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Autor: Schönborn, Gregor / Schumacher, Markus E.

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Controls on thrust tectonics along basement-cover detachment

by *Gregor Schönborn*[1] and *Markus E. Schumacher*[2]

Abstract

Décollement at the base of fold-and-thrust belts follows frequently the basement-cover contact. Pre-existing local conditions near this contact have a strong influence on thrust topography. Underneath the Orobic thrust in the Southern Alps of Italy, a whole series of different adaptations to local conditions can be examined. Far away from asperities the décollement layer itself is attenuated, and the lost material is piled up in duplex stacks more externally. Obstacles like hinterland dipping normal faults are overcome by larger duplexes requiring décollement along minor, less efficient detachment horizons. An upward ramping thrust encountering a graben with incompetent fill splits into many branches transposing the graben to a stack of imbrications. If the detachment has reached already the regional décollement horizon and a graben starts within the basement below, however, the detachment may step down to the base of the incompetent fill, rotating the graben deposits antitheticly and creating "extensional duplexes". Basement highs within the graben get detached and subsequently appear as imbrications between the cumulated basin deposits. Another possibility for a thrust to step down to a lower detachment in faulted area includes synthetical, domino-like rotation of the slabs between the faults. A thrust thus has numerous possibilities to react to pre-existing, not perfect layercake conditions.

Keywords: detachment, duplex, pre-existing fault, graben, thrust tectonics, Orobic thrust, Southern Alps.

Introduction

Thrust tectonics are often influenced by pre-existing faults. This is especially manifest when passive margins are later deformed into fold-and-thrust belts. Inherited faults responsible for facies changes oriented parallel to the subsequent main compressive direction may cause lateral ramps (e.g., THOMAS, 1990), others oriented obliquely or perpendicularly to future compression may cause inverse faults (e.g., SHERIDAN, 1974). Basal detachments of frontal fold-and-thrust belts follow frequently the contact between crystalline basement and sedimentary cover (Jura Mountains, BUXTORF, 1907; Pyrenees, WILLIAMS, 1985; Sulaiman Range in Pakistan, BANKS and WARBURTON, 1986; Rocky Mountains foothills, BALLY et al., 1966; Valley and Ridge province, RICH, 1934, and many more). Inherited faulting and folding of this contact hence becomes a first order boundary condition for the location of faults in the detached sedimentary cover above. This is suggested by field studies, balancing considerations (e.g., NOACK, in press), seismic interpretations (e.g., LAUBSCHER, 1986), photoelastic (WILTSCHKO and EASTMAN, 1983) and finite element models (SCHEDL and WILTSCHKO, 1978; BÖHI, 1994).

The central part of the western Southern Alps of Italy (Fig. 1) exhibits a south vergent fold-and-thrust belt involving pre-Moscovian (pre-Late Westphalian) crystalline basement, a several kilometers thick heterogeneous Triassic sequence, Upper Triassic to Lower Jurassic synrift deposits, thin Middle Jurassic to Lower Cretaceous deep sea sediments and Upper Cretaceous flysch. The facies of the early to middle Permian sediments indicates deposition in ENE trending pull-aparts indicative of transtensional tectonics (SCHÖNBORN, 1992). The Late Triassic to Early Jurassic extension preceding the opening of the Tethys gave rise to enormous thickness variations of the synrift sediments (e.g., some 6 to 9 km across the

[1] Institut de Géologie, rue Emile-Argand 11, CH-2007 Neuchâtel, Switzerland.
[2] Geologisch-Paläontologisches Institut, Bernoullistrasse 32, CH-4056 Basel, Switzerland.

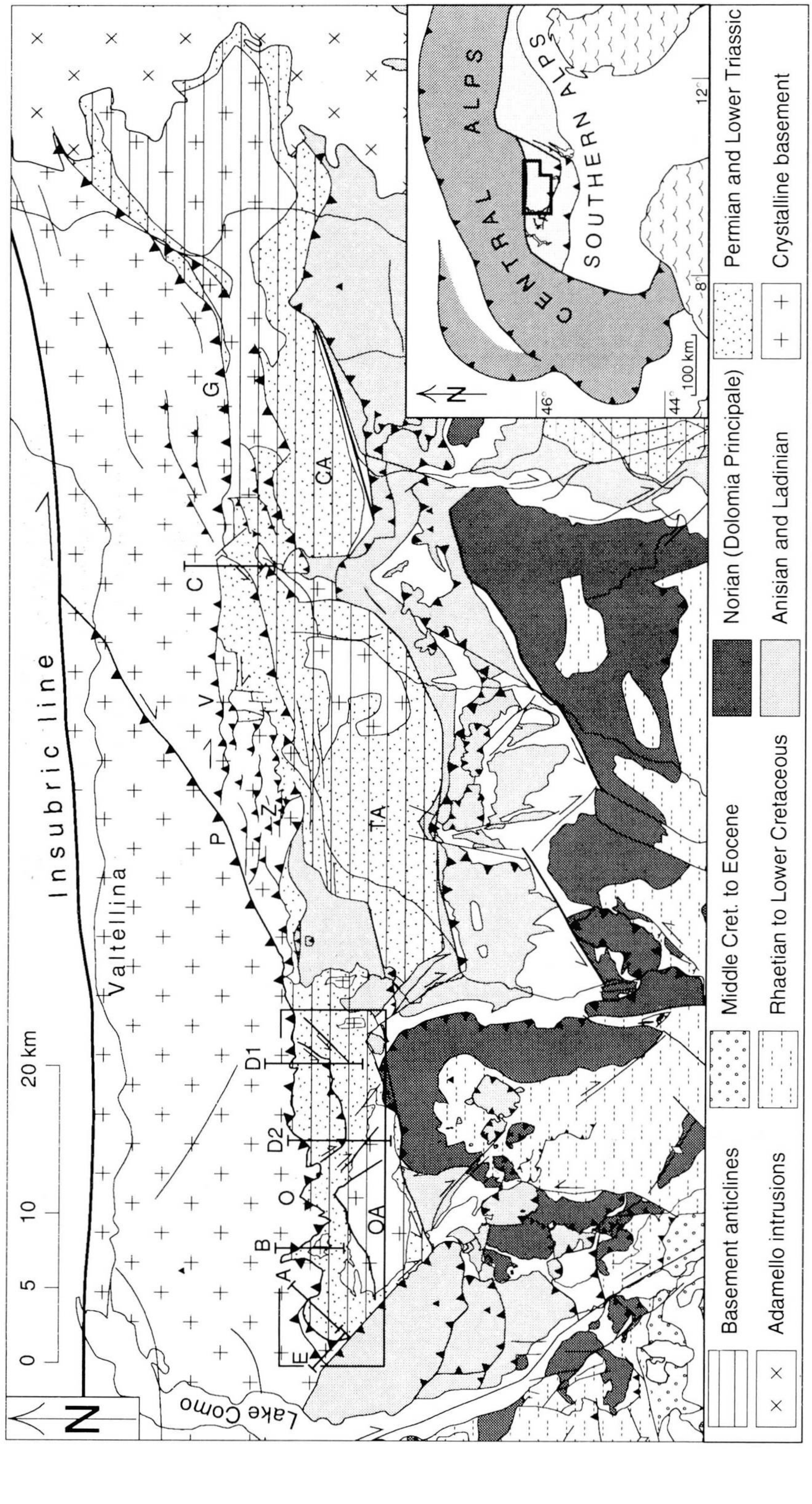

Fig. 1 Location and map of the area discussed. Cross-sections A–E refer to Figs 5–9 and 11. Square on Orobic anticline indicates location of plate 1. OA, TA, CA = Orobic, Trabuchello and Cedegolo basement anticline, respectively. G = Gallinera thrust, O = Orobic thrust, P = Porcile line, V = Venina line, Z = M. Zerna.

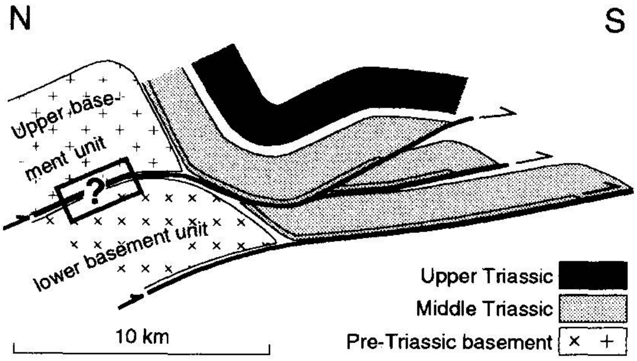

Fig. 2 Two nappes with basement and sedimentary units are exposed. Ramp-flat tectonic style lead to ramp-folds also in the upper part of the basement. The scope of this article is to investigate the detachment along the Orobic thrust at the top of the lower basement unit.

Lugano fault west of Fig. 1, BERNOULLI, 1964, BERTOTTI et al., 1993, Fig. 7 of SCHÖNBORN, 1992). Structures of both extensional events, the Early Permian as well as the Early Jurassic, influenced subsequent Alpine deformation. A first phase of Alpine thrusting including the Orobic thrust is older than middle Eocene intrusions (CORNELIUS and FURLANI-CORNELIUS, 1930; BRACK, 1984), presumably Late Cretaceous (BERNOULLI and WINKLER, 1990), a second phase can be dated with the help of seismics and drillholes in the Po basin as middle to late Miocene (PIERI and GROPPI, 1981). In the Triassic sequence, strongly contrasting rheologies between thick and rigid platform carbonate layers and evaporitic or shaly detachment horizons lead to distinct ramp-flat tectonics during Alpine compression. The fold-and-thrust belt is composed of at least three major nappes (called "thrust sheets" in SCHÖNBORN, 1992), each containing a basement and a sedimentary part. Basement-cover relationships can be studied at the nappe scale as well as at the meso or micro scale.

At the nappe scale, LAUBSCHER (1985) has shown that the same thrust (Orobic thrust) deforms the crystalline basement to frontal ramp-folds in the north and represents the base of the uppermost sedimentary thrust units farther south (Fig. 2). Underneath these ramp-folds, other basement anticlines of equal size are interpreted as ramp-folds of the next lower nappe ("lower basement unit" in Fig. 2, called Orobic, Trabuchello and Cedegolo anticlines, Fig. 1), although the basal thrusts are exposed only farther south (LAUBSCHER, 1985). The contact zone between the Triassic units and the basement folds is generally faulted; south vergent thrusts, north vergent backthrusts, extensional faults, strike-slip faults and combinations can be observed. Wherever this information is achievable, these faults begin at the basal nappe thrust (SCHÖNBORN, 1992). Fortunately, unfaulted sequences allow the correlation of sedimentary and basement units in some areas.

This paper, however, does not deal with nappe-scale aspects of basement-cover relationships, but it aims at the kinematics of the detachment near the basement-cover contact (? in Fig. 2). Crystalline basement of the upper nappe was transported along the Orobic thrust onto basement to Lower Triassic beds, creating during that transport the Suborobic imbrications (KELLER et al., 1987) discussed here. Subsequently, the Orobic thrust and the Suborobic imbrications were folded by the formation of the next lower nappe (Fig. 2, LAUBSCHER, 1985). The outstanding significance of this area with respect to the interplay of inherited structures and thrusting is that many features can actually be observed which commonly have to be constructed indirectly from folding observed high above, from seismics, or from numerical models with simplified parameters.

In the studied region, various methods reveal upper anchizone to lowermost greenschist facies conditions near the Orobic thrust (RIKLIN, 1983; SCHÖNBORN, 1992). Mesoscopic structures imply generally brittle deformation, except for the décollement horizons and the Permian shales, which are deformed in a more ductile manner.

Stratigraphic setting

Figure 3 depicts a simplified stratigraphic column: the crystalline basement consists of various gneisses and schists deformed under amphibolite and retrograde greenschist facies conditions during Variscan orogeny (MILANO et al., 1988). In parts of the area considered, light colored orthogneisses (Gneiss Chiari) appear at the top of the crystalline rocks. Their thickness varies between 0 m and some km (near Cimone di Margno, plate 1), their base is always tectonized and they might represent a Variscan nappe. Frequently observed within the uppermost nappe, they are absent in the lower, palinspastically more southerly located nappes. Their invariable position at the top of the crystalline basement gives some stratigraphic information.

During early to middle Permian (e.g. SUESS, 1869; CASATI and GNACCOLINI, 1967; CADEL, 1986) erosional debris of the Variscan mountain chain and volcanics were deposited in ENE trending graben (Collio formation, Fig. 3; DE SITTER and DE SITTER-KOOMANS, 1949; CADEL, 1986; CADEL

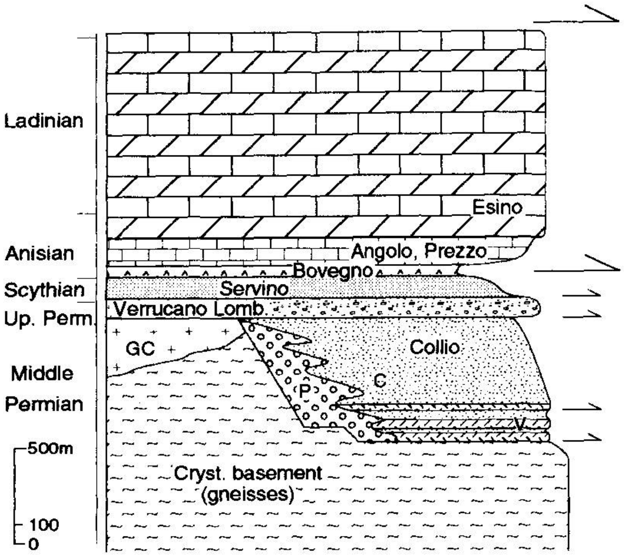

Fig. 3 Simplified stratigraphic column. Large arrows indicate regional detachment horizons (Servino/Bovegno fms and above the Ladinian Esino carbonates), small arrows mark minor detachment possibilities. GC = Gneiss Chiari, C = Carona shales, P = Ponteranica conglomerates, V = volcanites. C, P and V are different facies of the lower to middle Permian graben fill (Collio fm).

et al., 1987; Fig. 6 of SCHÖNBORN, 1992). On behalf of their geometry, these graben can be interpreted as pull-aparts (along either ENE trending dextral faults or along NW trending sinistral faults), presumably related to the huge and complex Stephanian-Autunian dextral transfer zone connecting the Appalachians with the Ural (ARTHAUD and MATTE, 1977; ZIEGLER, 1988). The porphyries and volcanoclastics that are especially abundant in the lower parts of the basin fill have the same age (270–290 Ma, CADEL et al., 1987) as granitic intrusions in the upper crust (Baveno, e.g., HUNZIKER and ZINGG, 1980) and ultramafic to mafic intrusions in the lower crust (e.g., main mafic formation in the Ivrea zone, VOSHAGE et al., 1990) documenting the deep crustal fracturing during this late Paleozoic wrench fault period. The Collio fm comprises rhyolitic lavas and pyroclastics generally in the lower part and terrigeneous clastics generally in the upper part. The clastics consist of shaly and sandy deposits and of conglomerates following commonly the margins of the troughs. The shaly facies (Carona shales) in the central parts of the graben record after CASSINIS et al. (1986) alluvial fan, sand flat and mud flat conditions. Occasionally found footprints of large land-organisms testify to extremely shallow lacustrine or subaeric conditions. A conglomerate sequence that comprises also crystalline components besides volcanics is called Ponteranica conglomerate. The thickness of the Collio fm is reported 800–1000 m on the Orobic anticline (CASATI and GNACCOLINI, 1967), 1500 m (CASSINIS et al., 1986) to more than 2000 m (DE SITTER and DE SITTER-KOOMANS, 1949; CADEL et al., 1987) farther east near cross-section C (Fig. 1), but 0 m outside the graben. See CASATI and GNACCOLINI (1967), CASSINIS et al. (1986) and CADEL et al. (1987) for a more detailed stratigraphy.

The graben are sealed by upper Permian conglomerates (Verrucano Lombardo fm, Fig. 3) which are part of a facies association ranging from proximal coarse alluvial fans in the Luganese (just west of Fig. 1) to finer grained alluvial plain and braided river deposits and finally evaporitic and then open marine deposits some 250 km farther east (ASSERETO and CASATI, 1965). The Verrucano Lombardo conglomerate includes pebbles of quartz porphyries and vein-type quartz in a red or green sandy to shaly matrix. Near the Orobic anticline this formation is some 100 to 150 m thick, but it reaches some 400–500 m near cross-section C and farther east (Fig. 1).

During the Early Triassic, westward transgression of the Paleotethys established marine conditions in the Southern Alps. The Servino fm (ca 120 m thick, Fig. 3) was deposited: above quartz conglomerates which occur only in the westernmost part of the area considered, quartz arenites and siltstones are followed by wackestones with dolomitic cement, then by sandy dolomites and finally by dolomites with thin silty and shaly intercalations. They merge upward into the "Carniola di Bovegno", cellular dolomites (rauhwacke) which may be a tectonofacies of the upper part of the Servino fm. This some 50 m thick horizon is a very important décollement that serves as basal detachment for the sedimentary tectonic units farther south.

After the Anisian transgression layered limestones were generally deposited on the shelf. During the late Anisian and the Ladinian strong subsidence lead to the buildup of carbonate platforms (up to 1500 m thick) adjacent to deep basins with hemipelagic and turbiditic sedimentation.

Location of the different imbrication types

Figure 4 shows the location of the imbrication types (A–E) discussed in this article between the Orobic thrust and the Orobic anticline, except for imbrication type C on cross-section C, which is located farther east (Fig. 1). The 100 m contours refer to the top of the Orobic anticline (cf. Fig. 1

and plate 1), which is considered as the frontal ramp-fold of the Mezzoldo unit (SCHÖNBORN, 1990), the basement part of nappe 2. The western part of the Orobic anticline plunges steadily northwest, but the eastern part is complicated by depressions and highs that are superimposed on the gentle eastward plunge. Two sets of ENE and NW trending faults cross-cut the anticline internally and delimit it to the south. All these faults were reactivated during Alpine compression as dextral (the NW directed set) or as sinistral (the ENE directed set) strike-slip or transpressional faults (SCHÖNBORN, 1992), but they apparently have a more complex history. The NW trending faults in the middle of figure 4 follow approximately the eastern border of a Permian trough, the ENE trending faults are parallel to the trough axis and its northern and southern margins as defined by the changing facies of the clastics. At least some of the faults depicted in the western sector are of Mesozoic (Liassic?) origin since they displace Lower Triassic strata and predate the Orobic thrust, presumably active during Late Cretaceous. The same two fault directions can be found in the whole area comprised in figure 1, delimiting laterally most of the thrust units and causing the en-échelon alignment of both the basement anticlines and the northern limits of exposed Upper Triassic units (cf. Fig. 1, SCHÖNBORN, 1992).

Figure 4 conveys the suggestion that the main masses of imbrications are associated with the irregularities of the Orobic anticline: type B north of the largest pre-existing faults with several hundreds of meters vertical throw, the large lenticular mass described in the cross-section D_1 and D_2 above a depression of the anticline, and the puzzling type E at the western end of the anticline.

East of the Orobic anticline, the imbrications along the basement-cover contact discussed here are no longer exposed, but imbrications of Triassic units along the front of the basement ramp-fold (KELLER, 1986).

Discussion will begin with the common situation far from obstacles (cross-section and imbrication type A, Fig. 4), then imbrications will be examined that developed in front of pre-existing normal faults disrupting the detachment horizon (type B). Next, a trough will be considered which was imbricated by an upward ramping thrust (cross-section C). Cross-sections D_1 and D_2 focus on two distinct troughs being scooped out one after the other by a thrust which seems to have reached the Lower Triassic detachment horizon already before the graben and then had to plough down to the bottom of the graben again. These kinematics are reminiscent of the series of overturned basement slabs discussed finally (type E).

Imbrication of the detachment horizon itself (type A)

Data: Figure 5a shows the situation near the western end of the Orobic anticline. Whereas in the northern part of the cross-section the décollement horizon (Servino and Carniola di Bovegno fms) is reduced tectonically to a few meters except for some thicker lenses, it is accumulated farther south. The sandstones and siltstones of the lower part of the Servino fm are piled up to an apparent thickness of some 850 m, although they are less than 60 m thick in the undeformed state. The beds dip steeply north, the fold axes trend subhorizontally WNW. The Verrucano layer and

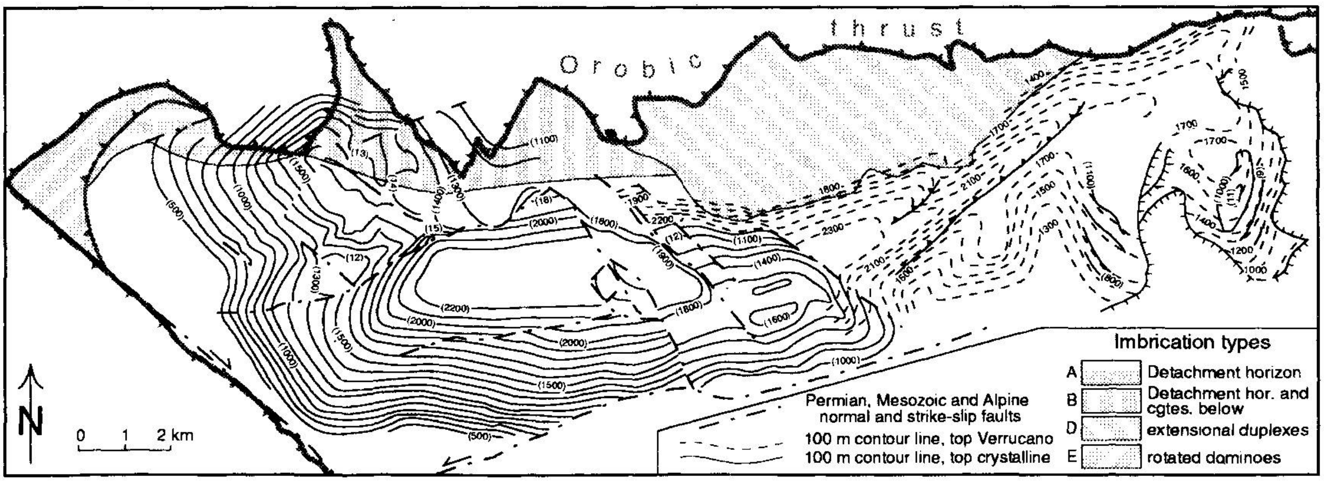

Fig. 4 Location of the different imbrication types (each correponds to the cross-section with the same letter) between the Orobic thrust above (shaded) and the Orobic anticline below (contours).

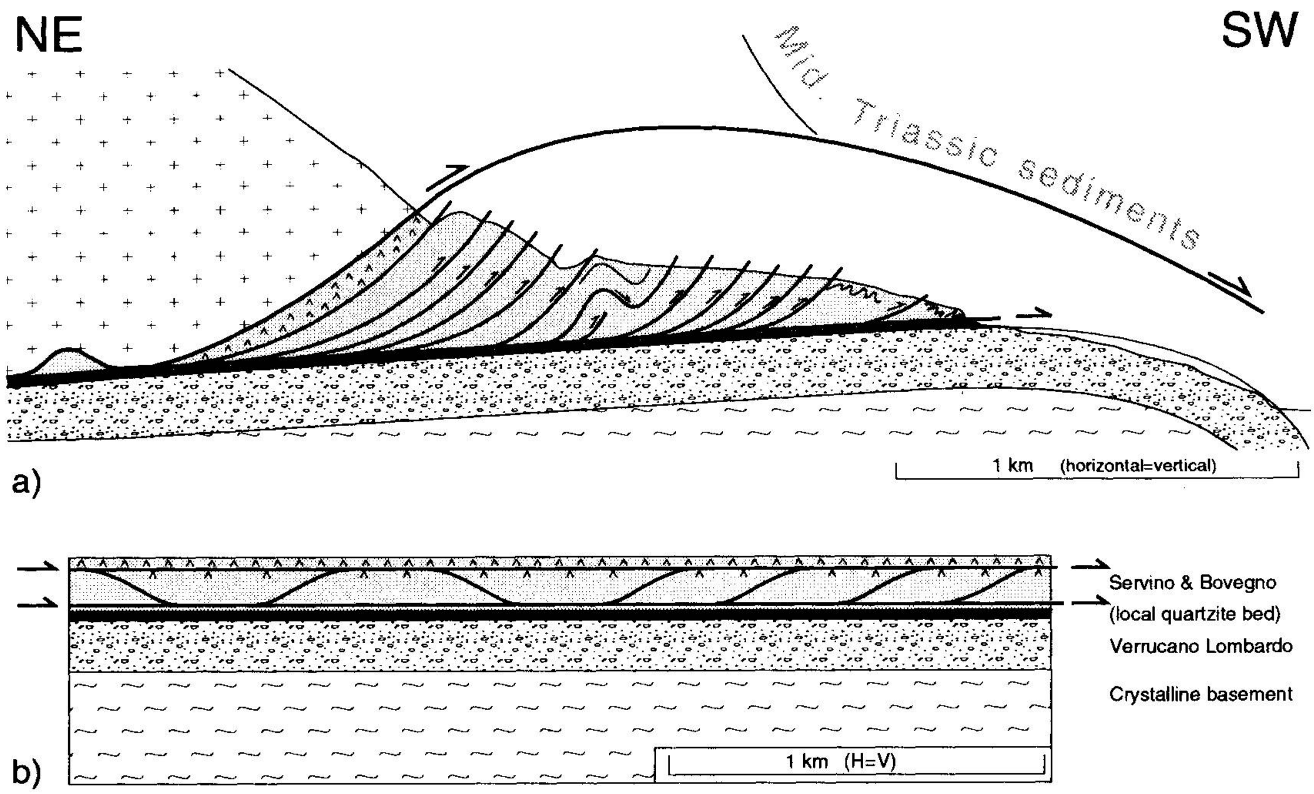

Fig. 5 Cross-section A across the western end of the Orobic anticline. For location see plate 1, for signatures figure 3. a) situation today, b) retrodeformed section (schematic). Far away from obstacles, the detachment horizon is attenuated except for some lenses with the help of downstepping thrusts between a floor thrust and a roof thrust. The missing material is accumulated to large imbricational stacks by upstepping thrusts. Figure 5a modified after SCHÖNBORN (1992).

the quartzite beds at the Verrucano-Servino transition are not affected by accumulation and folding.

Interpretation: Although just a few thrusts are exposed, the lower Servino beds must have been piled up by at least a dozen duplexes to achieve the thickness presently observed. This implies a floor and a roof thrust within the décollement horizon which are linked by upstepping but also by downstepping thrusts (Fig. 5b). The first enable accumulation in common duplex manner (e.g., BOYER and ELLIOTT, 1982), the latter enable thinning of the horizon (LAUBSCHER, 1989). Together they facilitate the formation of lenses of décollement material along the thrust. In fact, massive thinning of detachment horizons over long distances with accumulation of the missing material in certain places are extremely common in the Southern Alps and in other thrust belts with distinct décollements (e.g., the "Muschelkalkschuppenzone" along the front of the eastern Jura mountains, BITTERLI, 1988). In the Southern Alps accumulations of décollement material are observed frequently where two strike-slip faults meet.

Duplexes in front of hinterland dipping normal faults (type B)

Data: Figure 6a is a cross-section along Val Marcia (cf. plate 1). In the northern part of the valley classical duplexes composed of Verrucano conglomerates with a thin Servino cover are well exposed beneath the Orobic thrust. The Servino beds are intensely folded around gently west (260–270°) dipping fold axes. In the northernmost part of the valley dragfolds along intra-Servino thrusts indicate transport toward the south (170–180°). The upper part of the valley is cut by a number of faults. Four of them (in plate 1 from N to S the fault near point "968", the Dirotto and Dolcigo faults, and presumably also the Biandino fault) are of Mesozoic (Liassic?) origin, since they displace the Lower Triassic beds, but are cut by Alpine thrusts which were presumably active during the Late Cretaceous (cf. discussion in SCHÖNBORN, 1992). They are oriented either ENE or NW, and each fault lowers the northern side by several hundreds of meters. 2 km east of figure 6, a cliff reveals vertical throw along the Biandino fault of at least 500 m. Reactivation as strike-slip faults is indicated locally for the Dirotto and Biandino faults. In the southern part of figure 6a no Verrucano duplexes can be observed below the Orobic thrust, but complexely deformed and poorly exposed Servino and Bovegno beds.

Interpretation: The position of the Verrucano duplexes just north of the normal faults illustrates how duplexes were created to smooth out the large asperities in the detachment layer. The even Orobic thrust plane above the pre-existing normal faults supports this interpretation. The size of the obstacle evoked a larger duplexes mass than in the previous example (cross-section A). Thus a bed near the base of the Verrucano conglomerates and slightly above the crystalline basement was activated as detachment layer (Fig. 6b), although rheological contrasts are comparatively small there, and the lithology does not seem very suitable.

Another point of interest is the thrust cutting the normal fault. The thrust began to ramp through the Verrucano beds some 100 m in front of the first obstacle, cut the normal fault (the fault near "968" in plate 1) and carried away a basement slice of the normal fault's footwall. The vertical throw across the normal fault apparently formed an obstacle that was too large with respect to the thickness of the Verrucano-Servino sequence to be overcome without cutting off some crystalline basement.

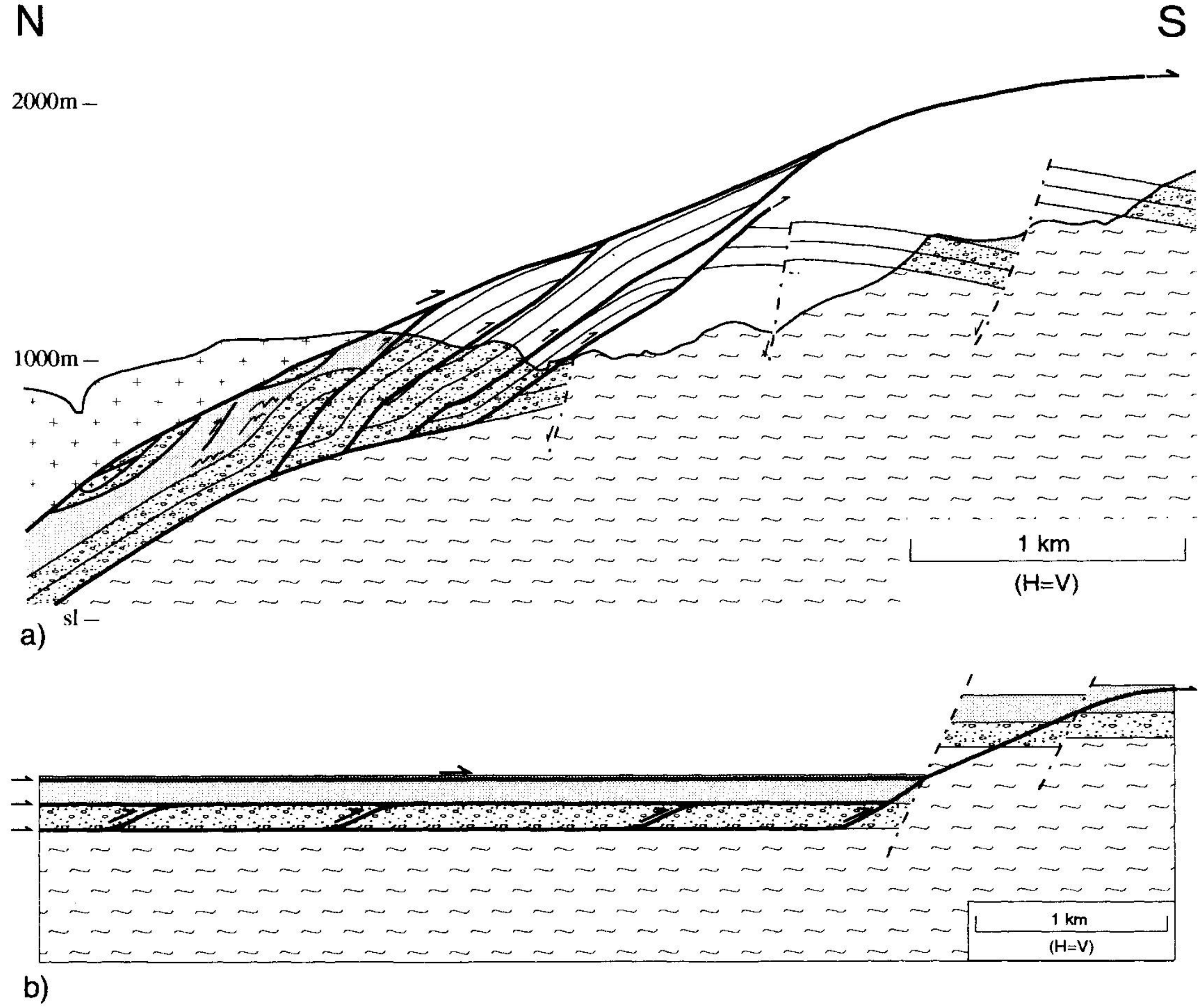

Fig. 6 Cross-section B along Val Marcia (see plate 1 for location, Fig. 3 for signatures). a) situation today, b) retrodeformed section. Hinterland dipping, pre-existing Mesozoic normal faults hinder detachment. This obstacle is overcome by a larger mass of duplexes and detachment along the less effective horizon between the crystalline basement and the overlying conglomerate layer. Geometry above the topographic line is projected some hundreds of meters from farther east.

Imbrication of a trough (type C)

Data: Figure 7a (cross-section C) displays a fairly typical cross-section through the northern part of the largest Permian graben in the western Southern Alps. See figure 1 for location of the cross-section. Steep, E–W trending faults cut the schists and gneisses north of the basin. They have a dip-slip component (uplifting the northern block, displacing markers) and a strike-slip component (generally dextral, small-scale criteria). West of figure 7 they are more frequent (cf. Fig. 1) and the more northerly they are located the steeper they tend to be. The present day northern rim of the trough also is composed of such a fault, and here the angular relation to the sediments shows that the fault was quite steep already in the beginning. Farther west this E–W oriented fault becomes intracrystalline (called Venina fault, "V" in Fig. 1). The conglomerates aligned along the northern trough rim seem to indicate that its original geometry was not profoundly distorted by Alpine tectonics. Most of the graben fill is composed of fine grained clastics, the Carona shales (or better: slates). These slates are intensely folded around subhorizontal, E to ENE trending fold axes with moderately to steeply north dipping axial planes (cf. CASSINIS et al., 1986; MILANO et al., 1988). Numerous small S to SSE vergent thrusts within the slates cause a lot of imbrications often less than 100 m thick, only a few of them are depicted in figure 7a. In contrast to the western part of the same trough, no basement slabs are exposed near cross-section C. The exposures of the basement-Permian contact in Val Seriana are not displaced by faults except the one on the right side of figure 7a. A major thrust in the middle of the trough transported a thick slab of Carona slates onto the overlying Verrucano beds (next Verrucano exposure is 1 km west of

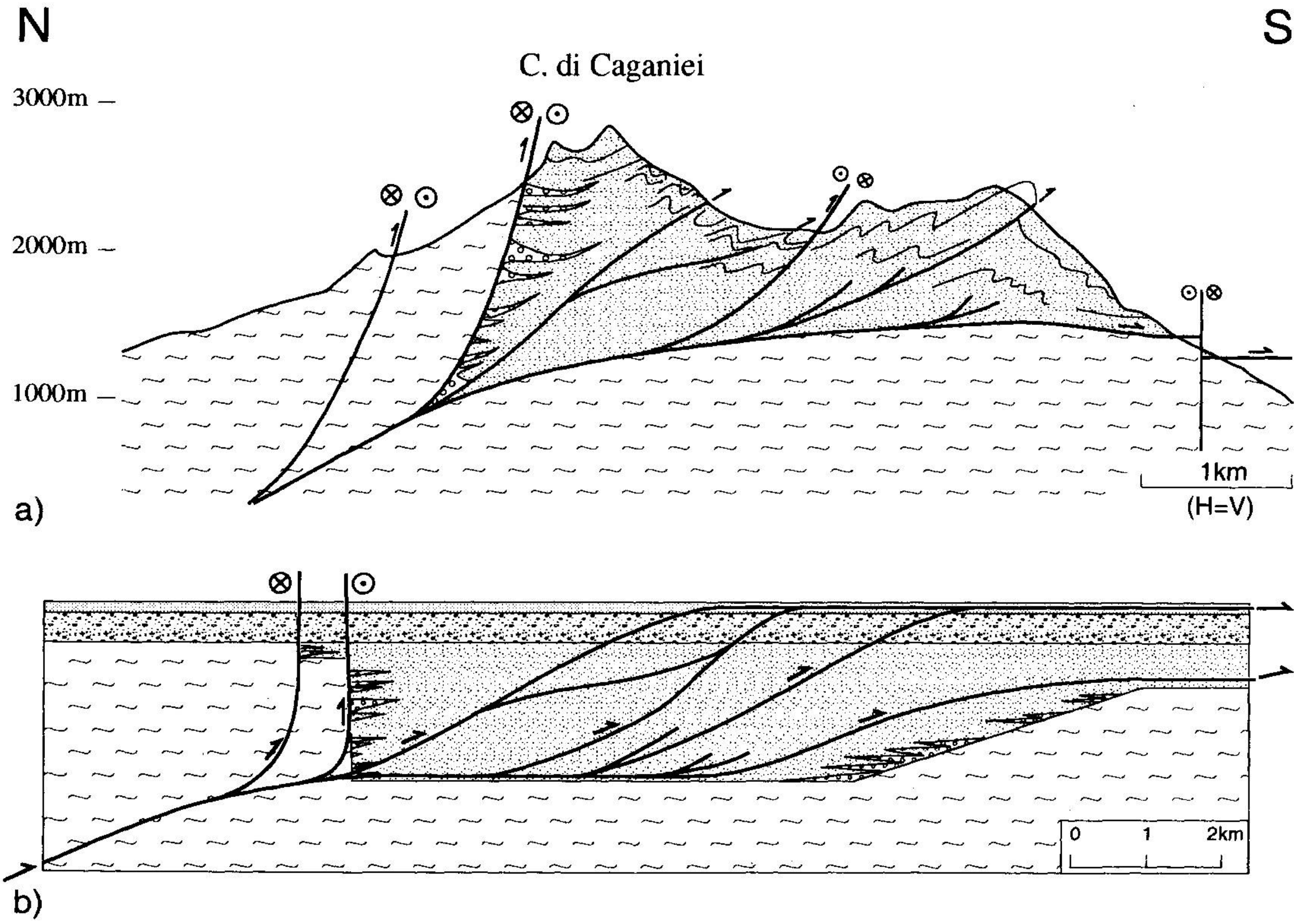

Fig. 7 Cross-section C through the main Permian trough in upper Val Seriana (Fig. 1, signatures like in Fig. 3). a) cross-section today, b) retrodeformed section (schematic). This graben rich in shales is imbricated and folded by numerous larger and minor thrusts. Some Verrucano outcrops appear just west of the section, but no basement slices can be found. This points to an even floor of the graben with no intervening basement highs. Permian normal faults near the northern rim of the graben were reactivated as transpressional upthrusts during Alpine compression. Figure 12f includes a schematic upward extrapolation of this section.

the section). Cross-section C is located at the eastern end of the lenticularly shaped hanging-wall where the thrust has a conspicuous sinistral strike-slip component (cf. Fig. 1).

Interpretation: This cross-section can be interpreted as a trough imbricated by an upward ramping thrust (Fig. 7b). The northern trough rim and Permian parallel faults farther north were reactivated as transpressional faults, the dextral strike-slip component of which is a regional phenomenon and possibly related to an eo-Alpine forerunner of the Insubric line (SCHÖNBORN, 1991, 1992). Late Oligocene to Early Miocene (Insubric) transpression was documented as major deformational event farther west (SCHUMACHER, 1990, 1991), but seems to be restricted to near the Insubric line in the area this article deals with. The steeper, partly even overturned dip (Venina fault) of the more northerly located faults points to steepening due to continued imbrication farther south. In some localities farther west (near M. Zerna, "Z" in Fig. 1) the northern rim of the trough dips much more gently north, its inclination depends apparently on the amount of dip-slip along the reactivated fault. The deformation of the Carona slates suggests a detachment near the floor of the trough with numerous smaller and one larger splay branching off. In Val Seriana there is some direct control on the base of the trough in its southern part, however, it cannot be excluded that other splays of the thrusts displace the floor of the Permian graben farther north. Probably no major basement horsts occurred within the trough – otherwise they presumably would have been cut off and carried along by the thrusts as observed in the western part of the same Collio trough (southwestern slope of M. Zerna, Fig. 1) and in another trough described in the next paragraph.

Scooping out of troughs by downstepping thrusts (type D)

Data: Figures 8a and 9 (cross-sections D_1 and D_2) cast light on the internal structure of the central-

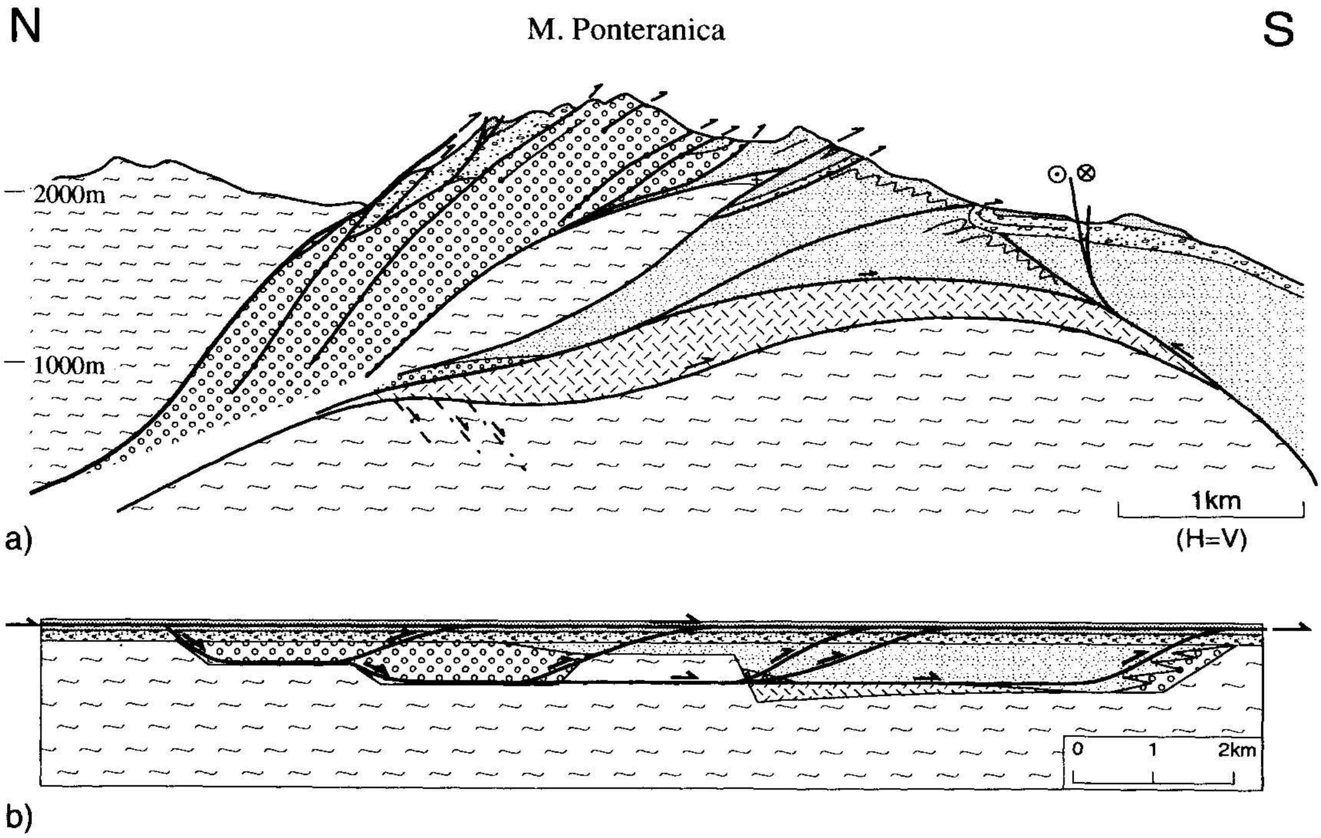

Fig. 8 Section D_1 crosses the eastern part of the Tre Signori-Ponteranica complex (cf. maps plate 1, Figs 1 and 4, signatures like in Fig. 3). a) situation today, b) palinspastic situation with a northern trough (Ponteranica trough) filled mainly with conglomerates, an intervening basement high (Salmurano) and a southern trough (Orobic trough) filled mainly with finer clastics. The two graben fills got superimposed during Alpine thrusting, the planed-off Salmurano basement pinched in between the two. Figure 8b includes thrusts that step down form the Servino layer to the base of the Ponteranica trough (cf. text and Fig. 10).

eastern part of the Orobic anticline. The anticline itself is overlain by a some 10 km wide lenticular mass, the Tre Signori-Ponteranica complex (plate 1, SCHUMACHER, 1986). The contours of the anticline are depressed underneath this large lense (Fig. 4), the Orobic thrust above is bent up. The complex is mainly composed of imbricated basin fill, i.e., of Ponteranica conglomerates along the borders and Carona shales in the center (plate 1). Verrucano and Servino beds are accumulated as imbrications only on the eastern and western ends of the lense. In the middle of the Tre Signori-Ponteranica complex a major crystalline body, called Salmurano high, also rests on the Permotriassic cover of the Orobic anticline. Thin slices of Gneiss Chiari are found along the Orobic thrust and also near the Giacomo thrust (CASATI and GNACCOLINI, 1967), the basal thrust of the complex. The Servino, Verrucano and Ponteranica beds are deformed by various north dipping thrusts, the Carona shales additionally by some folds (cf. Fig. 9). Of particular importance for the interpretation is the geometry of some of the imbrications underneath the Orobic thrust. Their rear limbs, e.g., near Lago di Pescegallo (SCHUMACHER, 1986), do not show common duplex geometry with thrusts cutting stratigraphically up-section, but in contrast they form the hangingwall of thrusts cutting stratigraphically down-section (normal fault relationship, see Fig. 10 and explanation in next paragraph). At its eastern end the complex is bounded by a sinistrally transpressive fault zone, dipping steeper north than the rest of the Giacomo thrust (SCHUMACHER, 1986). Similar structures can be observed along the western end of the lenticular mass: the Giacomo thrust dips steeper and is accompanied by dextral strike-slip faults. These faults cut up to 15 m thick, N–S trending ultracataclastic zones delimiting different Collio facies. Also the Orobic anticline itself is dissected by similar strike-slip systems in the foreland of the lenticular complex: near Rif. Grassi and Cima di Camisolo a number of dextral strike-slip faults are conspicuous (plate 1, cf. Fig. 4). Their eastern counterparts between Piani di Avaro and Montù (plate 1) are more complex, however. Steep sinistral transpressional faults go along with synthetic and antithetic Riedels and oblique triangle structures (SCHUMACHER, 1986).

In Val Biandino west of the Tre Signori-Ponteranica complex, the structure of the Permotriassic cover of the Orobic anticline can be examined (plate 1 and Fig. 9). Detached at the base (thrust faults above and below Rifugio Grassi in plate 1), the whole sedimentary sequence forms a north dipping homocline with northward increasing inclination. Verrucano slabs and poorly exposed but intricately deformed Servino beds overlie this homocline.

Interpretation: Retrodeforming the Tre Signori-Ponteranica complex puts it back to its northern position with respect to the cover of the Orobic anticline. The Permian facies associations with proximal conglomerates containing crystal-

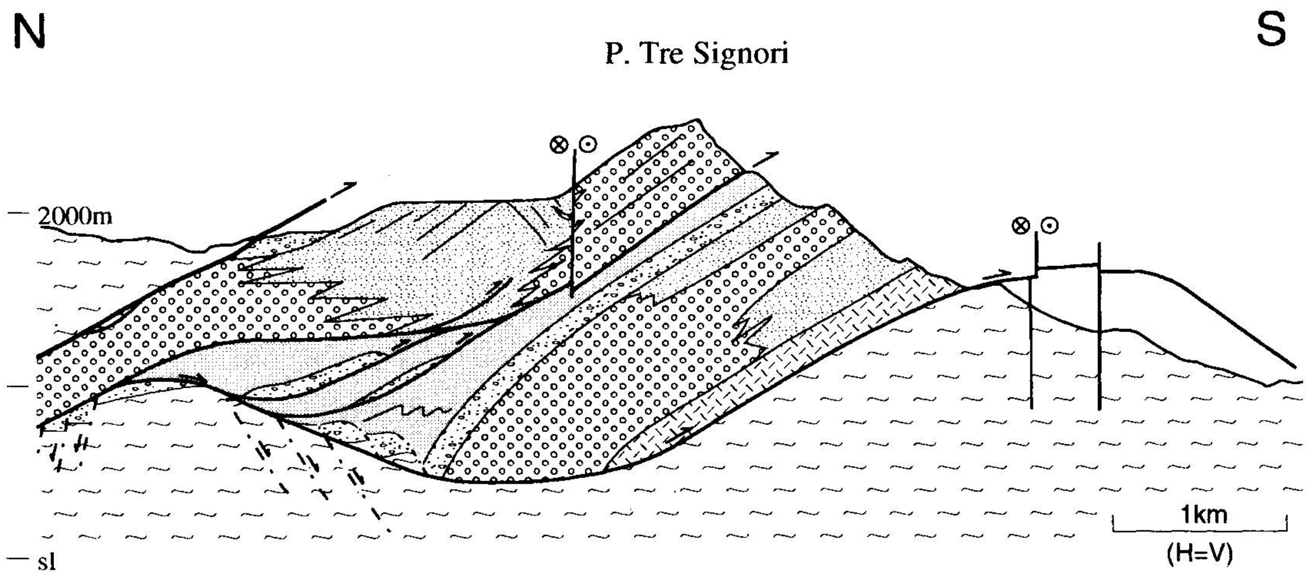

Fig. 9 Cross-section D_2 across the western part of the Tre Signori-Ponteranica complex (plate 1, Figs 1, 3 and 4). Like in figure 8, the fill of the Ponteranica-graben (note the facies arrangement) was thrust onto another graben, located more to the south. The lower part of this figure is projected from the west, disclosing the sooping out of the southern graben fill by a thrust stepping down from the regional décollement layer (Lower Triassic, light grey shading) to the base of the graben fill. Modified after SCHÖNBORN (1992).

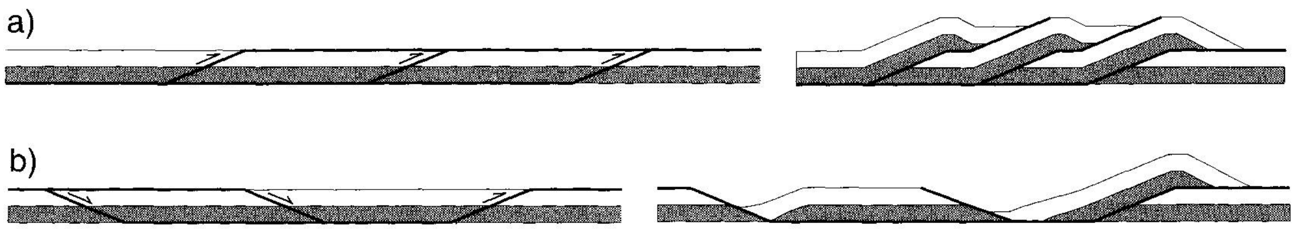

Fig. 10 *a)* Common duplex architecture involving thrusts ramping to a higher detachment. *b)* Thrusts stepping to a lower detachment level (extensional duplexes) cause imbrications reminiscent of extensional crenulation cleavage in more ductile domains. The geometry of the antithetically rotated rear limbs is different from those in figure 10a, but the front limbs very often are due to upstepping thrusts and have the same geometry as those in figure 10a. Cf. figures 8b and 9.

line pebbles along the sides and finer clastics in the center as well as the structural geometry indicate that this complex was the fill of a distinct northern branch of the through, delimited to the all sides by basement highs (Fig. 8a, cf. also Fig. 6 of SCHÖNBORN, 1992). The thick ultracataclastic zones mentioned might be part of the western border faults. The basin fill subsequently was thrust onto the cover of the Orobic anticline, which defines another, larger Permian trough that ends to the northwest near the Bocca Biandino-Grassi area (note the coarser clastics there, plate 1). No Collio sediments exists farther west. The result of a completely inverted graben fill is a lenticular thrust mass. This lense was pushed south between sinistral boundaries in the east and dextral in the west (large black arrows in plate 1), thereby bulging out the Orobic thrust above and depressing the footwall (prominent white arrows in plate 1). The Salmurano basement slab, structurally situated below the Permian deposits of the complex, was interpreted as the planed-off intermediate high between the two graben in figure 8a. Its lateral extent remains a matter of debate, but it is situated at the base of the Tre Signori-Ponteranica complex and carries deposits of the northern through. Interpretation as Alpine horst (CASATI and GNACCOLINI, 1967) is not compatible with the mapped structures (plate 1). During the emplacement of the complex not only south directed movements have been active, the accumulation of Verrucano-Servino beds at the eastern and western ends express also lateral squeezing underneath the Orobic thrust from the center to the sides of the lens.

Some peculiarities suggest that the Orobic thrust has reached the Servino décollement horizon already north of the graben, some branches subsequently ploughing down into the graben and scooping it out ("rabotage basal" of the French authors, Fig. 8b). The most important argument for this is the already mentioned geometry of the imbrications. Figure 10a shows common duplex architecture (like in Fig. 6, BOYER and ELLIOTT, 1982, and many others) as a result of upward ramping thrusts. Figure 10b exhibits imbricate structures indicative of downward stepping thrusts. LAUBSCHER (1989) called similar features in the Austroalpine realm "extensional duplexes". The distinction of the two groups of duplexes is possible at its rear limb: extensional duplexes show normal fault geometry there. At the front limbs, however, distinction is hardly possible, because also those of extensional duplexes are often defined by upstepping thrusts which commonly are abundant as soon as a thrust arrived at a lower detachment horizon. Another argument that detachment reached the top of the basement already north of the Ponteranica trough are the Gneiss Chiari slices underneath the Orobic thrust. These gneisses stem from the top of the crystalline basement, and near the Tre Signori-Ponteranica complex they are observed only as detached slices. Detachment thus at least has reached the uppermost parts of the basement, before ploughing down to the base of the graben.

Comparing figure 9 and plate 1 reveals that the north dipping cover of the Orobic anticline presumably also is a large extensional duplex. Although the thrust is no more exposed in the crucial area (400 m WNW Rifugio Pio X in plate 1), map and dip data strongly suggest such an interpretation. In fact, other interpretations require basement to be thrust onto the basin fill, which at least in the best exposed region (north of Rifugio Grassi, plate 1) is not the case. The kinematics implied in figure 9 include thrusting of the northern trough fill onto the southern trough and a branch of the thrust ploughing down to the base of the Permian deposits south of the intermediate basement horst.

Thrusts cutting down the stratigraphic sequence are not as unusual as they might seem to be at first sight. Stress concentrations near pre-existing, hinterland dipping faults are highest near the upper, internal edge of the horst (WILTSCHKO and EASTMAN, 1983). Failure thus begins there and has to propagate downward to the décollement horizon in the hangingwall of the preexisting normal fault. A similar situation exists, when a new detachment possiblity underneath the main décollement is offered, which did not exist more internally, e.g., a graben with incompetent fill. Failure in this case begins in the main décollement horizon above and propagates downward to the new detachment. BÖHI (1994) has shown by means of finite element models that a décollement is able to step down at a foreland dipping normal fault in principle, although the parameters he choose are not exactly valuable for the Permian graben. The general statement of always upward ramping thrusts hence is only valid in perfect layercake cases.

Downstepping of thrusts via synthetically rotated dominoes (type E)

Data: The Taceno complex at the western end of the Orobic anticline occupies a triangular area (Fig. 4 and plate 1) and is characterized by very peculiar features of its own. They consist of a repetition of overturned slabs of gneisses (mainly Gneiss Chiari) in stratigraphic contact with Verrucano conglomerates below which in turn pass into the basal sequence of the Lower Triassic Servino fm. The top side of the imbrications is almost invariably what appears as a normal fault: the hangingwall consists of younger rocks, Verrucano or Servino beds, the footwall of crystalline basement. In the southwest, the imbrications terminate at a northwest striking lineament (Valsassina line). At their terminations, they are folded around subvertical axes indicating a dextrally transpressive boundary. In the southeast, the imbrications are thrust onto large masses of cellular dolomite (Carniola di Bovegno), which in turn are separated from the Orobic anticline farther east by a steep, ENE trending fault (Margno fault, plate 1). Figure 11a shows a simplified cross-section, which implies bending of the fold axes from their observable subvertical dip near the Valsassina lineament to a more gentle inclination farther northeast. The bottom and the west end of the cross-section is because of the strongly three-dimensional nature of deformation not observable and therefore somewhat hypothetical.

Interpretation: In order to restore the imbrications to their palinspastic position, they have to be rotated back to right-side-up geometry (Fig. 11b, SCHÖNBORN and LAUBSCHER, 1986). To achieve the overturned structure actually observed, the imbrications first have to be separated by faults and then be rotated (Fig. 11c). During this process, parts of the detachment arrived at a lower, intracrystalline level essential for forming basement slabs. Finally, the whole complex was folded by the Orobic anticline in order to arrive at the present geometry (Fig. 11a). The overall situation is that of synthetically rotated dominoes separated by normal faults in a contractional regime. The space needed in order to rotate the dominoes might have been provided by the upper

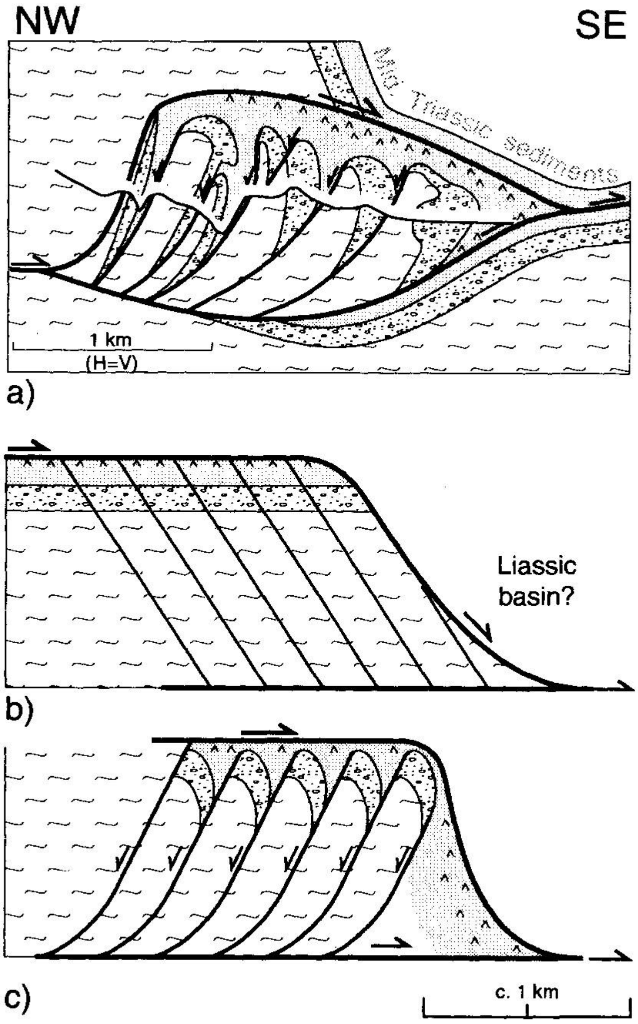

Fig. 11 *a)* Simplified cross-section E through the Taceno imbrications. Also the map (plate 1) shows the series of overturned slabs (basement above, Permotriassic underneath) at the western end of the Orobic anticline, separated from each other by steep normal faults. The complex is accompanied by accumulations of detached upper Servino and Bovegno beds at the top and the front. *11b* and *11c* show the inferred kinematics: detachment arrives at a lower, intra-basement level by rotating synthetically a series of slabs located between the originally steeply SE dipping faults. Redrawn after SCHÖNBORN and LAUBSCHER (1986).

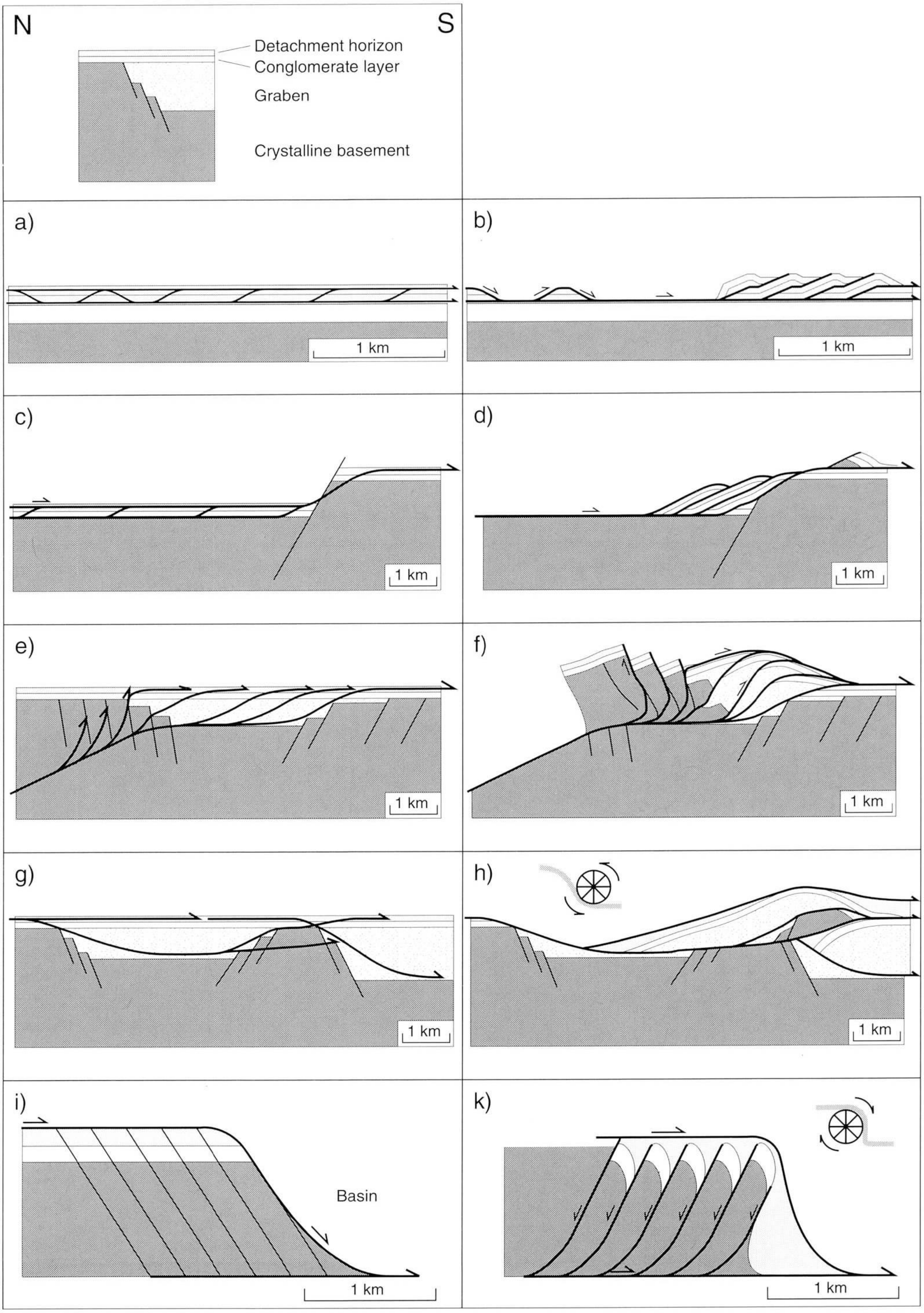

Fig. 12 Cause-and-effect sketch (left and right column, respectively) illustrating and generalizing figures 5 to 11. For explanation see previous figures or conclusions.

Servino and the Carniola di Bovegno beds which were stripped off the imbrications and are accumulated now at their front and their top. What exactly happened at the lower boundary of the rotated dominoes cannot be observed in field. Dragging along the lower detachment (Fig. 11a) seems possible at metamorphic conditions near the anchizone-greenschist facies transition. The whole imbricated complex occupies a triangular zone between the dextral Valsassina line and a more diffuse, NE trending sinistral zone (plate 1). Complex tectonics at the NE corner of this triangle could be explained by transpressive movements along this sinistral zone (near Codesino in plate 1).

The faults separating the imbrications have either the same age as the Orobic thrust or they are pre-existing. In the first case, they are synthetic Riedel shears of the thrust (Fig. 11b). In the second, they are Mesozoic (presumably Liassic) normal faults, because evidently the complex originated outside the Permian troughs. Furthermore, the imbrications and their delimiting faults are parallel to the Margno, the Dirotto and the Biandino faults (plate 1), the Mesozoic origin of the two latter was discussed already. Actually, in order to achieve the first case with the Riedel shears, which in map view are perpendicular to the vergence of the thrust, the generally south vergent Orobic thrust must have been deflected by some 20°. Such deflections happened in the Southern Alps (SCHÖNBORN, 1992), but always near large pre-existing faults. Hence, the Taceno complex could interpretatively be located initially near ENE trending Mesozoic faults, at the northwestern border of a presumably Liassic basin (Fig. 11b).

In this case, however, a strong analogy to the kinematics of the Ponteranica trough exists (Figs 8 and 9). In both scenarios thrusts plough down from higher décollements into a graben. In the Ponteranica scenario they step down within the graben rotating the graben fill antithetically, in the Taceno scenario they step down along several border faults, rotating them synthetically. Kinematics of the first could be compared to a undershot water-wheel (antithetical rotation), those of the latter to a overshot water-wheel (synthetical rotation). So far, both types of thrust systems are not accounted for in review articles (e.g., BOYER and ELLIOTT, 1982; MCCLAY, 1992).

Conclusions

Figure 12 conveys the attempt to generalize the above said to a cause-and-effect representation. Of course, we do not want to suggest that nature has to react this way to an inherited tectonic setting, but that it did sometimes. Figures 12 a and b depict the deformation within a décollement layer far from obstacles. Thrusts stepping down from the top to the base of the décollement layer are responsible for the thinning of this layer observed over large distances. Thrusts ramping from the bottom to the top of the décollement layer are responsible for the accumulation of the missing material in the pressure shadow of larger structures. An obstacle in form of a hinterland dipping normal fault (Figs 12 c, d) is overcome by means of larger duplexes, implying the activation of less efficient detachment horizons. A graben filled with relatively incompetent deposits standing in the way of an upward ramping thrust (Figs 12 e, f) gets imbricated and inverted by many branches of the thrust. Note the northward steepening of the imbrications and the tilted structure at the top of the hangingwall. Boundary faults of the graben might be rotated and reactivated as upthrusts. A graben underneath a décollement horizon may provoke the detachment to partly step down to the base of the incompetent fill and to scoop the graben out (Figs 12 g, h). Intermediate basement highs within the graben risk to get planed off. The synthetic figures 12 g and h combine the interpretation of figure 8 (northern graben and intervening horst) with that of figure 9 (southern graben). In the last scenario (Figs 12 i, k), a detachment arrives at a lower level by activating a series of normal faults to rotate the dominoes in between synthetically.

The Orobic thrust is obviously a rather poorly organized system, moving opportunistically as local conditions inherited from the past permit. In more mechanistical terms at each point in space the momentary influences of the surroundings, and particularly the conditions at the main boundaries of the moving mass were integrated. Of special importance apparently were conditions at the base, near the basement-cover contact.

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Plate 1 Map of the imbrications between the Orobic thrust and the Orobic anticline. For location see figure 1. Cross-sections A, B, D1, D2 and E refer to the figures 5a, 6a, 8a, 9, 11a, respectively. In Val Marcia, the quartzite beds are included in the Servino fm. Coordinates according to the Italian national grid. Drawn after CASATI and GNACCOLINI (1967) and own mapping (1985–94).