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Structural control on mass-movement evolution: A case study from the Vizze Valley, Italian Eastern Alps

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Key words: Mass movement, structural control, deep-seated gravitational slope deformation, lateral spread, *sackung*, rock-fall, Eastern Alps

ABSTRACT

A large post-glacial deep-seated mass movement is described from the area east of Vipiteno-Sterzing (Alto Adige–South Tyrol, Eastern Alps), mainly developing in calcschists of the ophiolitic Glockner nappe (southern antiform of SW Tauern window). A close relationship exists between differential slope evolution, structural setting, and slope attitude. Lateral spread develops in an area where the dominant schistosity is subvertical and parallel to the slope, and is facilitated by dissolution of evaporite-bearing bodies. *Sackung* develops in an area with low-angle schistosity and NNE-SSW high-angle faults, parallel to the ridge segment. A huge rock-fall was set off the intersection of the steep N-dipping schistosity with E-W and N-S to NNE-SSW faults and joints. As a whole, this deep-seated gravitational slope deformation (DSGSD) is an outstanding example of how the mechanics of large mass movements and their potential evolution are controlled by the structural framework, which is the ultimate result of a complex tectonic history.

RIASSUNTO

Una grande deformazione gravitativa, di età post-glaciale, è stata scoperta lungo la dorsale Monte Casaclusa – Passo di Trens – Cima del Cavo, a est di Vipiteno (Alto Adige-Sud Tirolo). La dorsale, impostata in corrispondenza di una antiforme di prevalenti calcescisti della falda ofiolitica del Glockner (Finestra dei Tauri SW), consente di documentare la stretta relazione esistente tra l'assetto strutturale duttile e fragile della regione, l'orientazione dei versanti e la loro evoluzione differenziale: spread laterale, facilitato da dissoluzione di corpi evaporitici, nei settori con scistosità subverticale e parallela al versante; *sackung* nei settori con scistosità poco inclinata e faglie ad alto angolo dirette NNE-SSW, parallele alla dorsale; distacco di una gigantesca frana di crollo da un settore dominato dall'intersezione di una scistosità fortemente pendente a nord con faglie dirette E-W, N-S e NNE-SSW. Nel loro insieme, queste deformazioni sono un chiaro esempio dell'importanza del controllo strutturale sulla genesi, la meccanica e l'evoluzione potenziale dei movimenti in massa.

1. Introduction

Deep-seated gravitational slope deformations (DSGSD; Terzaghi 1962) are large mass movements on the scale of the entire slope, and may involve areas of several square kilometres. These movements generally develop in high relief-energy slopes and are characterized by small displacements, when compared with the extent of the releasing slope. Distinctive gravitational morphostructures are double or multiple ridges, trenches, and uphill-facing scarps in the upper part of the slope.

Principal forerunners of DSGSD are active regional uplift coupled with fluvio-glacial erosion, leading to high relief-energy hill-slopes (Dramis 1984; Mortara & Sorzana 1987; Bistacchi & Massironi 2001). In this view, it is widely accepted that the major triggering factor is post-glacial slope release by differential unloading between ridge and slope bottom (e.g., Jahn 1964; Mahr 1977; Panizza 1974; Forcella 1984; Forcella et al. 2001). Lithological and structural settings are certainly the major controlling factors of slope evolution. In particular, a close relationship between gravitational morphostructures and brittle tectonic features is frequently a striking characteristic of these mass movements (e.g., Jahn 1964; Carraro et al. 1979; Forcella 1984; Bistacchi & Massironi 2001; Agliardi et al. 2001; Fellin et al. 2001).

Active tectonics, when present, are frequently masked by later and faster gravitational displacements, so that it is often difficult to assess their contribution to DSGSD development (Agliardi et al. 2001). Nevertheless, at least in some instances, they are considered as a key factor in triggering mass movements (Dramis & Sorriso-Valvo 1983; Forcella & Orombelli 1984; Pachoud 1990; Giardino & Polino 1997; Philip & Ritz 1999; Sauro & Zampieri 2001).

The absence of a clearly located gliding surface has been considered as a distinctive feature of DSGSD (Sorriso-Valvo

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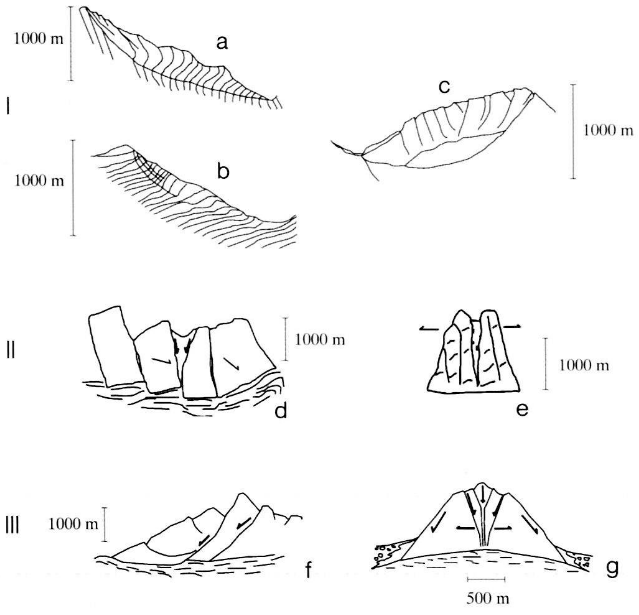

Fig. 1. Examples of types of DSGSD. I) *Sackung*: a) Zischinsky 1966; b) Nemcok 1972, c) Mahr, 1977; II) Lateral spread: d) Engelen 1963; e) Jahn 1964; III) Rock block slide: f) Guerricchio & Melidoro 1979; g) Beck 1968.

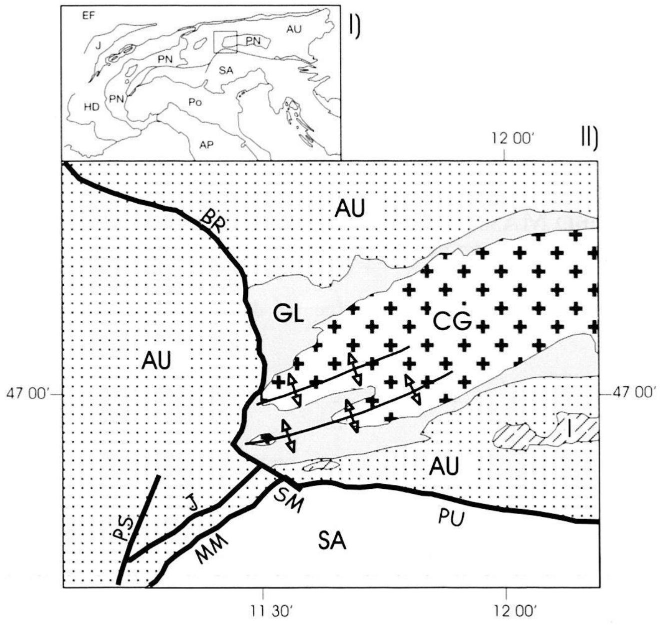

Fig. 2. I) Principal tectonic domains in the Alps: European foreland (EF), Jura (J), Helvetic-Dauphinois (HD), Penninic (PN), Austroalpine (AU), Southern Alps (SA), Po Plain (Po), Appennines (AP). Box = Fig. 2-II. II) Geological and structural sketch-map of west margin of Tauern window: Penninic continental basement (Central Gneiss: CG), Glockner nappe (GL), Austroalpine basement (AU), Tertiary intrusions (I), Southern Alps (SA). Faults: Brenner line (BR), Passiria line (PS), Jaufen line (J), Merano-Mules line (MM), Sprechestain-V. Mules line (SM), Pustertal line (PU). Fold-axis of huge Tux and Gran Veneziano-Zillertal antiforms also shown.

1995), but this is still a matter of debate (Agliardi et al. 2001), since it is a function of mass-movement type and evolution. Three main DSGSD processes are generally distinguished (Varnes 1978; Cruden & Varnes 1996), but intermediate cases are also documented (Fig. 1). The *sackung*-type DSGSD (Zischinsky 1966, 1969) or rock flows (Varnes 1978; Cruden & Varnes 1996) are typical of schistose metamorphic rocks and are characterized by low-velocity viscous-plastic continuous deformation throughout a wide, homogeneous basal zone. Consequently, the main mass-movement body is not transected by clearcut sliding surfaces, with the exception of discontinuous planes at its top and, less frequently, at its toe (Mencl 1968; Radbruch-Hall 1978). Nevertheless, Savage & Varnes (1987) and Varnes et al. (1989) suggest a plastic shear zone at the DSGSD base where the movement is concentrated; Zischinsky (1969) proposed evolution from *sackung* (no basal discontinuity) to mass movement with a well-defined basal sliding plane and potentially catastrophic high-velocity evolution (*Gleitung*; Zischinsky 1969). The *sackung* is generally characterized by the arched convex shape of the middle and lower parts of the slope, which contrasts with the generally concave shape of its upper part (depletion zone) (Zischinsky 1969). The rock block-slide type is characterized by clear preexisting or neo-generated surfaces along which creep is concentrated; it may also evolve to accelerated creep (Varnes 1978). Lastly, lateral spreading movements normally develop where rigid blocks overlie a plastic sequence (Varnes 1978; Cruden & Varnes 1996); although similar phenomena are also recorded in homogeneous rocks: in this case, displacement normally decreases with depth and no gliding surfaces can be identified (Jahn 1964). Lateral spread is particularly favoured by antiformal structures (Dramis & Sorriso-Valvo 1994).

Two previously unknown DSGSD were discovered and mapped during the geological field survey for the Brenner Basis Tunnel project (BBT). They occur along the Mt. Casaclusa – Passo di Trens – Cima del Cavo ridge, east of Vipiteno-Sterzing and on the northern side of Vizze-Pfitsch valley (Isarco-Eisach valley, Alto Adige-South Tyrol, Italy). The former is described in this paper. It highlights the impressive relationships between gravitational processes and geo-structural settings, showing that a single DSGSD may be subdivided into sectors with differing evolution and risk levels, mainly depending on the interplay between local topography and structural setting.

2 Alpine evolution and regional framework

The study area is situated in the axial part of the Alpine orogen, at the south-western edge of the Tauern window (Fig. 2). The Alps originated from the subduction of the Mesozoic Tethyan ocean (Cretaceous-Eocene) and the subsequent collision between the European and Adriatic (Insubric, African) continental margins (e.g., Frisch 1979; Kurz et al. 1998, and

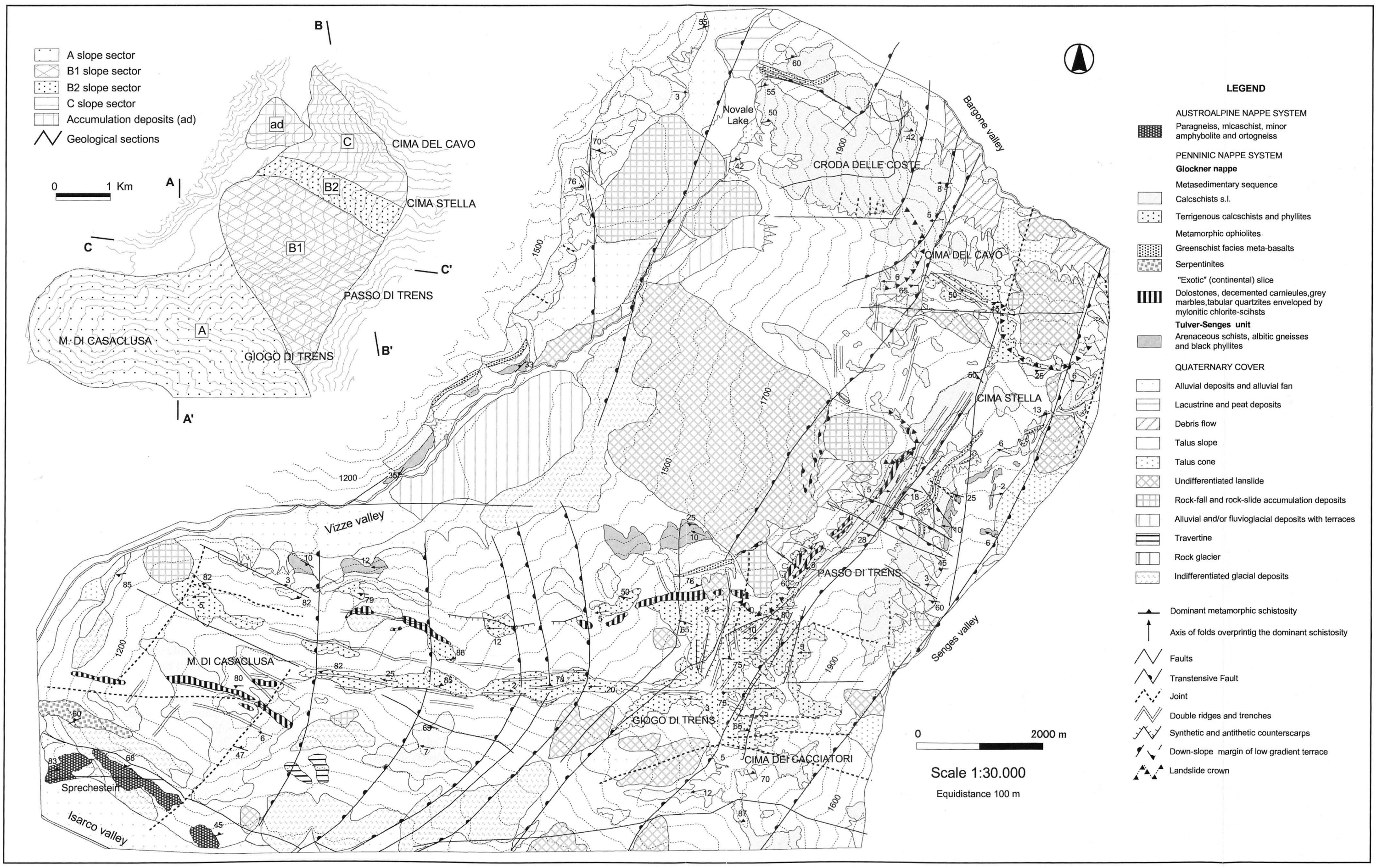

Fig. 3. Geological map of lower Vizze valley. Inset: slope sectors.

refs. therein). In the Eastern Alps, the collisional nappe-stack is characterized by subduction-related eclogite or blueschist facies metamorphism (scattered relics) of Cretaceous-Eocene age, and a Barrovian (amphibolite to greenschist facies) regional overprint of Late Eocene-Oligocene age (Hoinkes et al. 1999; Thöni 1999). The nappe-stack consists of: (1) the Adria-derived Austroalpine continental basement and cover nappe system; (2) the Penninic system exposed in the Tauern window, including (2a) the ophiolite-bearing Glockner nappe and (2b) the underlying Europe-derived Tux – Gran Veneziano continental basement (Central Gneiss) and cover nappes (Fig. 2). To the south, the Austroalpine-Penninic wedge is tectonically juxtaposed to the Adria-vergent Southern Alps along the Periadriatic fault system.

During the Oligocene, rapid uplift took place, together with extensional tectonics and post-collisional calc-alkaline magmatism (Von Blanckenburg & Davies 1995; Dal Piaz 1999). From the Neogene onwards, north-south plate convergence continued and the rigid South-Alpine lithospheric indenter pushed against the softened (Barrovian metamorphism) inner part of the orogenic wedge, causing rapid exhumation of the Penninic nappes and development of the Tauern window (Selverstone 1985, 1988). The process was facilitated by lateral displacement of the Austroalpine orogenic lid, thanks to E-W extension along the W-dipping Brenner low-angle detachment and strike-slip faults at the northern and southern edges of the escaping block (main examples: Inntal, Salzachtal-Ennstal, Defereggen-Antholz-Vals and Pustertal faults; Behrmann 1988; Selverstone 1988; Ratschbacher et al. 1991). In the meantime, the north-vergent frontal thrust system propagated towards the Helvetic domain and the inner Molasse foredeep basin, whereas in the Southern Alps an antithetic (Adria-vergent) shallow thrust-and-fold belt developed, propagating towards the Po Plain.

Rapid uplift of the study area and surroundings in the Neogene is well documented by fission track dating on zircons and apatites (Grundmann & Morteani 1985; Fügenschuh et al. 1997). Repeated geodetic measurements along the railway tunnel of the Hohen Tauern show a current uplift of 1mm/y (Senftl & Exner 1973). In addition, close analogies between the Neogene kinematic evolution and the large-scale active strain field (from geodetic GPS measurements), in situ stress measurements (borehole breakouts) and seismotectonic data (epicentre distribution and focal mechanisms) suggest the maintenance of a steady-state regional strain pattern until the Present (Müller et al. 1992; Zoback 1992; Bressan et al. 1998; Caporali et al. 2001; Caporali et al. 2002).

During the Pleistocene glaciations, the study area was covered by glaciers, as testified by the widespread morainic deposits and morphology. Post-glacial evolution was dominated by gravitational processes which were predisposed by the interplay among glacial erosion and active uplift, which originated high-energy slopes, and glacial retreat which caused differential unloading between ridge and slope bottom. The study ridge was not affected by the glacial advance of the Little Ice Age.

3. Geological and structural setting

The Mt. Casaclusa – Passo di Trens – Cima del Cavo ridge is located between the Vizze-Pfitsch and Senges valleys, north-east of the Isarco valley, and develops in the Glockner nappe and underlying Tulver-Senges unit. The area is located at the south-western edge of the Tauern window, in the footwall of the Brenner detachment fault zone (Fig. 2), and was involved in long-lasting differential rapid uplift driven by recent (active?) faults. This tectonic setting, coupled with fluvial-glacial erosion, favours the development of large-scale landslides and DSGSD.

The Penninic nappe stack exposed in the western Tauern window is regionally characterized by two huge east-west trending antiforms, evidenced by the Central Gneiss core (Gran Veneziano-Zillertal to the south, and Tux to the north), and overlying continental to oceanic units (Sander 1929; Lammerer et al. 1981; De Vecchi & Baggio 1982; Lammerer 1986; Bigi et al. 1990; Fig. 2). The Tux-Gran Veneziano nappe system consists of dominant granitic-granodioritic orthogneiss (Central Gneiss), with minor pre-granitic paragneiss, adhering to detached cover sequences of Permian-Mesozoic age. Among these, only the Tulver-Senges unit is exposed in the study area, as a small window (Fig. 3) consisting of arenaceous schists and albitic gneisses with quartzitic lenses, minor carbonaceous beds and rare metaconglomerates. As shown in Fig. 4, it is sandwiched between the Glockner nappe and the buried Jurassic Hochstegen marble, supposedly enveloping the gneissic core. The capping Glockner nappe is composed of Mesozoic carbonate to terrigenous calcschists, minor marble and quartzite, with some interleavings of metamorphic ophiolite (mainly greenschist facies meta-basalts and scarce serpentinite lenses; Fig. 3).

To the west, the gneissic core and related cover units disappear below the Glockner nappe, although the antiformal axis is nearly subhorizontal on a regional scale. This is the result of the "staircase" westward lowering of the nappe pile due to a set of NNE-trending high-angle normal faults (Figs. 3, 4, 5), partly identified by De Vecchi & Baggio (1982). Consequently, in the study area, which roughly coincides with the southern antiform hinge (Gran Veneziano-Zillertal), the calcschists of the Glockner nappe are extensively exposed, whereas the underlying continental units outcrop only (and partly) in the Tulver-Senges tectonic window.

The DSGSD examined here extends from the Mt. Casaclusa – Passo di Trens – Cima del Cavo ridge to the left-hand slope of the lower Vizze Valley, covering an area of 20 km^2 (Fig. 3). The arenaceous gneiss of the Tulver-Senges unit outcrops at the base of this slope, below the ophiolitic Glockner nappe. From bottom to top, the latter consists of tabular grey marble, followed by carbonate and minor terrigenous calcschists. In the upper-middle part, this sequence includes a pluri-kilometric trail of "exotic" bodies (continental-cover rocks; Fig. 5C), mainly represented by mylonitic chloriteschist, marble, yellow dolostone, carnieul and minor quartzite, probably of Triassic age.

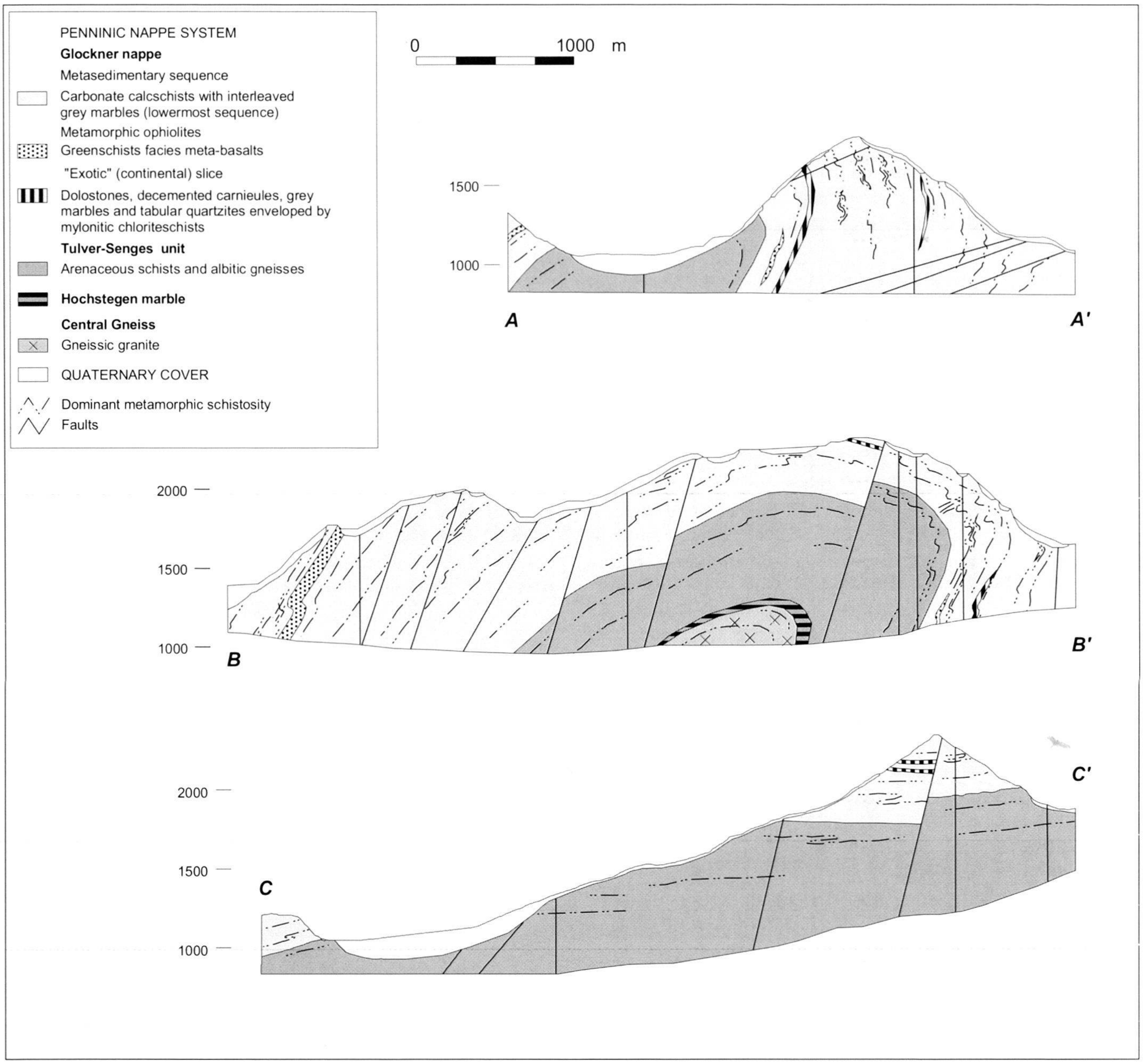

Fig. 4. Geological sections (scale = 1:40.000 ca., see Fig. 3 for location).

Owing to the changing trend of the lower Vizze valley (E-W in the southern part vs. NNE-SSW in the northern part), its left-hand (SE) slope cuts the Gran Veneziano-Zillertal antiform along variously oriented sections. The E-W Mt. Casaclusa – Giogo di Trens ridge segment (A in Fig. 3) is nearly parallel to the antiformal axis and is located along the southern fold limb, so that the dominant schistosity is subvertical or steeply dipping to the north, and its strike is parallel to the slope contour-lines (Figs. 4, 6). In contrast, along the NNE-SSW Giogo di Trens – Cima del Cavo ridge segment, the slope obliquely cuts the antiformal hinge. This segment may be subdivided into two sub-sectors (B and C in Fig. 3): in B, the schistosity is characterized by low to intermediate dip angles (crest of the antiform) and cuts the slope at high angle; in C, the schistosity deepens to the north, at a high to intermediate angle, in places close to the slope gradient (Figs. 4, 6).

The study area is cut by a complex network of major deformation horizons, faults and joints (Figs. 3, 7, 8). These features are not homogeneously distributed, and consequently their influence may be different in each sector of the ridge.

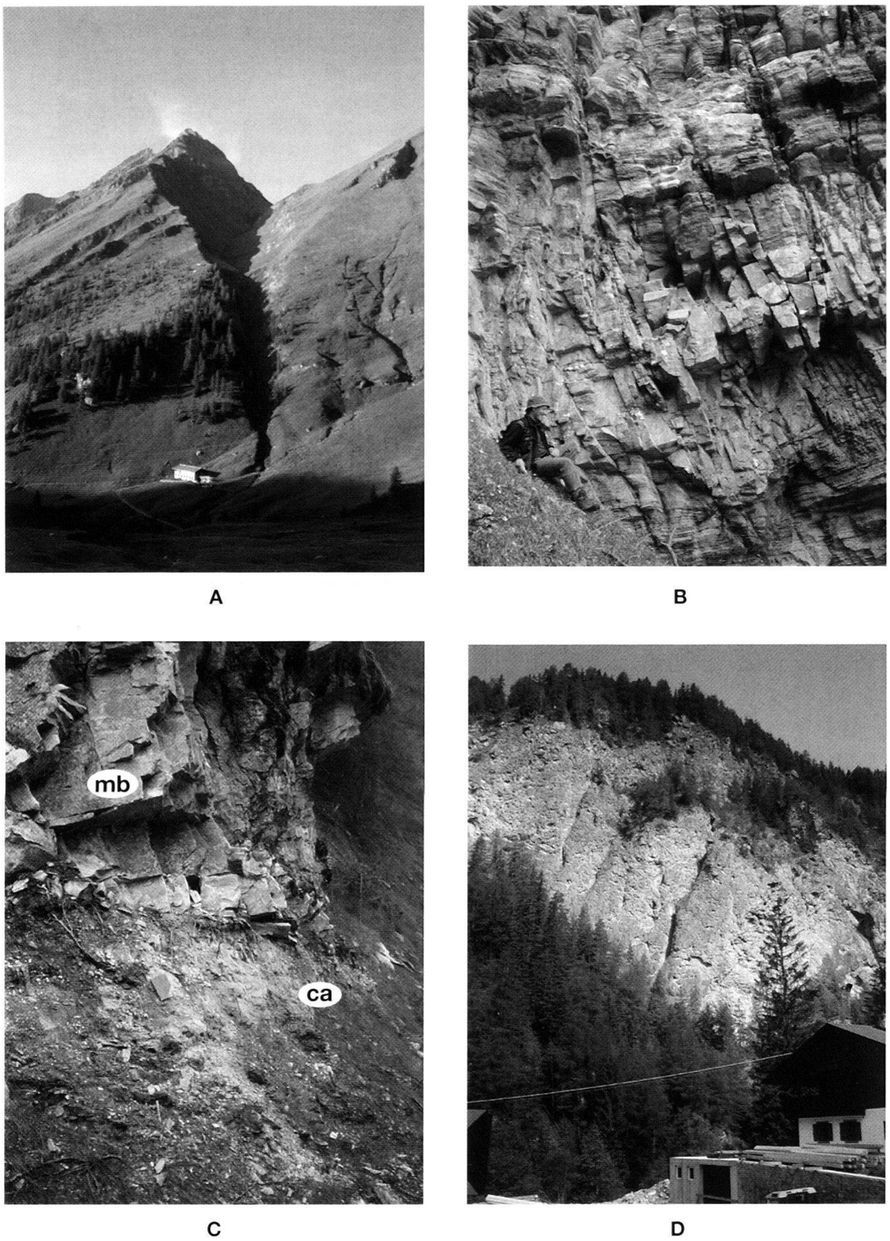

Fig. 5. A) Morphological expression of a NNE-SSW fault (Mt Grande valley); B) High-angle NNE-SSW meso-faults and joints cutting the low-angle schistosity of Glockner grey marbles, southern edge of Passo di Trens DSGSD; C) Exotic decemented carnieul (ca) and grey marble (mb) interbedded in Glockner calcschists; D) Accumulation deposits of Cima del Cavo rock-fall, composed of cemented breccia with large calcschist blocks.

The major tectonic feature is the N-trending Brenner detachment horizon, which is characterized by SC' structures with E-W extensional kinematics. This deformation zone extends 2 km from the Isarco valley to the east, and consequently involves only the southern part of the ridge (A in Fig. 3). SC' structures developed at the brittle-ductile transition along the low to intermediate angle west-dipping schistosity. Foliations show this attitude only in the lower part of the slope, so that the Brenner detachment zone probably contributed little to slope evolution.

A penetrative set of N-S to NNE-SSW high-angle dilatant joints and faults (e.g. Fig. 5A-B, 8), mainly with top-down-to-the-W/sinistral transtensional kinematics, crosscuts the entire area and structurally controls the Giogo di Trens – Cima del Cavo ridge (B in Fig. 3). This set is kinematically coherent with the Brenner low-angle detachment.

A major dextral strike-slip brittle deformation horizon marks the eastern slope of the Isarco valley at its confluence with the Vizze valley, and brings the Glockner calcschists in contact with the Austroalpine basement; to the SE it dextrally displaces the Pustertal fault. We refer to this deformation zone as the Sprechenstein – Val di Mules fault (Figs. 2, 3, 7). This brittle feature and the NNE-SSW fault – more or less coinciding with the Giogo di Trens – Cima Stella ridge – are associat-

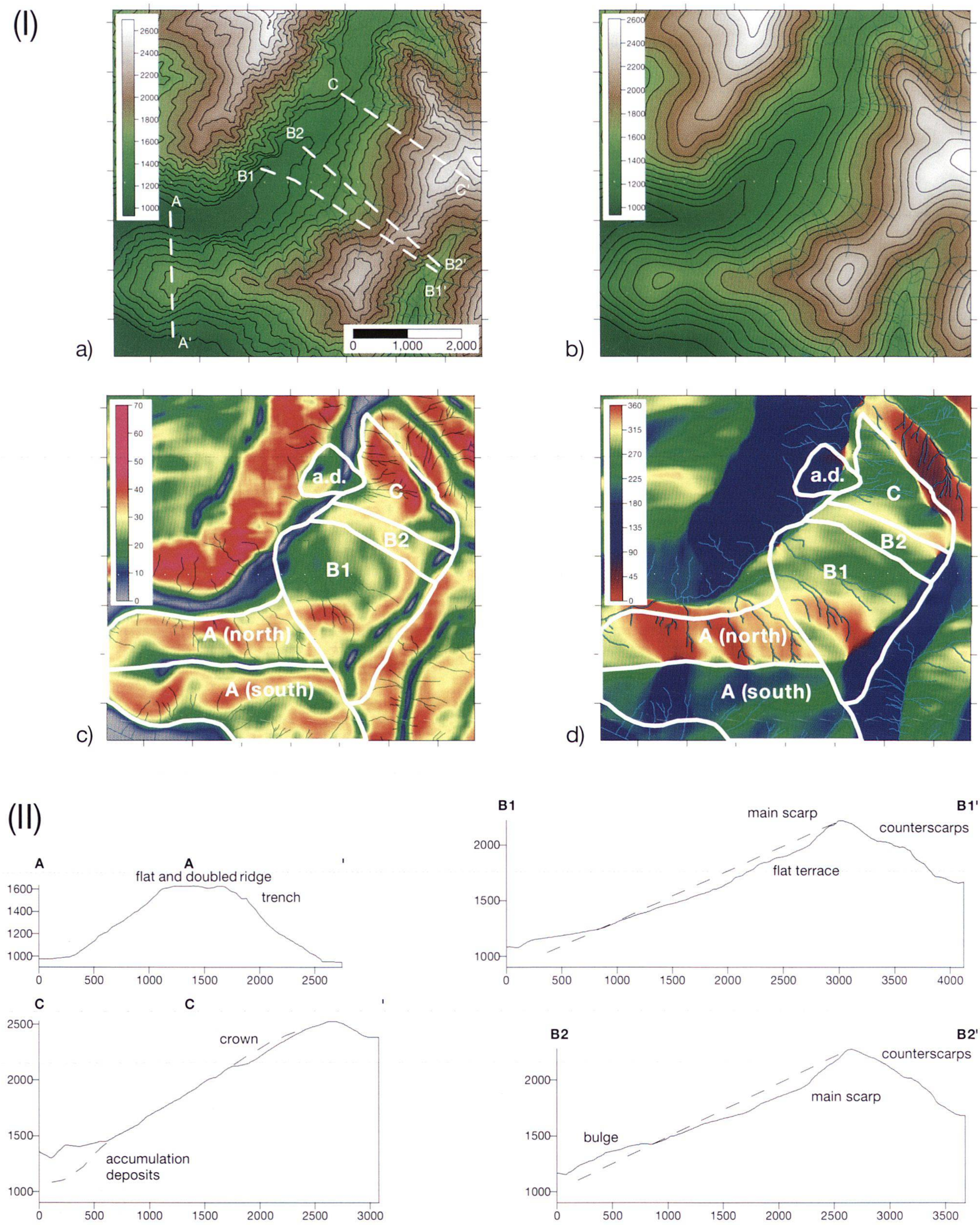

Fig. 6. I) Modelling steps from high-resolution DTM (digital terrain model): a) topography (15x15m DTM), b) smoothed topography (210x210m moving average), c) slope gradient map derived from smoothed topography, d) slope aspect map derived from smoothed topography. A, B1, B2, C and Malga Fannes accumulation deposits (a. d.) are highlighted in white. II) Topographic profiles perpendicular to ridge sectors A, B1, B2 and C (for location, see Ia).

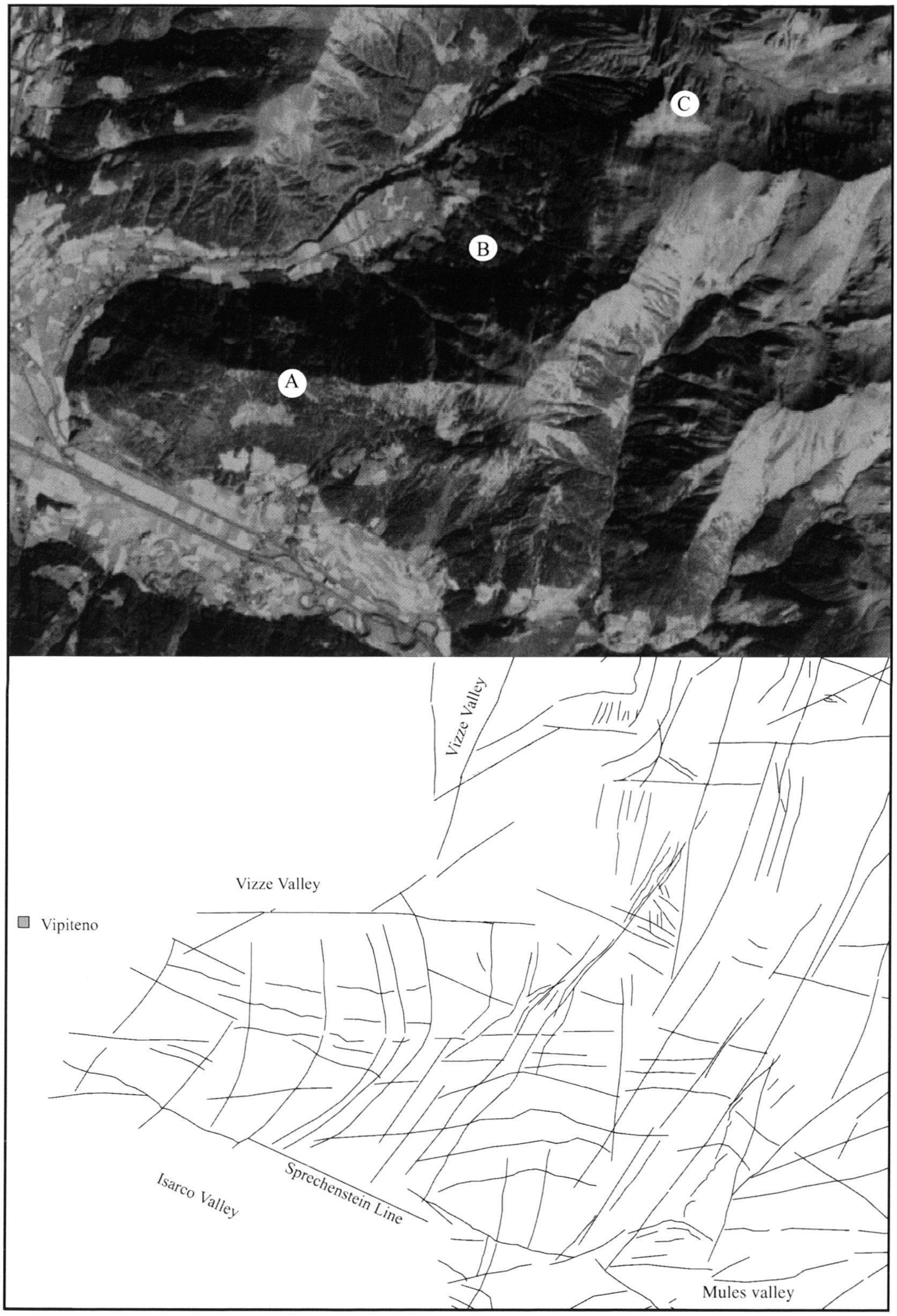

Fig. 7. Fault and joint network in Isarco, Vizze and Mules valleys. Landsat 7 ETM panchromatic data. A-B-C: segments of DSGSD. Crown of Cima del Cavo rock-fall (left of C) is at intersection of E-W and N-S to NNE-SSW faults.

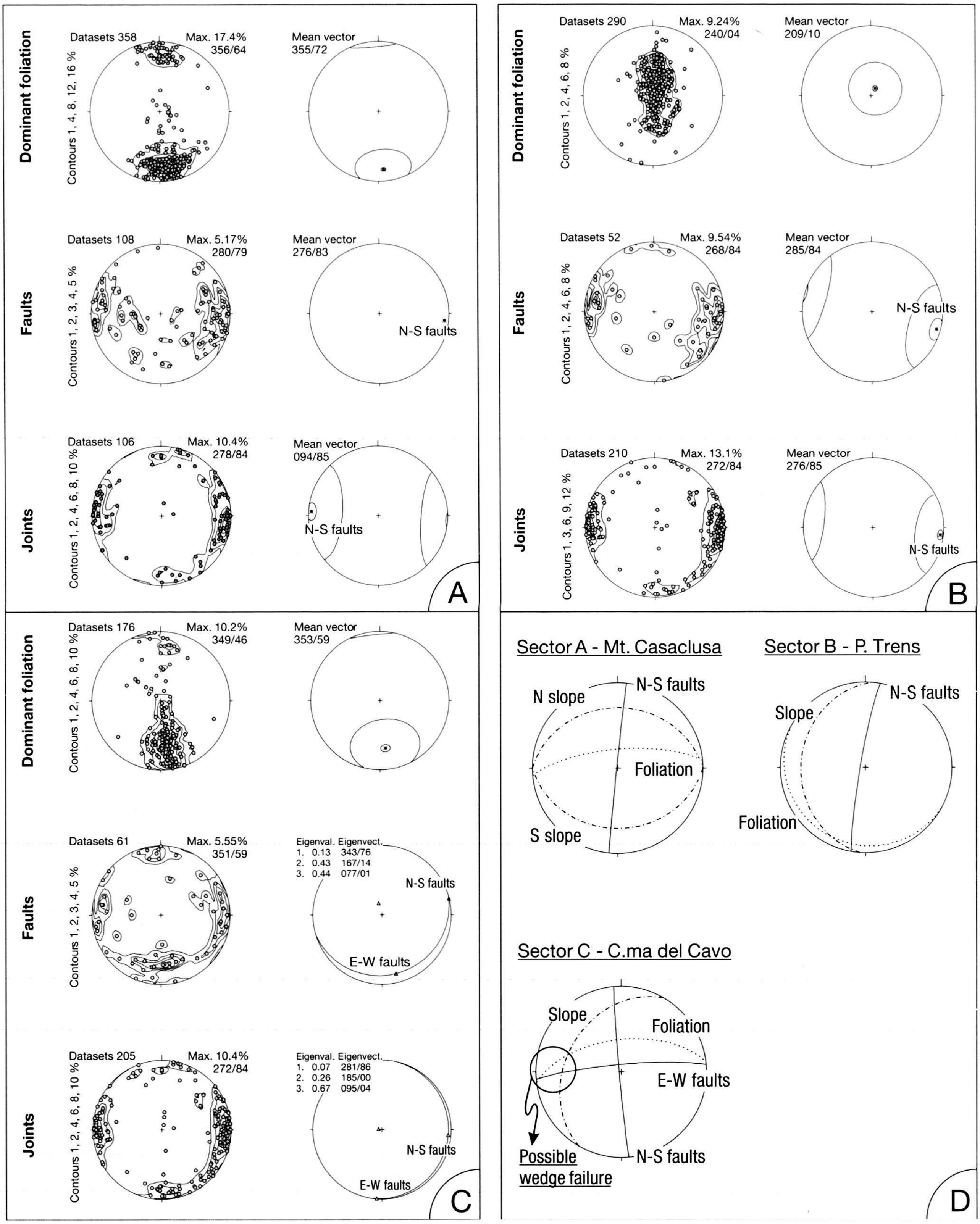

Fig. 8. Stereoplots of dominant metamorphic schistosity and brittle discontinuities in sectors A (Mt. Casaclusa), B (Passo di Trens) and C (C.ma del Cavo). D) Comparison between facets of model slope, mean values of dominant metamorphic schistosity and prevailing sets of brittle discontinuities in sectors A, B and C.

ed with 50-100 m-thick deformation horizons characterized by fault rocks including cataclasites, fault breccias and fault gouges. Both sinistral transtension along the NNE-SSW fault system and dextral transcurrence along the Sprechenstein-Val di Mules fault are consistent with continuing N-S Adria-Europe contraction, extensional activity of the Brenner low-angle detachment, and eastward lateral extrusion of the Penninic units.

Lastly, minor WSW-ENE and E-W striking faults cut the left-hand ridge of the lower Vizze valley; their presence is particularly relevant in the C sector, where the main subvertical scarps are E-W trending (Figs. 3, 7, 8).

In order to model the geometrical relationships between slopes deformed by mass movements and previous structural features, the left (southern) slope of the lower Vizze valley has been discretized into constant-attitude facets by orientation and gradient. Modelling was achieved via filtering, smoothing and classification of a high-resolution DTM (digital terrain model) (Fig. 6). The attitude of the facets of the model slope was compared with mean values of dominant schistosity and prevailing sets of brittle discontinuities (Fig. 8D).

4. Gravitational slope deformations in the lower Vizze valley

The northern slope of the ridge connecting Mt. Casaclusa to Cima del Cavo is deformed by three major mass movements. Their peculiar evolution closely depends on the above-discussed geological and structural variability. Nevertheless, the continuous extent of major morphostructures along the ridge suggests that these mass movements are linked to each other, constituting the composite result of a single gravitational process (Fig. 3).

4.1. Sector A (Mt. Casaclusa)

The E-W trending Mt. Casaclusa is a flat ridge (Fig. 4) with relatively low topographic stress: the relative relief is 600-700 m and the slope angle is in the 20-35° range (locally 40°). Hence, according to Engelen (1963) and Dramis (1984), no deep-seated gravitational slope deformation should be expected in this area. However, open trenches, flat-bottomed depressions and scarps are quite common, clearly indicating some kind of active slope deformation (Figs. 3, 6).

The important role of groundwater flow in the development of this deformation is supported by: (i) widespread travertine deposits, continuously mantling the southern slope of Mt. Casaclusa along the Sprechenstein – Val di Mules fault (Fig. 3); (ii) strongly de-cemented carnieuls, interbedded in the Glockner nappe calcschists with subvertical regional schistosity (Fig. 4, 5C).

The entire ridge is devoid of surface water, which extensively infiltrates through the flat-bottomed depressions and open trenches. Infiltrating water may reach: i) deep fractured rock-aquifers which extend beyond the study area, ii) alluvial aquifers below the Vizze and Isarco valley floors, iii) the surface at the landslide toe. The last case was not observed, whereas the first two are the more reliable hypotheses, indicating a DSGSD process. Part of the groundwater was probably forced to reach the surface, along the high-permeability Sprechenstein-Val di Mules fault, by the low-permeability barrier of the Austroalpine, allowing Ca^{2+} ions to re-depose here as travertine. It may be noted that low-salinity water, typical of high-mountain areas and glaciers, is very effective in dissolving the anhydrite component of evaporitic deposits. Although the dissolution of anhydrite probably causes limited volume loss, and does not adequately explain the observed collapse of the Mt. Casaclusa ridge, it may have dramatically reduced the strength of the carnieul-bearing exotic bodies, facilitating the generation of tensile features even in conditions of low topographic stress. Positive feedback is typical of dissolution and deformation processes, as increasing dissolution leads to easier deformation, and more deformation means enhanced permeability. Hence, a lateral spread mechanism, reactivating the sub-vertical schistosity, is the most probable DSGSD process for this ridge sector. The contribution of faults and joints is moderate because they strike perpendicular to the ridge itself (Figs. 3, 7). A low-angle discontinuity or a soft substratum at the base of the mass movement is not necessarily implied.

4.2. Sector B (Passo di Trens)

Sector B displays a high relative relief (about 1100 m) which favours DSGSD development, despite a moderate overall slope gradient (25-35°). This is not surprising, since great variability in slope gradient is reported for DSGSD (generally from 20° to 50°; Zischinsky 1966, 1969; Radbruch-Hall et al. 1976; Mahr 1977; Mortara & Sorzana 1987).

The most impressive geomorphological features are the gravitational morphostructures occurring on both sides of the ridge (Figs. 4, 9, 10). The classic nomenclature has long disregarded their kinematic significance (Radbruch-Hall et al. 1977; Bovis 1982; Hutchinson 1988; Cruden & Varnes, 1996), and only recently have some efforts in this direction been made by Agliardi et al. (2001). We suggest that distinctions should be made among uphill-facing scarps, which may be subdivided into doubled ridges (or crest doubling), antithetic counterscarps (or antithetic uphill-facing scarps) and synthetic counterscarps (or synthetic uphill-facing scarps; Fig. 3, 10). Accordingly, the upper part of the collapsed slope is characterized by a clearcut main scarp with associated minor antithetic counterscarps (Passo di Trens), several continuous doubled ridges along the crest, and some synthetic counterscarps on the opposite side (southern slope; Figs. 3, 9, 10). The latter features show an upslope movement consistent with the downslope displacement along the main scarps and doubled ridges. In addition, these morphostructures constantly follow the NNE-trending high-angle faults (Fig. 3). Flat-bottomed depressions are rare and reflect mass-movement evolution different from that recorded in sector A.

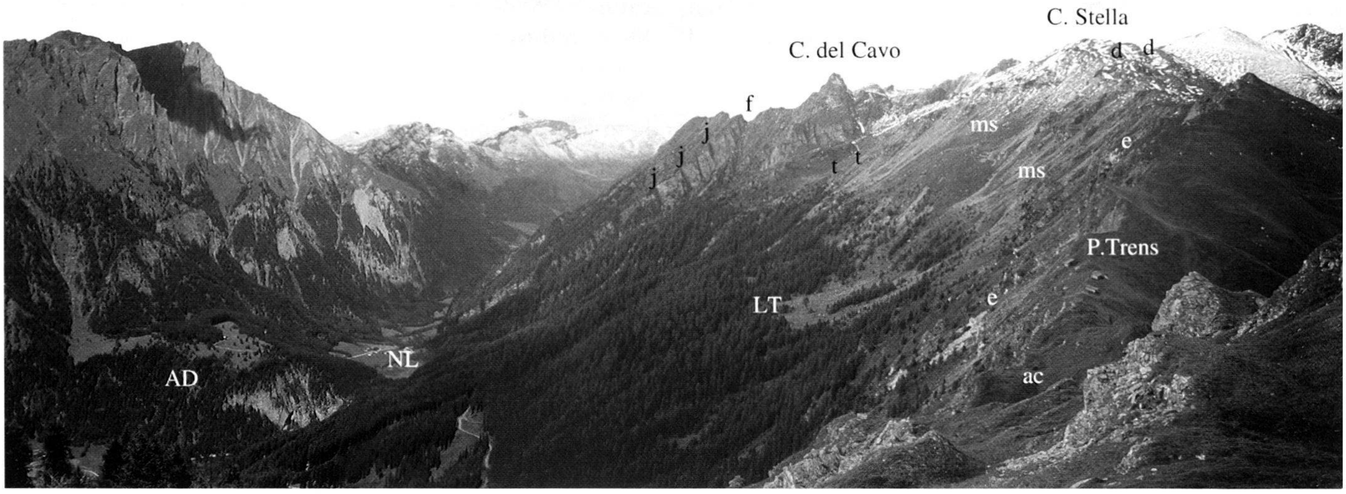

Fig. 9. View of Passo Trens *sackung* from Giogo di Trens looking north: lake of Novale (NL), accumulation deposits (AD – Malga Fannes) of Cima del Cavo rock-fall, low-gradient terrace (LT), exotic dolostone (e); fault (f), doubled ridges (d), antithetic counterscarps (ac), main scarp (ms), antithetic joints (j), trenches (t).

The observed types and distribution of major and secondary scarps suggest the occurrence of multiple discrete sliding surfaces in the upper part of the slope, partly reactivating previous tectonic discontinuities. However, there is no evidence of a localised basal surface on the slope bottom. As in sector A, no surface water (streams, pools, etc.) can be found anywhere on the slope, indicating very effective infiltration favoured by severe fracturing, whereas the lack of persistent springs at the toe of the mass movement suggests the absence of a localised basal gliding discontinuity outcropping at the surface. In this view the groundwater probably reaches the alluvial aquifer below the Vizze valley floor.

The upper half of the slope in sector B1 has a concave profile (a scarp followed by a low-gradient terrace; Fig. 3, 4, 6, 9), typical of a *sackung* process, which indicates downhill mass transfer. Instead, in contrast to "typical" *sackung* examples, the lower half of the slope does not have a well-defined bulge (convex profile; Fig. 6).

The lower part of the slope and a large area at its foot are covered by a continuous blanket of debris-flow, rock-fall and other shallow landslide deposits, which overlie till deposits attributed to the Last Glacial Maximum. Therefore, the former lower bulge of the DSGSD may have been removed by erosion (facilitated by related fracturing) and smaller mass movements developing on its surface.

Given its overall characteristics, this mass movement may be considered as a *sackung* or complex *sackung*/block-slide DSGSD because of the absence of a single basal gliding plane, although numerous discrete surfaces are clearly visible on the top of the ridge.

Most of the slope in sector B1 seems to be in an advanced state of morphological evolution, as demonstrated by the scarcity of open trenches and the absence of a bulge in the middle and lower parts of the main body, and therefore this huge mass movement may be considered dormant (Cruden & Varnes 1996; Keaton & De Graff 1996). Evidence of current instability is limited to shallow processes. In this view, one problematic zone is the southern margin of sector B1, not far from Giogo di Trens, where rock sliding may be facilitated by the same joint pattern which generated the impressive counterscarps antithetically related to the main scarp (Fig. 10).

Some peculiar features are visible in the northern part of the slope (B2 in Fig. 3), i.e., a suspended bulge and numerous open trenches (Fig. 6). Some trenches cut a rock-glacier which may be referred to the Little Ice Age – hence they are probably active. The surface mass movements which reduce the bulge to the south-west (B1) do not occur here. Therefore, this area has great potential for further mobility, and its expected evolution will be discussed later.

4.3. Sector C (Cima del Cavo)

Sector C contains the large crown of a major rock-fall. Accumulation deposits (Malga Fannes) completely barred the Vizze valley, generating a large lacustrine basin which extended for some km north of the present lake of Novale (Fig. 3, 9). The rock-fall deposits are a cemented breccia made up of large calcschist blocks (Fig. 5D). The rock-fall is clearly younger than the Late Glacial Maximum, because the lacustrine sediments linked to the valley barrage overlie the glacial deposits.

This rock-fall is most probably the result of a single catastrophic event, with mass sliding of huge blocks along the dihe-

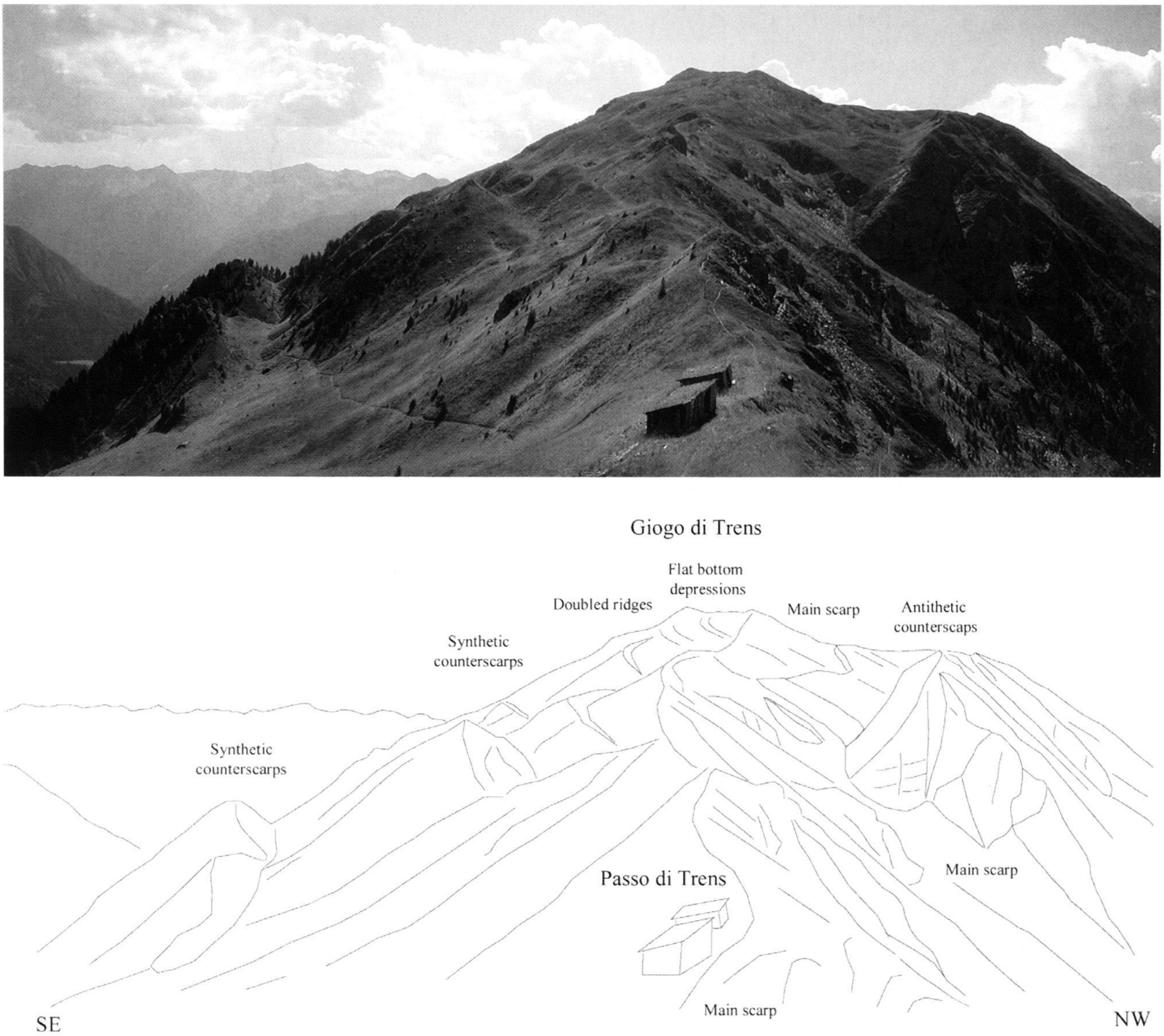

Fig. 10. Gravitational morphostructures of Giogo -Passo di Trens ridge looking south.

dron delimited by the regional schistosity (steeply dipping to the N) and a subvertical E-striking fault-set (Fig. 3, 7, 8). The crown developed along a regular system of N to NNE-striking faults and open joints (Fig. 3, 7, 8), which also constitute a very important channel for water infiltration in the main body of the mass movement.

The ridge to the N of the crown still has a high relative relief (> 1200 m, with respect to the valley bottom) and very steep slopes (35-60°), mainly calcschist walls, without major loose deposits. This sub-vertical E-W scarp is crosscut by a regular network of open joints, which are antithetically related to the NNE-SSW high-angle faults and coincide with trenches and counterscarps (Fig. 3, 9). Hence, some of the conditions which facilitated the large rock-slide still exist here.

5. Discussion and conclusions

Relationships between slope attitude, principal anisotropic surfaces and defined discontinuities, summarised in Fig. 8D, may explain the contrasting evolution recorded in the various sectors (A, B, C) of the Mt. Casaclusa – Passo di Trens – Cima del Cavo DSGSD.

Starting from sector C, the intersection of the N-dipping schistosity and E-W striking faults forms a dihedron, which transects the rather steep slope at a high angle. Large blocks bounded by this dihedron and N-S to NNE-SSW faults can easily slide down, as shown in Fig. 11. This interpretation is supported by a detail from a satellite image, showing that the crown of the Cima del Cavo rock-fall is located at the in-

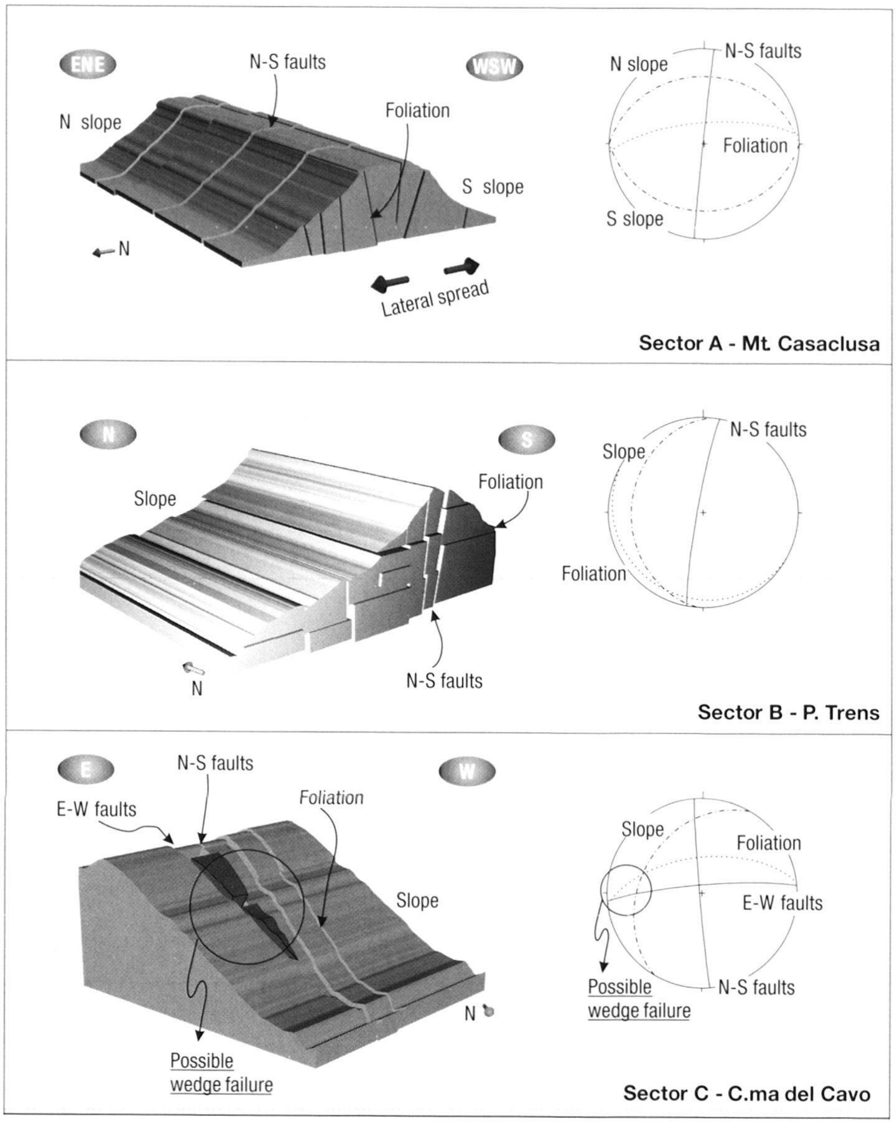

Fig. 11. Block-models showing different evolution of each ridge sector; stereoplots of fig. 8D are shown for comparison. A) lateral spread; B) *sackung*; C) rock-fall.

tersection of two E-W and N-S to NNE-SSW fault systems (Fig. 7)

In sectors A and B, the relationships among schistosity, brittle fractures and slope do not allow large blocks to be released, so that large-scale rock-falls are not a feasible mode of slope instability.

In sector A, the regional schistosity is subvertical and parallel to the slope, whereas NNE-SSW faults are almost perpendicular to it (Fig. 11). This setting induces high permeability and deep water circulation, leading to carnieuls dissolution and facilitating lateral-spread-type failure of the ridge. This interpretation is confirmed by evidence of ongoing dissolution of carnieules and the overall slope profile, which is consistent with a lateral spread model.

Lastly, in sector B, the intersection of low-angle schistosity and NNE-striking faults with the slope does not release large blocks, but is very favourable to continuous, diffuse creep along the low-angle schistosity (Fig. 11). This leads to the development of extensive *sackung* and widespread surface instability caused by severe *sackung*-induced fracturing. The combined activity of penetrative discontinuities, with dilatant deformation mechanisms, is supported by the high permeability of the entire slope (no surface water), whereas large-scale *sackung* kinematics are confirmed by the concave/convex slope profile and impressive morphostructures of the Giogo di Trens – Cima Stella ridge (Figs. 6, 9, 10).

In the boundary region between sectors B and C (B2 in Fig. 3), the schistosity is steeper than in sector B, but E-W striking major faults (very important in releasing large blocks in sector C) have only been found at the B2-C transition and to the north. Hence, the evolution which may be predicted for this sector will probably be more similar to that of sector B1 (*sackung*) than that of sector C (rock-falls).

As a general conclusion, the DSGSD studied here is an outstanding example of the control exerted on slope evolution by a ductile and brittle structural framework, which in turn is the ultimate result of a complex tectonic history. Hence, basic structural studies are useful in understanding the origin, mechanics and potential evolution of large mass movements. In particular, knowledge of large-scale structures is very effective in reconstructing the architecture of major discontinuities at depth, which is generally a main issue when dealing with DSGSD.

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