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Notes

Evolution of a poly-deformed relay zone between fault segments in the eastern Southern Alps, Italy

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Abstract: In the eastern Southern Alps (NE Italy), Liassic north–south extensional structures are prominent. The southern Trento Platform also experienced extension during the Palaeogene, when reactivation of some pre-existing faults occurred, coupled with nucleation of new faults. During Neogene shortening, these structures were reactivated once again, but with strike-slip kinematics. In this framework, the Gamonda–Tormeno restraining stepover represents the final result of an overlap zone which evolved through time. In the first stage (Lias to Early Cretaceous) a prominent splay developed at the tip of the Gamonda Fault by lateral propagation and breaching of independent segments. At the same time, there was kinematic interaction between the antithetic Gamonda and Tormeno faults, followed by diachronous motion on crossing faults and the development of a narrow graben. During the second stage of extensional tectonics (Palaeocene to Early Oligocene), the reactivation and propagation of the overlapping faults along with the generation of new faults led to deepening of the graben. In the third stage (Miocene to present), the final structure of a strike-slip restraining stepover was accomplished. Due to the mechanical stratigraphy and complex inherited architecture of the relay zone where stratigraphic sequences with different rheological properties are juxtaposed, the style of shortening is different in the western and eastern sides of the stepover. The Gamonda–Tormeno structure represents a unique example of how a relay zone may change through time.

The existence and geometry of relay zones between fault segments (accommodation and transfer zones) have important implications for seismic hazard evaluation of tectonically active regions, hydrocarbon and groundwater migration and accumulation, and mineral deposition (Faulds & Varga 1998 and references therein). Relay zones are observed in all tectonic settings across a broad range of scales (e.g. Dahlstrom 1969; Boyer & Elliott 1982; Morley *et al.* 1990; Peacock & Sanderson 1991; Peacock & Zhang 1993; Trudgill & Cartwright 1994; Peacock 2003). Due to their effect on topography and sedimentation, relay structures of extensional and strike-slip domains are studied more frequently than those of contractional domains. The best-known transfer structures are extensional relay ramps (Larsen 1988; Childs *et al.* 1995; Crider & Pollard 1998) and strike-slip pull-apart basins (Aydin & Nur 1982; Mann *et al.* 1983).

Whilst studies of relay structures commonly include analysis of features formed in a single tectonic event, except for a few case-histories (e.g. Reijs & McClay 1998), examples of relay structures which evolved through different deformation events are lacking in the literature. However, reworking of inherited structures is quite a common event in nature, and the study of reactivated relay zones can provide unique insights into understanding the evolution of different linkage mechanisms in variable stress fields. The aim of this study is (1) to unravel the evolution of an exceptionally well-exposed kilometre-scale relay structure between conjugate fault segments, and (2) to increase the knowledge of strike-slip contractional relay zones and factors influencing strain distribution and deformational styles inside stepovers.

Regional geology

Stratigraphy

The study area is located within the eastern Southern Alps mountain chain, and during most of the Jurassic it lay within a horst of the passive margin of the Adria plate known as the Trento Platform (Fig. 1). The oldest rocks exposed (Recoaro Phyllites) belong to the pre-Permian Variscan crystalline basement. The overlying sedimentary cover has a thickness of 2.5–3 km. The complex Permian–Middle Triassic stratigraphy includes several siliciclastic and carbonate units intruded and capped by Ladinian volcanics. However, the surface geology is dominated by Upper Triassic to

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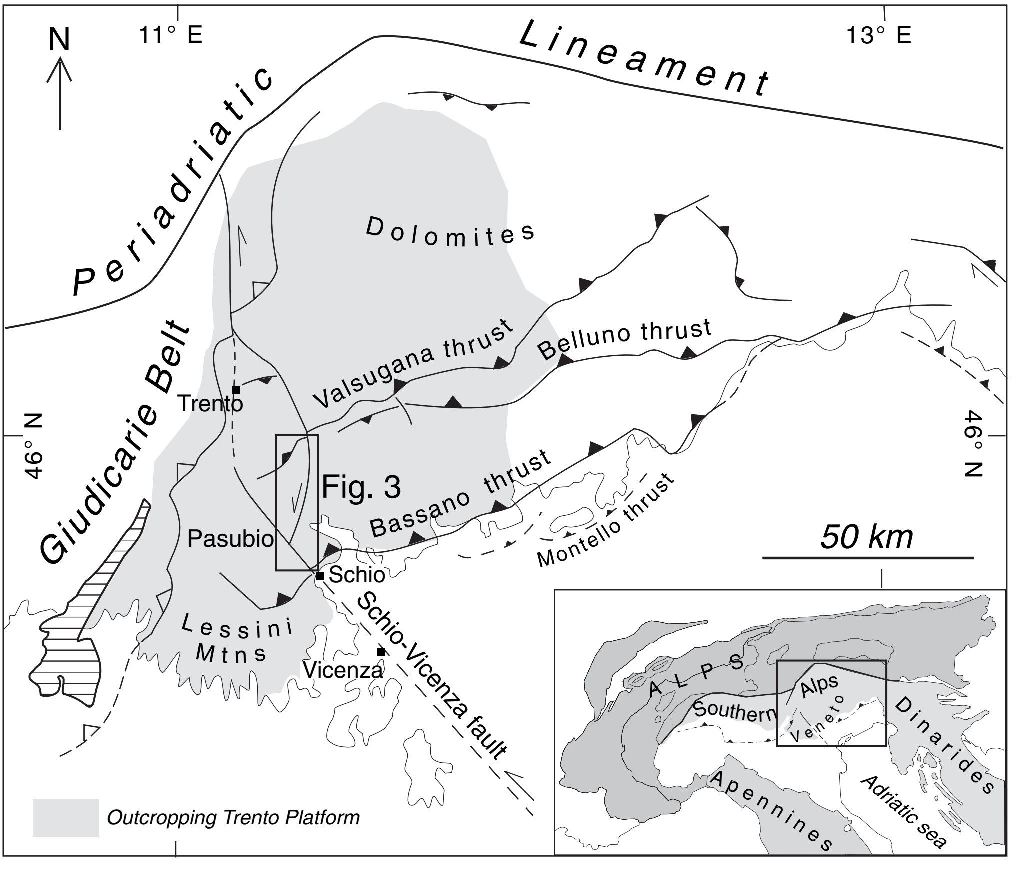


Fig. 1. Simplified structural map of the central-eastern Southern Alps, showing the main faults and the areal extent of the outcropping Trento Platform.

Lower Cretaceous carbonates. Within this interval, the thickest unit is the Upper Triassic Dolomia Principale (*c.* 800 m) (Fig. 2), a peri-tidal succession with a wide regional distribution. In the study area, this formation lies on Middle Triassic volcanics or on the Carnian soft rocks (claystones, conglomerates, evaporites) of the Raibl Group. The overlying Calcari Grigi Group (Early Jurassic) is a non-dolomitized carbonate platform unit. It includes three formations: from the bottom they are the Mount Zugna Formation, a peri-tidal succession; the Loppio oolitic limestone, a massive 20-m-thick bed of oolitic grainstones; and the Rotzo Formation, which is composed of biostromes, micrite beds, marls and black shales (Tobaldo *et al.* 2004). The St. Vigilio oolitic limestone is the youngest shallow-water unit of the Trento Platform. The overlying Middle–Upper Jurassic Ammonitico Rosso unit is composed of a condensed pelagic red nodular limestone. The Lower Cretaceous is made up of pelagic thinly bedded limestones (Maiolica Formation). All rocks are intruded by Palaeogene mafic to ultramafic dykes and explosion necks (De Vecchi 1966).

The mechanical stratigraphy of the outcropping geology is broadly composed of two units: (1) a lower thick competent unit including the Dolomia Principale, Mount Zugna and Loppio limestone Formations, and (2) an upper thin incompetent unit including the Rotzo, St Vigilio oolitic limestone, Ammonitico Rosso and Maiolica formations (Fig. 2).

Kinematic evolution of the eastern Southern Alps

The eastern Southern Alps are a SSE-verging mountain belt (Fig. 1), which mainly developed during the Neogene by contraction and oblique inversion of the Mesozoic passive margin of the Adria plate (e.g. Bertotti *et al.* 1993). The mountains consist of an imbricate fan of thrust sheets

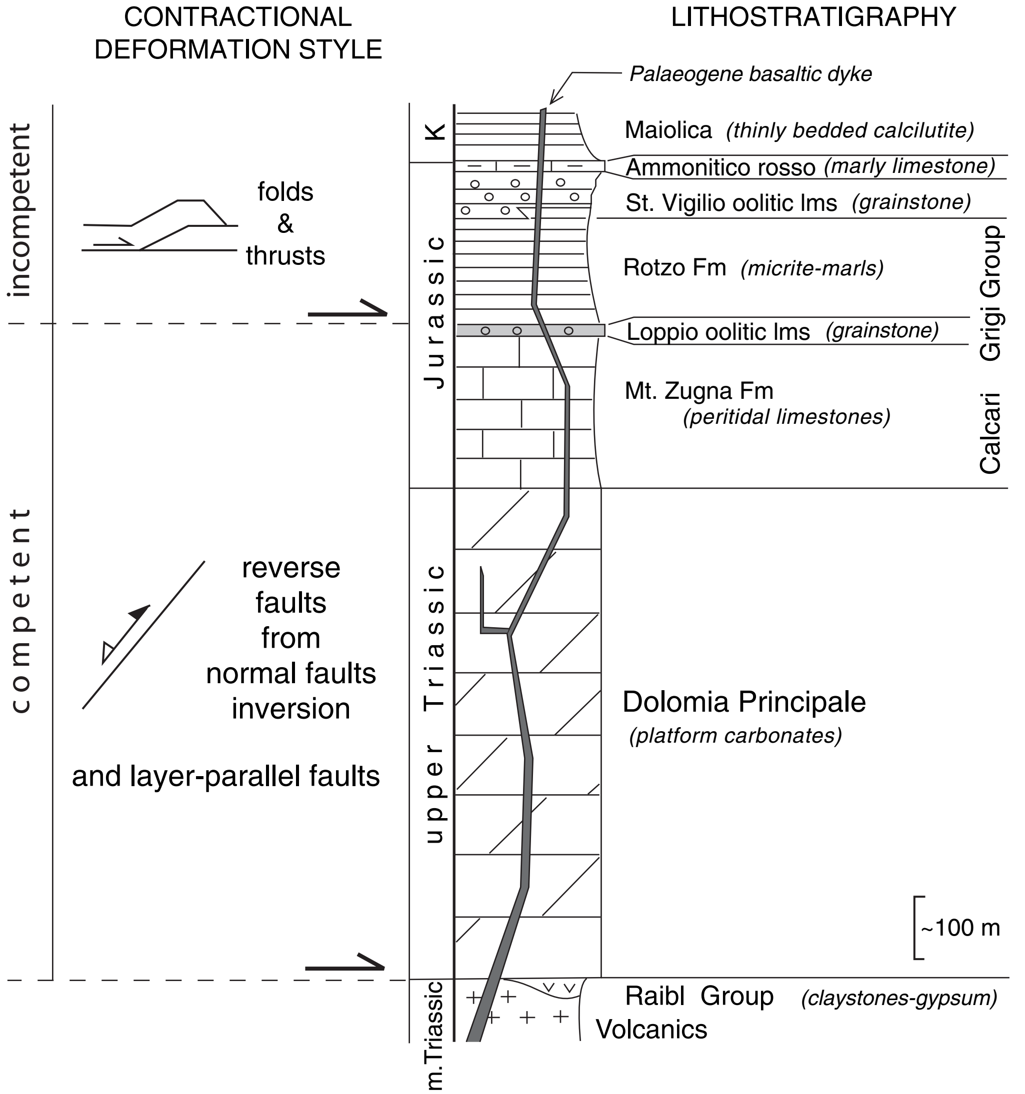
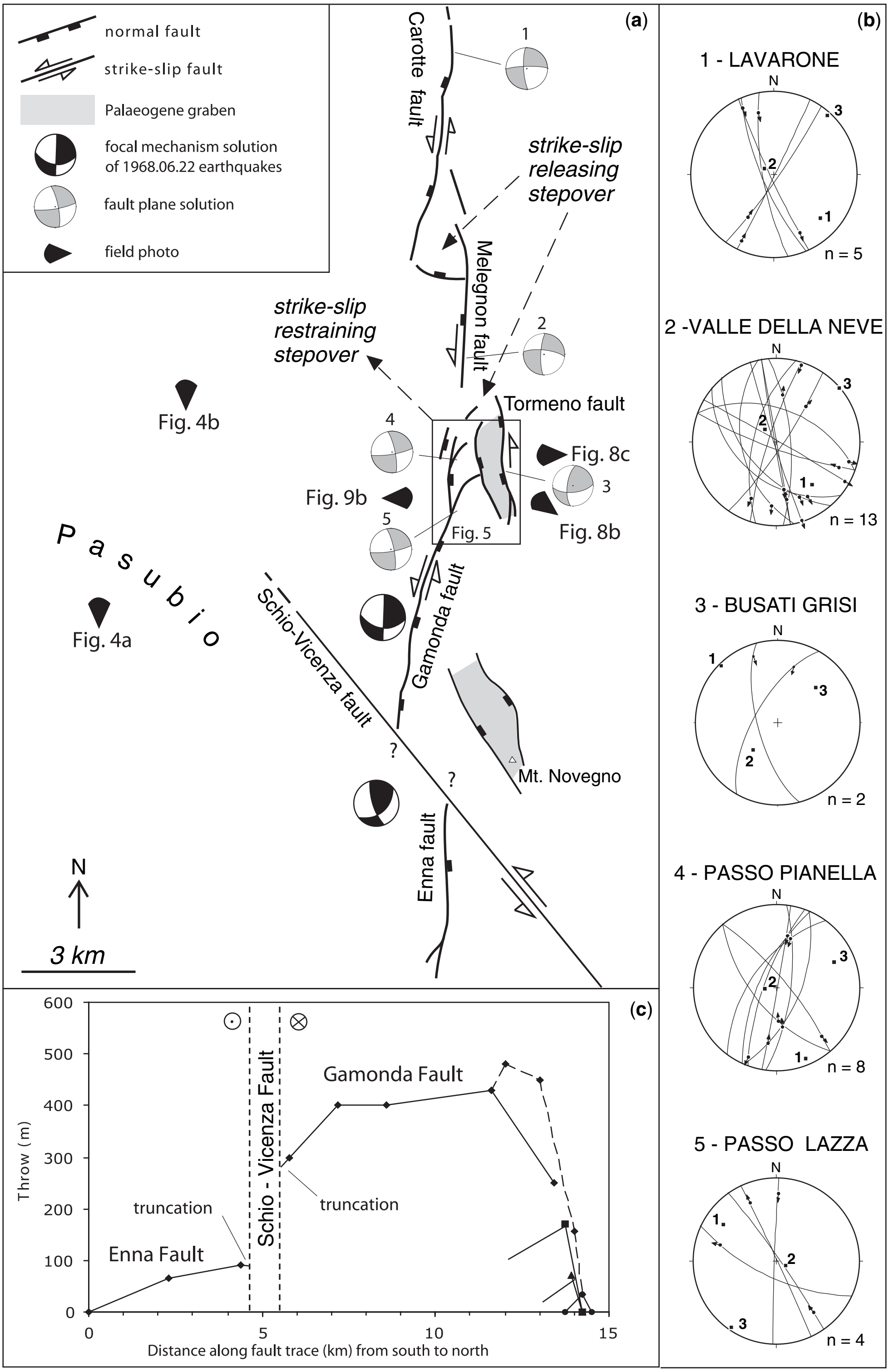


Fig. 2. Schematic column of the stratigraphy cropping out in the study area.

involving the crystalline basement (Doglioni & Bosellini 1987; Doglioni 1990; Schönborn 1999; Transalp Working Group 2002). In plan view, the thrusts show several undulations controlled by inherited features, such as Norian–Early Cretaceous normal faults and, in the western Veneto region, occasional Palaeogene normal faults. The mainly north–south-trending normal faults developed during several extensional phases in the framework of the thinning of the Adria margin (from Norian to Early Cretaceous) and the occurrence of the Early Tertiary magmatic event (De Vecchi *et al.* 1976; Zampieri 1995*a*; Figs 3 & 4).

The subsequent Neogene (Alpine) contraction with a maximum principal stress axis trending NNW (Doglioni & Bosellini 1987; Castellarin *et al.* 1992; Castellarin & Cantelli 2000) reactivated the steep north- to NNE-trending normal faults with sinistral strike-slip kinematics (Zampieri *et al.* 2003; Massironi *et al.* 2006). Recent investigations have recognized that restraining and releasing structures developed at various scales by interaction and linkage of these stepped fault segments (Zampieri 2000; Zampieri *et al.* 2003). The structure described in this study is a complex km-scale restraining stepover, which has deformed a pre-existing extensional



normal fault
strike-slip fault
Palaeogene graben
focal mechanism solution of 1968.06.22 earthquakes
fault plane solution
field photo
(a)
Carotte fault
strike-slip releasing stepover
Melegnon fault
strike-slip restraining stepover
Tormeno fault
Fig. 4b
Fig. 8c
Fig. 9b
Fig. 8b
Fig. 5
Pasubio
Gamonda fault
Schio-Vicenza fault
Fig. 4a
Mt. Novegno
Enna fault
N
3 km
(b)
1 - LAVARONE
n = 5
2 -VALLE DELLA NEVE
n = 13
3 - BUSATI GRISI
n = 2
4 - PASSO PIANELLA
n = 8
5 - PASSO LAZZA
n = 4
(c)
Throw (m)
Schio - Vicenza Fault
Gamonda Fault
truncation
Enna Fault
Distance along fault trace (km) from south to north

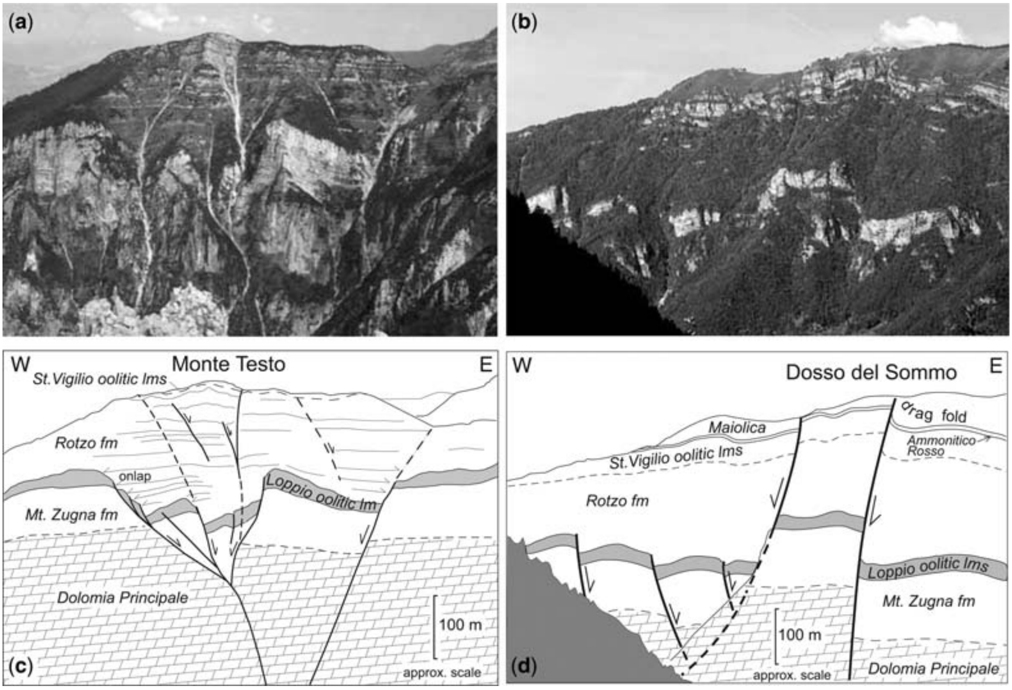


Fig. 4. Liassic extensional structures showing prominent thickness variations of the synkinematic layer, represented by the Rotzo Formation: (**a**) structure exposed on the southern cliff face of Mount Testo in the Pasubio Massif (slightly modified after Tobaldo *et al.* 2004). The location is shown in Figure 3a. (**b**) Structure exposed on the south face of Dosso del Sommo, just east of Pasubio Massif. Note the subsequent reactivation of a fault shown by the drag fold affecting Lower Cretaceous rocks. Location shown in Figure 3a. (**c**) Line drawing of Figure 4a. (**d**) Line drawing of Figure 4b.

structure, at present lying on the hanging-wall block of the SSE-verging Bassano Thrust (Fig. 1).

Present-day activity

The seismotectonics of Italy are the result of the relative motion between Africa and Eurasia. Considerable debate exists about whether the recent motion of the Adria plate occurred in conjunction with or independent of the rotation of Africa (e.g. Muttoni *et al.* 2001; Oldow *et al.* 2002). In the eastern Southern Alps, shallow-crustal seismicity is located on south-verging thrust faults within the Adriatic cover (Chiarabba *et al.* 2005). The southernmost active thrust is located in the foothills, where growth folding occurs (Montello Thrust, Fig. 1; Benedetti *et al.* 2000). The overall north–south contraction causes large thrust-related earthquakes and strike-slip earthquakes on the inherited faults. The seismicity is clustered in the eastern and westernmost parts (Slejko *et al.* 1989; Bressan *et al.* 1998) at the intersection with the Dinaric and Giudicarie belts respectively, whilst the central-western chain front shows an absence of recent seismic activity where future earthquakes are more likely to occur (Chiarabba *et al.* 2005; Galadini *et al.* 2005); the study area lies in the central western chain.

Fig. 3. (**a**) Segmented Mesozoic to Quaternary fault zone, including Tertiary grabens (see Fig. 1 for location) and the location of the Figure 4 synsedimentary extensional structures. The focal mechanisms belong to earthquakes with $M = 4.5$ and 4.1 respectively, occurring nearly contemporaneously on 22 June 1968. Their epicentral location is poorly constrained, but the solutions are consistent respectively with sinistral strike-slip activity along a north-trending fault and possibly a Riedel shear fracture (R of a northward-trending fault or P of the Schio–Vicenza Fault). (**b**) Stereographic lower-hemisphere equal-angle projections of strike-slip fault data (modified after Zampieri *et al.* 2003). The numbers 1, 2 and 3 represent the computed principal palaeostress axes. (**c**) Displacement profile of the Enna and Gamonda normal faults. Throw values have been obtained from published (De Vecchi *et al.* 1986; Braga *et al.* 1968) and unpublished geological maps, and from our field surveys. The dashed line is the summed displacement profile (main fault and splays).

It is interesting to note that in the period 1900–1980 the most important earthquakes were two events of 22 June 1968 ($M = 4.1$ and $M = 4.5$; epicentral area Pasubio), whose focal mechanism solutions are consistent with sinistral transpression along north–south-trending faults (Slejko *et al.* 1989, p. 124, fig. 9; Fig. 3, this paper). In the subsequent 1981–2002 period, once again the three most important events ($4 < M < 5$) plot in the same area (Castello *et al.* 2004). Although focal mechanism solutions are not available, their position is consistent with that of the two previous events and two of them define a north–south alignment east of Pasubio. In addition, data from the seismic network of the Provincia Autonoma di Trento for the 1982–1997 time span show activity along the north–south fault system (Galadini & Galli 1999, p. 172, Fig. 1). Therefore, all the available seismic data, along with geological studies (Zampieri *et al.* 2003; Massironi *et al.* 2006), suggest that the north–south fault array lying between the Lessini Mountains and the Valsugana Valley (Fig. 1) is presently active.

The Gamonda–Tormeno relay structure

Some fault segments (Enna, Gamonda, Tormeno, Melegnon and Carotte) compose a prominent north–south-trending fault array cutting the region between the Lessini Mountains and the Valsugana Valley for about 30 km (Braga *et al.* 1968; Figs 1 & 3). This fault array is inferred to be a synsedimentary Liassic structure, because in this area north–south-trending extensional synsedimentary structures can be demonstrated from well-documented thickness variations of Liassic units and also in outstanding exposures on east–west-trending cliff faces (Zampieri 1995*b*; Tobaldo *et al.* 2004; Fig. 4). These faults control differences in thickness mainly within the Rotzo Formation, pointing to a Sinemurian–Pliensbachian climax of activity.

The Gamonda Fault is an extensional east-dipping segment whose trace length is *c.* 8.5 km. The maximum throw is *c.* 400 m. Considering the fault length, the thickness of the sedimentary cover (2.5–3 km), and that outcropping Anisian units are clearly cross-cut, the fault is presumed to penetrate the metamorphic basement. Towards the south, the fault intersects the NW-trending strike-slip Schio–Vicenza Line, which displays recent sinistral kinematics (Castellarin & Cantelli 2000; Zampieri *et al.* 2003; Massironi *et al.* 2006). On the other side of the Schio–Vicenza Fault, an east-dipping normal-fault segment (the Enna Fault) appears to be the offset continuation of the Gamonda Fault.

The Tormeno Fault is an extensional westward-dipping segment, whose trace length is *c.* 4.8 km. The maximum throw is *c.* 340 m. The fault partially overlaps with the northern termination of the Gamonda Fault, creating a right stepover. The fault spacing is *c.* 2 km. The stepover is composed of two parts, separated by the eastward-dipping Malga Zolle Fault, which is synthetic to the Gamonda Fault and antithetic to the Tormeno Fault. Therefore, the structure composed by the Tormeno and the Malga Zolle faults is a narrow graben, where Lower Cretaceous rocks (Maiolica) are still preserved (Figs 3 & 5).

Within the overstepping zone, basaltic dykes belonging to the Palaeogene mafic to ultramafic magmatism of the southern Trento Platform are widespread (Fig. 5; De Vecchi *et al.* 1976), whereas in the surrounding area they are rare. This magmatism was coupled with ENE extension affecting the region from the Palaeocene to the Early Oligocene (Zampieri 1995*a*).

Exposed fault planes generally show indications of the last phase of activity; the latest transcurrent movements obliterated the former dip-slip slickenlines. Fault-slip data relative to the strike-slip activity (Fig. 3*b*) show that the plunges of the slip vectors are nearly equally distributed between northerly and southerly quadrants. Therefore, the resulting overall slip of the Gamonda Fault can be assumed to be subhorizontal, with a negligible vertical component.

Evolution of the polyphase Gamonda–Tormeno relay structure

Extension and evolution of extensional splays, overlaps and crossing faults

The extensional origin of the north–south-trending fault array is readily seen in the Schio sheet of the Carta Geologica d'Italia (Braga *et al.* 1968), where it is also possible to recognize the westward dip of the Carotte, Melegnon and Tormeno Faults and the eastward dip of the Gamonda and Enna faults.

A link between the Gamonda and Enna Faults was first proposed by De Boer (1963), and later reported by De Vecchi *et al.* (1986). A throw versus distance profile was constructed (Fig. 3c) using original and published data and taking into account the base of the Dolomia Principale as a reference level. This diagram is a confident representation of the cumulative throw of the extensional stages, since the vertical component of strike-slip activity is negligible (see the stereoplots in Fig. 3b). The prominent difference of the throw of the Gamonda and Enna faults at the Schio–Vicenza intersection can be explained by a transfer fault connecting the two fault segments. In this case, the observed offset of the Gamonda and

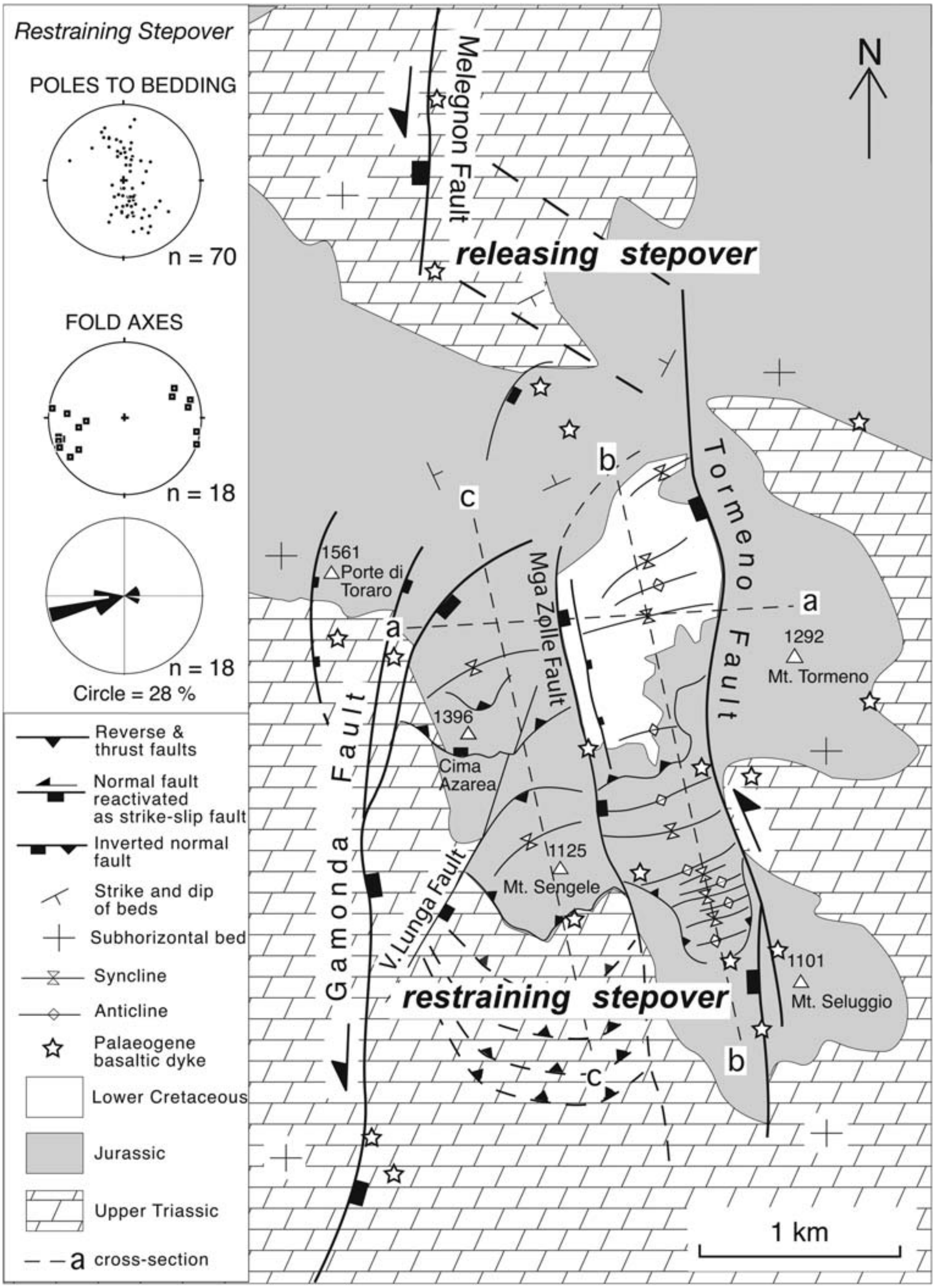


Fig. 5. Structural map of the Gamonda–Tormeno restraining stepover (see Figs 1 & 3 for location).

Enna faults does not indicate the strike-slip displacement of the Schio–Vicenza Fault.

The northern termination of the Gamonda Fault presents a horsetail splay typical of the tip damage zones of normal faults (McGrath & Davison 1995). The splay is truncated by the synthetic Malga Zolle Fault, which with its antithetic conjugate (the Tormeno Fault), forms a narrow graben where

Lower Cretaceous sediments (Maiolica) are still preserved (Figs 3 & 5). The involvement of Lower Cretaceous rocks in the graben demands extensional Upper Cretaceous and/or Tertiary activity of the Malga Zolle and Tormeno faults (see also Fig. 4d). Alternatively, the same result may have been obtained by synsedimentary Lower Cretaceous extensional activity of the two graben-bounding faults. It is likely that the high throws are the result of long-lived activity, ranging from the Lias to the Early Tertiary.

Looking to the throw profile of the Gamonda Fault (Fig. 3c), it is evident that the cumulative curve has an asymmetrical shape characterized at its northern end by a displacement maximum followed by a steep gradient termination. This effect could be explained with phases of synchronous activity of the overlapping Gamonda and Tormeno, and/or Gamonda and Malga Zolle faults. Therefore, the throw maximum and steep gradient at the northern termination of the Gamonda Fault suggest development of a true relay zone at the overlapping area during Mesozoic to Tertiary extension. A further consideration that should be taken into account when interpreting the throw profile of the Gamonda Fault is the evolution of its synthetic splays. Some authors have modelled fault growth processes by lateral propagation and breaching of initially independent overlapping segments in extensional relay zones (e.g. Childs *et al.* 1995). These studies and numerically computed experiments of intersecting normal faults (Maerten *et al.* 1999) show high slip gradients within relay zones and at fault intersections. It is very likely that similar processes also occurred at the Gamonda fault tip, inducing a further contribution to the asymmetry of the profile.

Balancing the extensional Gamonda–Tormeno cross-section

The Gamonda–Tormeno overlap zone is a narrow region of crustal extension typically composed of conjugate normal faults (Fig. 6a). Crossing conjugate normal faults are quite common in nature (e.g. Odonne & Massonnat 1992), and the surface geometry of the studied structure is consistent with an evolution by mutual offsetting of the conjugate faults. It has been demonstrated that simultaneous slip on crossing conjugate normal faults requires loss, gain, or localized redistribution of the cross-sectional area (Odonne & Massonat 1992; Ferrill *et al.* 2000). In the case-study, a possible area gain could have occurred by intrusion of Palaeogene magma, but the existence of large magmatic bodies is not proved, and the cumulative thickness of the basaltic dykes across any section allows only a very limited contribution to balancing of the section if simultaneous slip has occurred. Other mechanisms, such as salt injection, salt removal, pressure solution and sediment compaction must be excluded. In contrast, the balancing of the cross-section of Figure 6a without invoking additional hypotheses can be achieved through: (1) the model of alternating sequential movement on crossing conjugate faults (Ferrill *et al.* 2000); (2) the flattening of faults along a detachment located at the base of Dolomia Principale. No consistent evidence of extensional detachments has been found in the study area, therefore we have opted for the cross-cutting conjugate planar fault model. The balanced cross-section of Figure 6a is therefore one viable solution to the field data-set.

The long-term extensional activity of the region may have permitted alternating periods of simultaneous motions of the main faults (the development of relay zones between the Gamonda and Tormeno faults and between the Gamonda and Malga Zolle faults) and of diachronous reactivation of the faults.

The cross-section in Figure 6a includes four primary fault segments. Assuming a planar geometry for these faults, we interpret the following sequence depicted in Figure 7 as follows:

1. The east-dipping Gamonda Fault formed (stage 2), interacted (stage 3) with, and was subsequently cut by, the west-dipping Tormeno Fault (stage 4).
2. The displaced deep section of the Gamonda Fault reactivated and propagated upward (stage 5). The shallow fault resulting from propagation corresponds with the Malga Zolle Fault, whilst the resulting east-dipping fault offsetting the Tormeno Fault is composed of the shallow Malga Zolle and the deep Gamonda faults.
3. Reactivation and downward propagation of the shallow Gamonda Fault along with formation of a new synthetic fault occurred (stage 6).

The northern part of the Gamonda Fault may have been active during the last stages of extension (stages 6–7), as suggested by the injection of Palaeogene basaltic dykes. This sequence may well explain the extensional Gamonda–Tormeno overlap structure, which is composed of prominent normal faults even in the presence of successive contractional features (Fig. 5).

Contraction and evolution of the restraining stepover

After extension, the relay zone between the Gamonda and Tormeno faults experienced contraction shown by compressional structures like reverse

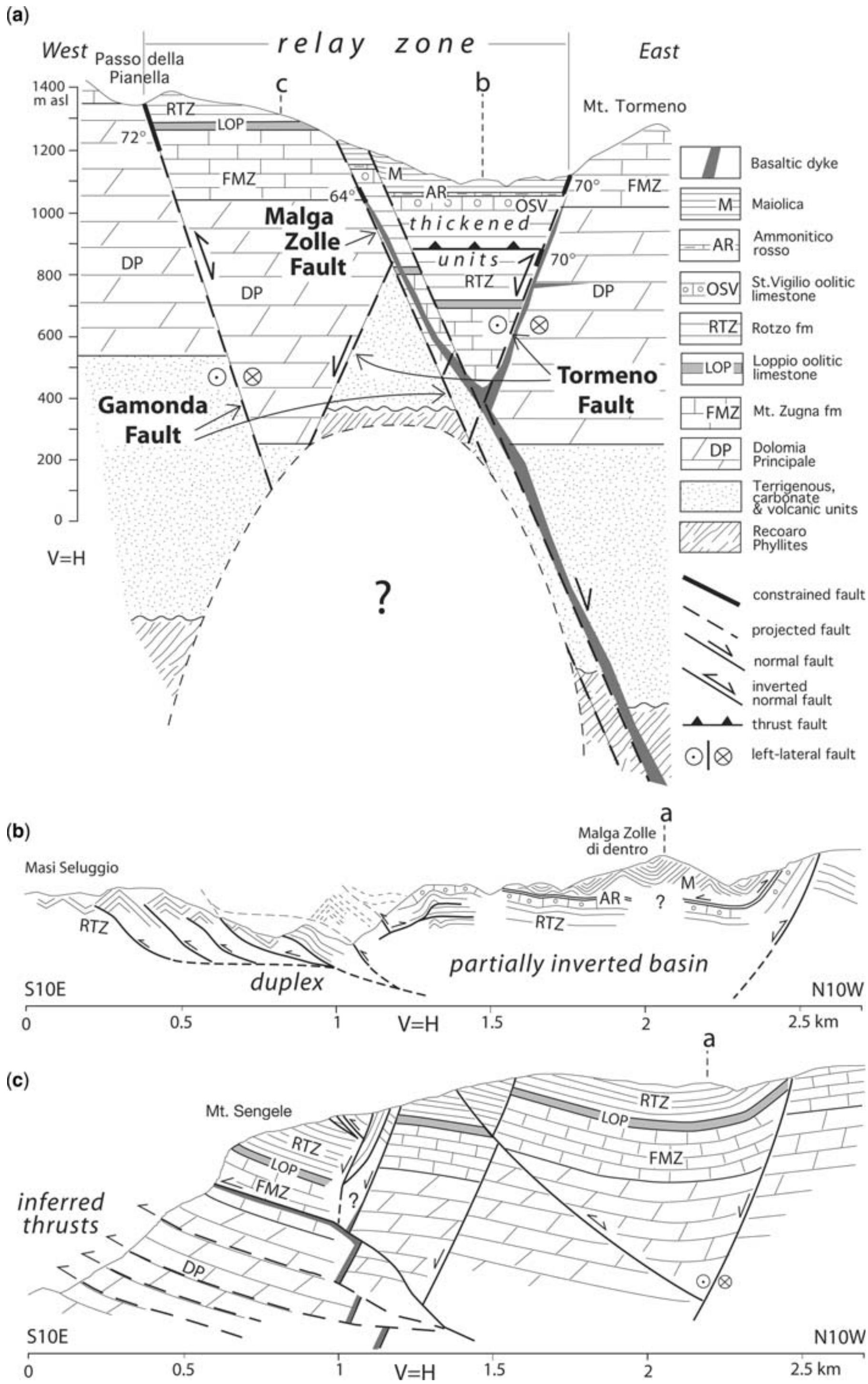


Fig. 6. (**a**) Schematic transverse cross-section of the Gamonda–Tormeno stepover. (**b**) Along-fault strike cross-section of the eastern sector of the stepover. (**c**) Along-fault strike cross-section of the western sector of the stepover. Locations shown in Figure 5.

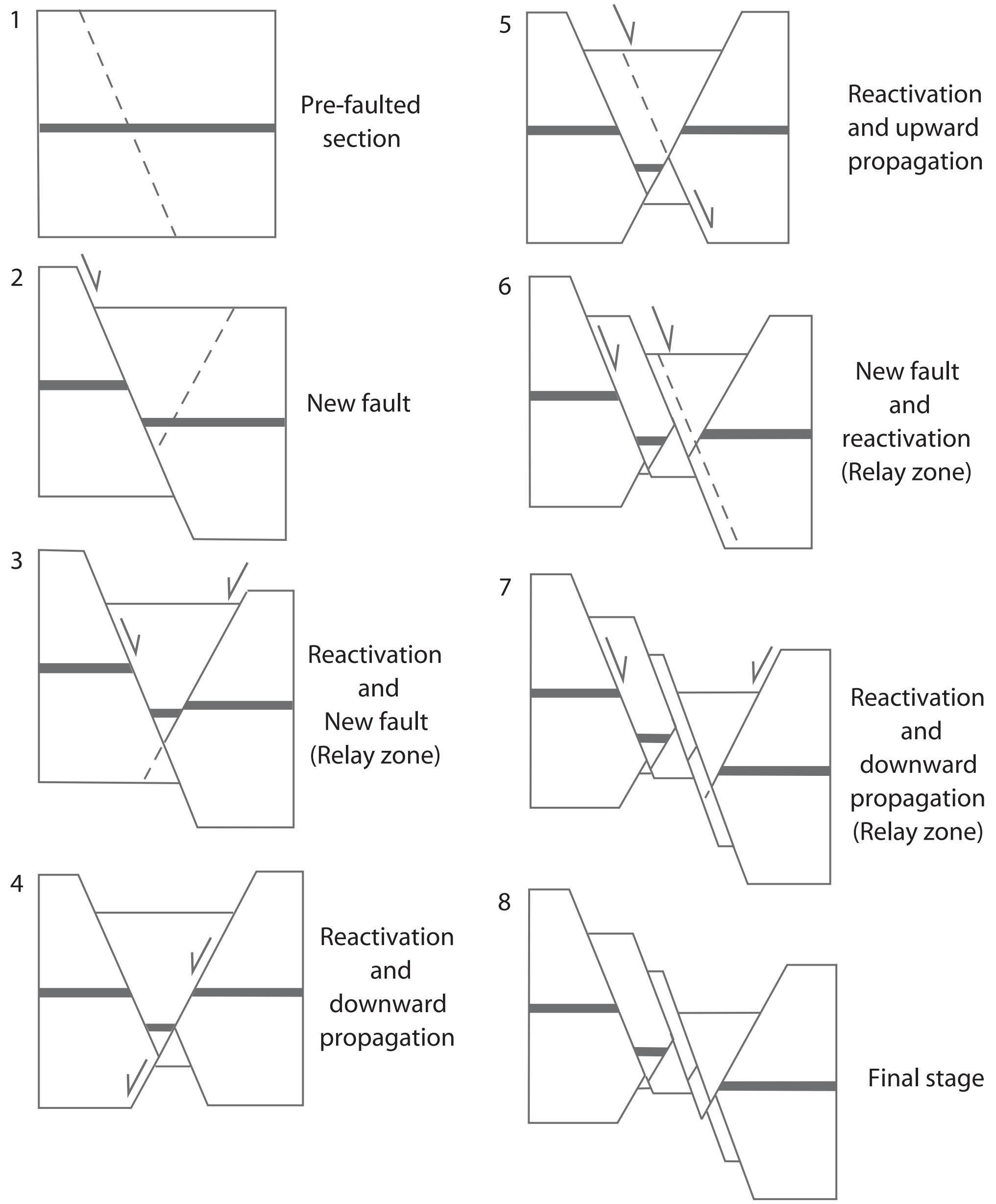
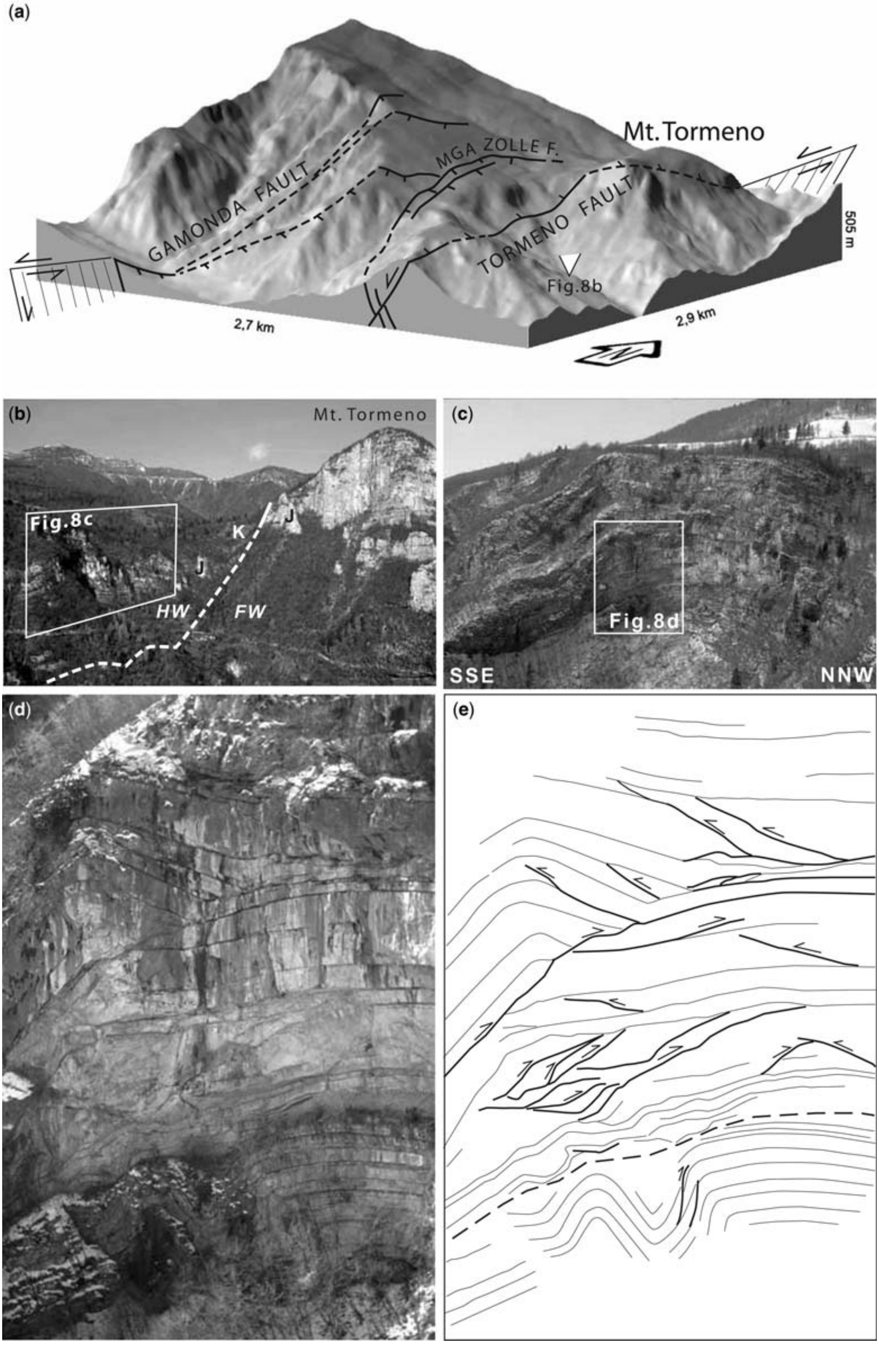


Fig. 7. Model of sequential faulting for the cross-section of Figure 6a. The synsedimentary extensional activity started in Mesozoic times (stages 1–5), and ended in Palaeogene times (stages 6–7). It is likely that ephemeral relay zones between conjugate and synthetic faults developed during some stages (stages 3, 6 and 7).

Fig. 8. Structures exposed on the eastern subzone of the Gamonda Tormeno stepover. (**a**) Digital elevation model of the Gamonda–Tormeno stepover from the SE. (**b**) Oblique view of the Mount Tormeno Fault, juxtaposing the Lower Cretaceous rocks (K) of the hanging wall (HW) against the Jurassic rocks (J) of the footwall (FW). (**c**) Large box fold in the HW of the Mount Tormeno Fault. (**d**) Detail of Figure 8c. (**e**) Line drawing of Figure 8d.


(a)
Mt. Tormeno
MGA ZOLLE F.
GAMONDA FAULT
TORMENO FAULT
Fig.8b
505 m
2,7 km
2,9 km
N
(b)
Mt. Tormeno
Fig.8c
K
J
J
HW
FW
(c)
Fig.8d
SSE
NNW
(d)
(e)

and thrust faults and folds. In contrast, in the surrounding area, the sedimentary rocks are flat-lying and nearly undeformed (Fig. 5). This is easily explained by reactivation of the bounding faults under strike-slip activity, which produced a restraining stepover. The geometry of the Gamonda and Tormeno faults interference is that of a right stepover. Therefore, local compression needs sinistral strike-slip activity of the faults, as proved by the kinematic indicators on fault planes (Zampieri *et al.* 2003) and Miocene–Quaternary orientation of the stress field with the maximum principal axis trending NNW to NW (Doglioni & Bosellini 1987; Castellarin *et al.* 1992; Castellarin & Cantelli 2000). In the southern Trento Platform, two sets of slickenlines on north–south to NNE fault planes are very common. The first generation of slickenside lineations is systematically dip-slip or oblique-slip extensional. The second generation is always sinistral strike-slip or shallow dipping, and overprints the first one (Zampieri 2000; Zampieri *et al.* 2003; Fig. 3b). Only in the westernmost part, close to the Giudicarie front belt, are dip-slip reverse movements found on north- to NNE fault planes (Prosser 1998). Therefore, the Gamonda–Tormeno strike-slip stepover is consistent with the regional kinematics. Its reactivation has been strongly controlled by inherited architecture and dramatically different deformation styles developed at the eastern and western blocks of the relay zone.

Eastern subzone. The eastern part of the restraining stepover is bound to the east by the Tormeno Fault and to the west by the Malga Zolle Fault (Figs 5, 6 & 7). These convergent antithetic normal faults bound a relatively small rock volume defining the narrow graben composed of the Rotzo, Ammonitico Rosso and the lower part of the Maiolica formations. These units form a weak mechanical body, because they are thin bedded and contain clay interlayers where slip localizes.

The local NNW–SSE compression induced by the development of a restraining stepover structure has produced a number of ramp–flat structures and attendant folds at various scales. The NNW- and SSE-verging thrust faults are associated with ENE–WSW-trending folds. Major folds have a chevron geometry, but box folds are also present (Figs 6 & 8). Due to intense flexural slip, duplexes, domino structures and pressure-solution cleavage occur on limbs, whilst in hinge zones saddle reefs are common. A rough estimation of the amount of the shortening along the cross-section of Figure 6b is 60%, corresponding with 1.5 km. This value corresponds with the minimum horizontal slip along the Gamonda and Tormeno faults.

Western subzone. The western part of the restraining stepover is bound to the west by the northern termination of the Gamonda Fault and to the east by the Malga Zolle Fault. These synthetic normal faults dip to the east. The rock volume in between is from the upper part of the Dolomia Principale and the Calcari Grigi Group. The Rotzo Formation is preserved at the core of two wide synclines with the axis subparallel to NE-trending steep faults (Fig. 5c). These folds are interpreted to be Mesozoic hanging-wall drag folds adjacent to normal-fault segments belonging to the splay termination of the Gamonda Fault. During subsequent contraction, these folds were ultimately reworked and normal faults were locally inverted. This is clearly documented on the western face of Cima Azarea, where a NNW-dipping fault shows both extensional and contractional features (Fig. 9). The western subzone shows less contraction than the eastern subzone. A rough estimate of the amount of the shortening accommodated by the structures exposed along the cross-section of Figure 6c is $<10\%$, corresponding to *c.* 200 m. Because the stepover structure transfers strike-slip displacement from the Gamonda Fault to the Tormeno Fault, the shortening on any north–south profile must be more or less the same and equal to the transferred displacement. Therefore, we infer that the corresponding difference in shortening of the eastern and western parts of the stepover is accommodated by contractional structures which are not exposed. The only zone where such structures may exist is the lower slope of Mount Sengele (Fig. 5), composed of the Dolomia Principale Formation and covered by vegetation. In this slope, the beds dip 20° towards NNW. In the upper part of the slope, beds belonging to the base of the Mount Zugna Formation show prominent layer-parallel faults. It is very likely that pervasive layer-parallel faulting also occurred in the rocks below. In this way, slip partitioned on to a large number of bedding surfaces may account for the apparent difference in shortening between the eastern and the western subzones of the stepover. The different structures of the eastern and western parts of the stepover are highlighted in the 3D sketch of Figure 10.

Conclusions

The poly-deformed Gamonda–Tormeno relay zone records two different tectonic regimes (Fig. 11). Prolonged extensional activity started in the Lias and ended in the Palaeogene, followed by contractional activity in the Neogene.

During the first extensional stage (Lias–Early Cretaceous), a prominent splay at the northern termination of the Gamonda normal fault developed

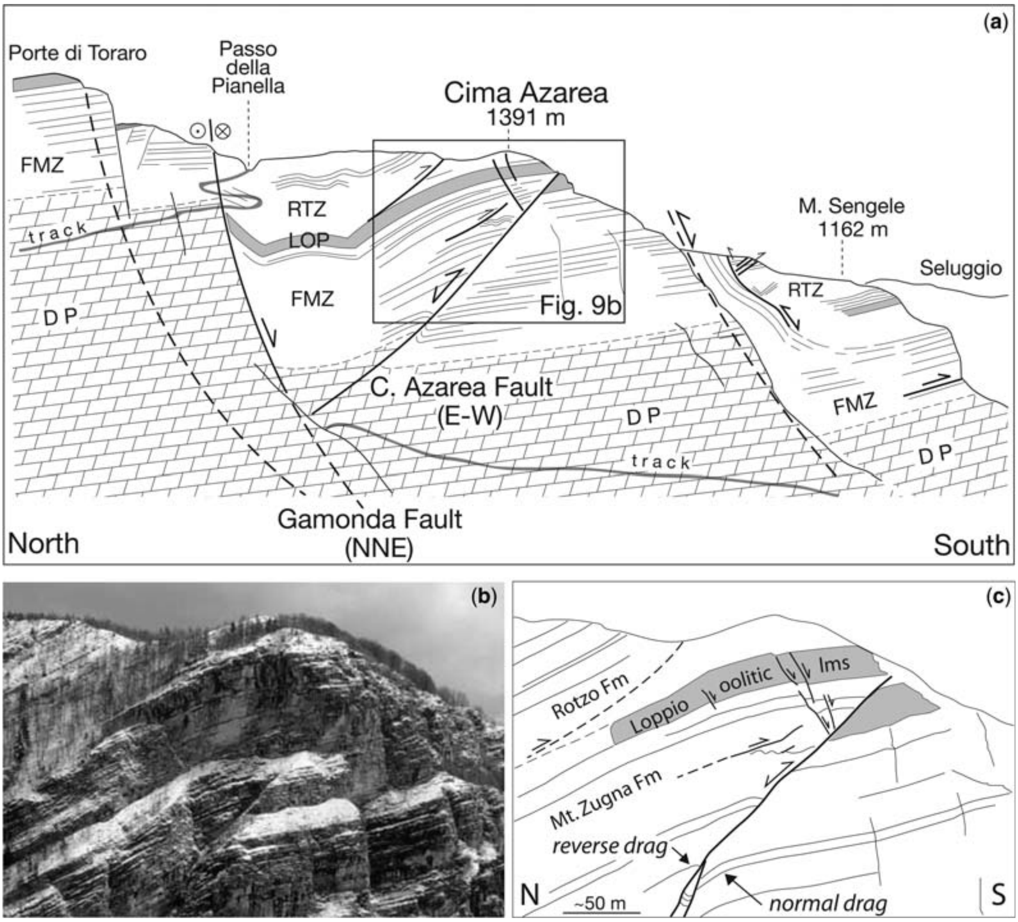


Fig. 9. (**a**) Line drawing of the western subzone structure of the Gamonda–Tormeno stepover looking east. DP: Dolomia Principale; FMZ: Mount Zugna Formation; LOP: Loppio oolitic limestone; and RTZ: Rotzo Formation. (**b**) The Cima Azarea western face. (**c**) Line drawing of the Cima Azarea structures.

in conjunction with an ephemeral transfer zone with the antithetic Tormeno Fault.

During the second extensional stage (Palaeogene), the narrow graben bound by the Malga Zolle and Tormeno faults deepened by reactivation and propagation of normal faults along with formation of new faults. The graben partly overlaps with the Gamonda fault splay juxtaposing low-competence younger rocks against the older competent rock pile.

In the third stage of evolution (Neogene to Present), the two overlapping Gamonda and Tormeno faults were reactivated with sinistral strike-slip kinematics, and the complex overlap zone became a restraining stepover. The eastern and western subzones of the stepover, composed respectively of incompetent and competent rocks, experienced deformation with varying structural styles. The eastern subzone was shortened by development of thrusts and folds, while the western subzone was shortened by inversion of pre-existing normal faults and layer-parallel faulting.

The Tormeno–Gamonda restraining stepover is an example of a relay structure which has experienced a multi-stage history. Structural relationships within the stepover demonstrate that early-formed overlap zones between normal faults are weakness zones susceptible to subsequent strike-slip reactivation in a different tectonic regime. In addition, this example shows the strong influence of inherited fault geometries and different rheological properties of rocks inside the stepover on the style of deformation of different subzones.

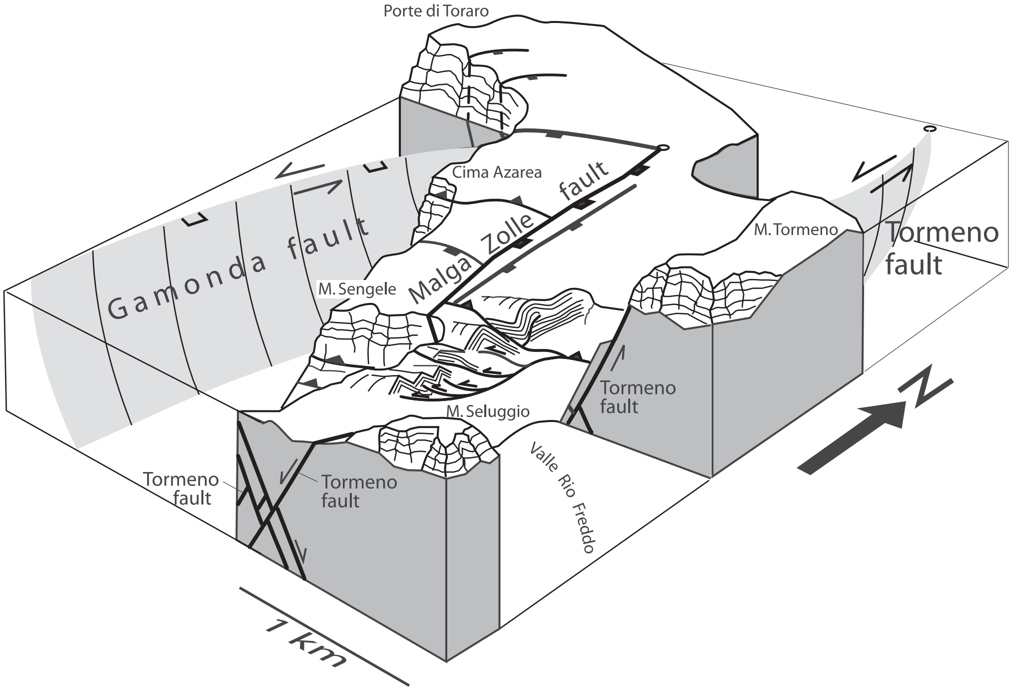


Fig. 10. Three-dimensional reconstruction of the Gamonda–Tormeno stepover.

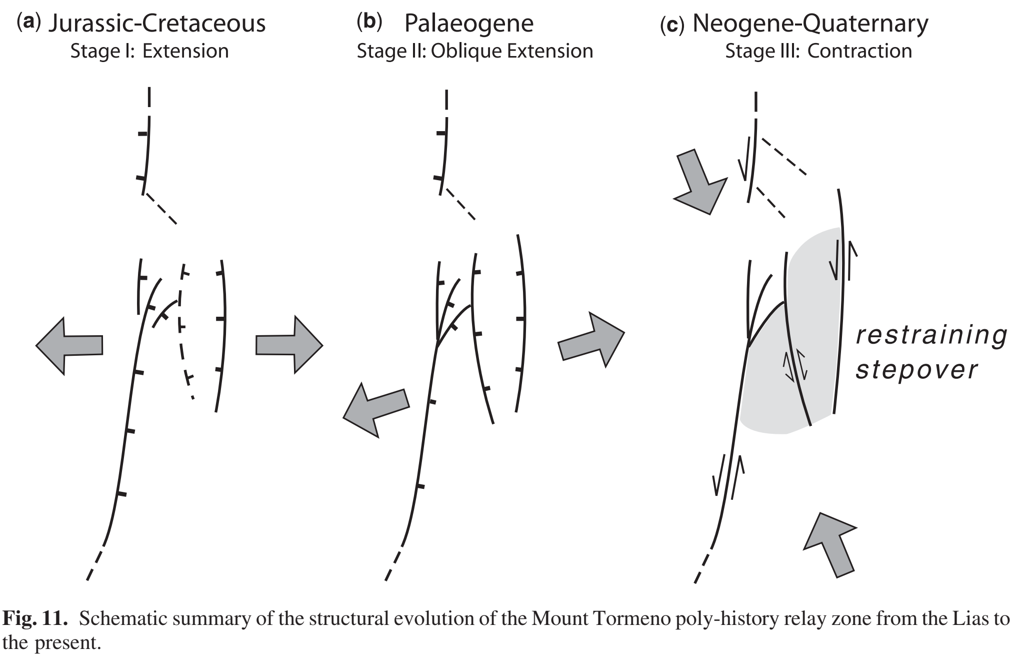


Fig. 11. Schematic summary of the structural evolution of the Mount Tormeno poly-history relay zone from the Lias to the present.

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