCK, D. C. P. & SANDERSON, D. J. 1991. Displacement, segment linkage and relay ramps in normal fault zones. *Journal of Structural Geology*, **13**, 721–733.

PELLEGRINI, G. B. 1988. Aspetti morfologici ed evidenze neotettoniche della linea Schio–Vicenza. *Supplementi di Geografia Fisica Diname dinamica Quaternaria*, **1**, 69–82.

PFIFFNER, O. A. & HITZ, L. 1997. Geologic interpretation of the seismic profiles of the eastern traverse (lines E1–E3, E7–E9); Eastern Swiss Alps. *In*: PFIFFNER, O. A., LEHNER, P., HEITZMAN, P., MUELLER, S. & STECK, A. (eds) *Results of NRP 20; Deep Structure of the Swiss Alps.* Birkhäuser, Basel, 73–100.

PICOTTI, V., PROSSER, G. & CASTELLARIN, A. 1995. Structures and kinematics of the Giudicarie–Val Trompia fold and thrust belt (Central Southern Alps, Northern Italy). *Memorie di Scienze Geologiche*, **47**, 95–109.

PLATT, J. P., BEHRMANN, J. H., CUNNINGHAM, P. C., ET AL. 1989. Kinematics of the Alpine arc and the motion history of Adria. *Nature*, **337**, 158–161.

PONDRELLI, S., MORELLI, A., EKSTRÖM, G., MAZZA, S., BOSCHI, E. & DZIEWONSKI, A. M. 2002. European–Mediterranean regional centroid-moment tensors: 1997–2000. *Physics of the Earth and Planetary Interiors*, **130**, 71–101.

PONDRELLI, S., MORELLI, A. & EKSTRÖM, G. 2004. European–Mediterranean regional centroid moment tensor catalog: solutions for years 2001 and 2002. *Physics of the Earth and Planetary Interiors*, **145**, 127–147.

PROSSER, G. 1998. Strike-slip movements and thrusting along a transpressive fault zone: the North Giudicarie line (Insubric line, northern Italy). *Tectonics*, **17**, 921–937.

PROSSER, G. 2000. The development of the North Giudicarie fault zone (Insubric line, Northern Italy). *Journal of Geodynamics*, **30**, 229–250.

RATSCHBACHER, L., MERLE, O., DAVY, O. & COBBOLD, P. 1991*a*. Lateral extrusion in the Eastern Alps, Part 1: Boundary conditions and experiments scaled for gravity. *Tectonics*, **10**, 245–256.

RATSCHBACHER, L. W., FRISCH, H., LINZER, G. & MERLE, O. 1991*b*. Lateral extrusion in the Eastern Alps, Part 2: Structural analysis. *Tectonics*, **10**, 257–271.

REGENAUER-LIEB, K. & PETIT, J. P. 1997. Cutting of the European continental lithosphere; plasticity theory applied to the present Alpine collision. *Journal of Geophysical Research*, **102**, 7731–7746.

REITER, F., ORTNER, H. & BRANDNER, R. 2002. Seismically active Inntal fault zone: inverted European rift structures control upper plate deformation. *Memorie di Scienze Geologiche*, **54**, 233–234.

RENNER, G. & SLEJKO, D. 1994. Some comments on the seismicity of the Adriatic region. *Bollettino di Geofisica Teorica ed Applicata*, **36**, 141–144.

ROSENBERG, C. L. 2004. Shear zones and magma ascent: a model based on a review of a Tertiary magmatism in the Alps. *Tectonics*, **23**, TC3002, DOI: 10.1029/2003TC001526.

ROYDEN, L., PATACCA, E. & SCANDONE, P. 1987. Segmentation and configuration of subducted lithosphere in Italy: an important control on thrust-belt and foredeep-basin evolution. *Geology*, **15**, 714–717.

SANDER, B. 1912. Über einige Gesteinsgruppen des Tauernwestendes. *Jahrbuch der Geologischen Reichsanstalt*, **62**(2), 219–287.

SCHMID, S. M., PFIFFNER, O. A., SCHÖNBORN, G., FROITZHEIM, N. & KISSLING, E. 1997. Integrated cross-section and tectonic evolution of the Alps along the eastern traverse. *In*: PFIFFNER, O. A., LEHNER, P., HEITZMAN, P., MUELLER, S. & STECK, A. (eds) *Deep Structure of the Swiss Alps.* Birkhäuser, Basel, 289–304.

SCHORN, J. 1902. *Die Erdbeben von Tirol und Voralberg*. Zeitschrift des Ferdinandeums, III Folge, 46 Heft.

SELLI, L. 1998. Il lineamento della Valsugana fra Trento e Cima d'Asta: cinematica neogenica ed eredità strutturali permo-mesozoiche nel quadro evolutivo del Sudalpino orientale (NE-Italia). *Memorie della Società Geologica Italiana*, **53**, 503–541.

SELVERSTONE, J. 1988. Evidence for east–west crustal extension in the eastern Alps: implications for the unroofing history of the Tauern window. *Tectonics*, **7**, 87–105.

SELVERSTONE, J. 1993. Micro- to macroscale interactions between deformational and metamorphic processes, Tauern Window, Eastern Alps. *Schweizerische Mineralogische und Petrographische Mitteilungen*, **73**, 229–239.

SEMENZA, E. 1974. La fase Giudicariese nel quadro di una nuova ipotesi sull'orogenesi alpina nell'area italo-dinarica. *Memorie della Società Geologica Italiana*, **13**, 187–226.

SLEJKO, D., CARULLI, G. B., CARRARO, F., *ET AL.* 1987. *Modello sismotettonico dell'Italia nord-orientale.* CNR, *Gruppo Nazionale Difesa Terremoti, rendiconto* **1**, 1–82.

SLEJKO, D., CARULLI, G. B., NICOLICH, R., *ET AL.* 1989. Seismotectonics of the Eastern Southern Alps: a review. *Bollettino di Geofisica Teorica ed Applicata*, **31**(122), 109–136.

SPIESS, R., MARINI, M., FRANK, W., MARCOLONGO, B. & CAVAZZINI, G. 2001. The kinematics of the southern Passeier fault: radiometric and petrographic constraints. *Schweizerische Mineralogische und Petrographische Mitteilungen*, **81**, 197–212.

TIKOFF, B. & TEYSSIER, C. 1994. Strain modeling of displacement-field partitioning in transpressional orogens. *Journal of Structural Geology*, **16**, 1575–1588.

TREVISAN, L. 1938. Il fascio di fratture tra l'Adige a la Linea delle Giudicarie e i suoi rapporti col massiccio intrusivo dell'Adamello. *Studi Trentini di Scienze Naturale*, **19**, 177–187.

VALENSISE, G. & PANTOSTI, D. 2001. *Database of potential sources for earthquakes larger than M 5.5 in Italy.* Istituto Nazionale di Geofisica e Vulcanologia, CD-rom, Version 2.0.

VENZO, S. 1941. Studio geotettonico del trentino meridionale–orientale tra Borgo Valsugana e il M. Coppolo. *Memorie della Istituto Geologica Reale Università di Padova*, **14**, 1–86.

VIOLA, G., MANCKTELOW, N. & SEWARD, D. 2001. Late Oligocene–Neogene evolution of Europe–Adria collision: new structural and geochronological evidence from the Giudicarie fault system (Italian Eastern Alps). *Tectonics*, **20**, 999–1020.

VIOLA, G., MANCKTELOW, N., SEWARD, D., MEIER, A. & MARTIN, S. 2003. The Pejo fault system: an example of multiple tectonic activity in the Italian Eastern Alps. *Geological Society of America Bulletin*, **115**, 515–532.

VIOLA, G., ODONNE, F. & MANCKTELOW, N. S. 2004. Analogue modelling of reverse fault reactivation in strike-slip and transpressive regimes: application to the Giudicarie fault system, Italian Eastern Alps. *Journal of Structural Geology*, **36**, 401–408.

VON BLANCKENBURG, F., VILLA, I. M., BAUR, H., MORTEANI, G. & STEIGER, R. H. 1989. Time calibration of a P–T-path from the western Tauern window, Eastern Alps: the problem of closure temperature. *Contributions to Mineralogy and Petrology*, **101**, 1–11.

VON BLACKENBURG, F. & DAVIES, J. H. 1995. Slab breakoff: a model for syncollisional magmatism and tectonics in the Alps. *Tectonics*, **14**, 120–131.

ZAMPIERI, D. 1995*a*. Tertiary extension in the southern Trento Platform, Southern Alps, Italy. *Tectonics*, **14**, 645–657.

ZAMPIERI, D. 1995*b*. L'anticlinale di roll-over liassica dei Sogli Bianchi nel Monte Pasubio (Vicenza). *Atti Ticinensi di Scienze della Terra (serie speciale)*, **3**, 3–9.

ZAMPIERI, D. 2000. Segmentation and linkage of the Lessini Mountains normal faults, Southern Alps, Italy. *Tectonophysics*, **319**, 19–31.

ZAMPIERI, D., MASSIRONI, M., SEDEA, R. & SPARACINO, V. 2003. Strike-slip contractional stepovers in the Southern Alps (northeastern Italy). *Eclogae Geologicale Helvetiae*, **96**, 115–123.

ZANFERRARI, A., BOLLETTINARI, G., CAROBENE, L., *ET AL.* 1982. Evoluzione neotettonica dell'Italia nord-orientale. *Memorie di Scienze Geologiche*, **35**, 355–376.

ZIMMERMANN, R., HAMMERSCHMIDT, K. & FRANZ, G. 1994. Eocene high pressure metamorphism in the Pennine units of the Tauern window (Eastern Alps). Evidence from ^{40}Ar–^{39}Ar dating and petrological investigations. *Contributions to Mineralogy and Petrology*, **117**, 175–186.

ZOBACK, M. L. 1992. First and second order patterns of stress in the lithosphere: the World Stress Map Project. *Journal of Geophysical Research*, **97**, 11,703–11,728.