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A kinematic model of the western Bergamasc Alps, Southern Alps, Italy

By Gregor Schönborn[1])

ABSTRACT

The tectonics of the Southern Alps is dominated by a south-vergent ramp-flat thrust system, directed by transverse zones. New detailed mapping and computer-aided construction of cross-sections have helped in expanding, improving and modifying existing kinematic models. Starting with the Grigna mountain segment east of Lake Como, shortenings of 17 km and 25.4 km, respectively, have resulted for the first and second kinematic stage. These quantities were then applied to the more complex Valtorta-Albenza segment further east, resulting in the following model:

The Middle Triassic Bruco klippen unit is equivalent to the Grigna-N and Grigna-S units, but was thrust onto the Upper Triassic in the first stage. Later the Coltignone sheet developed in the Grigna segment, separated by a sinistral strike-slip zone from its eastern equivalent, which consists of two superposed units. During this second stage not only south-vergent thrusting but also backthrusting and east-vergent thrusting in the Valtorta-Taleggio area took place. The whole edifice then was transported south in a third stage.

RIASSUNTO

La tettonica delle Alpi Meridionali è dominata da un sistema di sovrascorrimenti sud-vergenti di tipo «ramp-flat», controllato da zone trasversali. I modelli cinematici esistenti sono stati modificati sulla base di un nuovo dettagliato rilevamento geologico e di sezioni geologiche construite con l'aiuto di un programma di bilanciamento. Inizialmente è stata esaminata la zona delle Grigne, lungo il Lago di Como. In tale area è stato riconosciuto un raccorciamento rispettivamente di 17 e 25.4 km durante le prime due fasi Alpine. Questi valori sono stati applicati al segmento orientale, la zona Valtorta-Albenza. Il modello che ne risulta è il seguente:

L'unità medio-triassica dei klippen di Bruco è equivalente alle unità della Grigna settentrionale e della Grigna meridionale, ma è sovrascorsa sopra la Dolomia Principale durante la prima fase. L'unità di Coltignone nel segmento delle Grigne trova corrispondenza in due unità sovrapposte ad est della zona trasversale. La loro messa in posto avviene durante la seconda fase, che si esprime nell'area Valtorta-Taleggio con sovrascorrimenti verso sud, verso nord (backthrust) e anche verso est. L'intero edificio ha subito infine, durante una terza fase, un trasporto verso sud.

Introduction

The Lombardian part of the Southern Alps (Fig. 1) is a south-vergent thrust belt consisting of a ramp-flat system of sediments and basement slivers that is segmented by north-south striking transverse zones. Alpine metamorphism is absent or of very low grade in the deeper parts, and brittle behavior dominates everywhere. Although detailed investigations date back to the last century, and excellent work has been done

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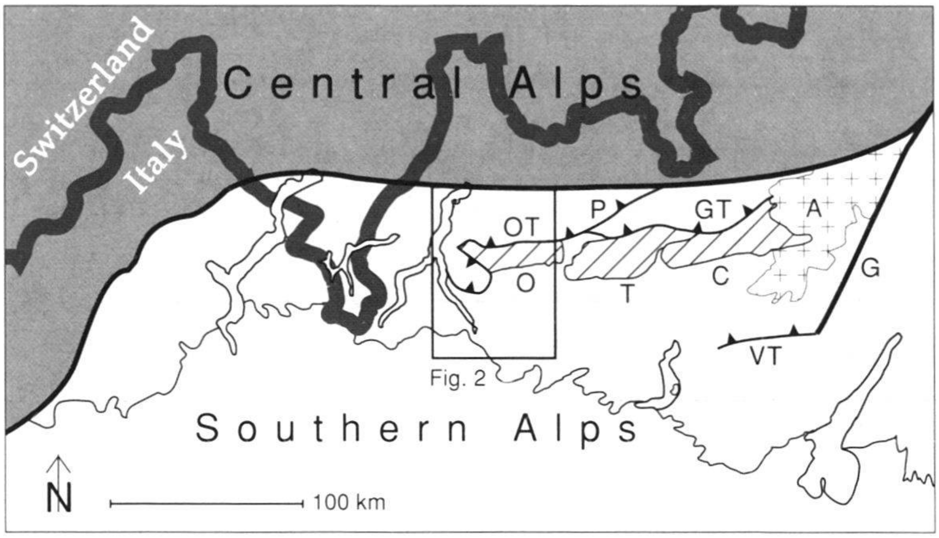


Fig. 1. Location of the investigated area east of Lake Como. A = Adamello; G = Giudicarie line; GT = Gallinera thrust; O, T, C = Orobic, Trabuchello and Cedegolo anticlines, respectively; OT = Orobic thrust; P = Porcile line; VT = Val Trompia line.

among others by the Dutch school (see overview by DE SITTER & DE SITTER-KOOMANS 1949, and DE JONG 1967) many fundamental questions remained, particularly those concerning the role of the basement and of the transverse zones. The Dutch authors advocated the concept of vertical basement uplifts without appreciable shortening, and gravitational sliding that led to the thrusts and folds in the sediments. Later investigators assumed a modest amount of crustal shortening (GAETANI & JADOUL 1979; CASTELLARIN 1978). Much further work was done by Italian geologists, but it concerned mostly the detailed stratigraphy and paleotectonics. LAUBSCHER (1985) constructed generalized balanced sections to estimate the amount of shortening. His analysis, however, was based essentially on the published literature. Preliminary results of the deep reflection seismic survey of NFP-20 support his model (major basement slivers, thrust sheets of detached Triassic sediments down to a depth of more than 10 kilometers) in the southern Ticino area (BERNOULLI et al. 1990).

My own work aimed at clarifying the kinematic role of the transverse zones in the Southern Alps. To seize the distribution of the three-dimensional masses as accurate as possible, mapping at a scale of 1:5000 and 1:10000 was done. Coming from the premises of a thrust belt with brittle deformation where balanced cross-sections can be drawn, the presented models are obtained, attaching importance to kinematic plausibility. In order to maximize ease and accuracy of profile construction, computer-aided balancing with the preservation of bedlength and thickness (GEOSEC- 20™©, GeoLogic Systems, Inc.) was applied. More balanced sections of the transverse zones themselves are necessary, in turn, for unraveling their complex kinematics. This article presents partial results of my work: first, new balanced cross-sections through the Grigna and the Valtorta-Albenza segments, and second, a new kinematic model of the latter which is quantitatively consistent with the development of the Grigna segment and accounts for some features that so far have resisted explanation.

Methods, geometry and style of deformation

In the Triassic sediments, classical ramp-flat tectonics developed in relation to the stratigraphy: two competent layers – more than one kilometer thick sequences of rigid platform carbonates – are both sandwiched between very incompetent décollement horizons. Therefore distinct "layer-cake tectonics" developed: Ramps (23°–28°) in the Middle Triassic Esino Formation (limestone and dolomite) and the Upper Triassic Dolomia Principale, flats in the Lower Triassic Servino Formation (shales and evaporites), the Carnian Raibl Beds (shales and evaporites) and the lower Rhaetian Argillite di Riva di Solto (shales). In the Jurassic and Cretaceous strata, which appear as a narrow belt in the southern part of the region, ramp-flat style is less dominant. For the construction of cross-sections, it is important to emphasize that the vertical projection of structures across décollement horizons is rather risky and should not be made without lateral information or kinematic concepts.

Although the ramp-flat concept was developed for sediment strata with sharp contrasts in competence, it is applied here also for the basement. Interpreting the southern flank of the Orobic anticline as the frontal limb of a ramp-fold, a thickness of about 4.2 km is obtained for the basement unit, or some 5 km, if the Permian below the Lower Triassic detachment horizon is included. The geometry of the frontal parts of the basement units correspond as far as they are exposed to Suppe's (1983) models of fault-bend folds. Further to the north these units may get thicker; no direct data is available on that topic till now. The deeper parts of the basement probably deform more ductilely, consequently the sections are somewhat inaccurate there. However, basement shortening in the presented model is in excellent agreement with the one observed in the sediments. The crystalline units show analogy to many other basement nappes with a sharp lower boundary and a thickness of 4 to 5 km, especially to the Austroalpine Oetztal nappe (compare Laubscher 1983). 5 km of pre-Mesozoic and more than 5 km of Mesozoic strata lead to a depth of over 10 km of the detachment of the San Marco unit.

Alpine thrusting of the sediments is subdivided into compartments of differing geometry by transverse zones. Probably developing in the Late Triassic to Early Liassic as normal faults preceeding the opening of the Tethys, they acted as pronounced zones of inherited mechanical weakness and lead to the segmentation of the Lombardian Alps during subsequent thrusting. A Late Triassic to Early Liassic origin is shown for example for the Lugano line (Bernoulli 1964; Bertotti 1990) and the Lecco line (Lichtensteiger 1986).

The cross-sections run N-S, because all compressional stages are roughly southvergent, as it is indicated by the large E-W trending structures: the Orobic and the Gallinera thrusts (basement, Fig. 1) as well as the Grigna and Presolana thrusts (sediments) active during stage 1; the Orobic, the Trabuchello and the Cedegolo anticlines thrust during stage 2 (their en-échelon alignment is most plausibly explained by reactivated Permian horst and graben structures, compare de Sitter 1963); the frontal range flexure ("flessura frontale") between Como and Lake Iseo folded during stage 3. The Milan belt, the thrusts below the Po plain (Pieri & Groppi 1981; Cassano et. al. 1986), also shows E-W strike. South vergence is supported by other large-scale structures, e. g. the Giudicarie fault, which together with the Giudicarie thrust belt and the

Val Trompia line shows southward transport during Miocene thrusting (Laubscher 1990). Small-scale criteria may differ from these general trends, especially in the transverse zones, adapting local structures. There are signs of dextral transpression near the Insubric line, but they are of minor importance as compared to the area further west (Schumacher 1990). The Orobic, Trabuchello and Cedegolo anticlines, however, have possibly been accentuated by dextral transpression.

Unexposed but geometrically necessary structures are drawn as simple as possible in the discussed tectonic style. Calculations refer to the model and show its internal compatibility.

The properties of the discussed area (e. g. problematic projection through the detachment horizons, non-cylindricity across the transverse zones, unknown basal depth of the whole thrust pile, brittle deformation during at least five subsequent tectonical stages – Mesozoic normal faulting, stages 1 to 3, thrusting of the Milan belt) require quantitative kinematic modelling. Conventional structural methods just can give hints that have to be fit into such a scenario. E. g. striations on fault planes, an indicator for transport directions often used in brittle domains, only show the last transport increment and additionally are not easy to find because of shales along the faults or dolomitisation. An internally compatible, balanced kinematic model does not exclude, theoretically, all other solutions, but it definitely does many of them. A model should explain as many features as simple and as plausible as possible, it never is reality.

The Grigna section

In the Grigna Mountains east of Lake Como (Fig. 2) a pile of three thrust sheets of Middle Triassic is well exposed. Already in the last century it was recognized as a beautiful example for thrusting (Benecke 1884; Philippi 1896). The Grigna segment is the most unequivocal in Lombardy and may serve as a key for unraveling the more problematic structures. Located between two joining transverse zones (the Lecco lineament and the Ballabio-Barzio zone, Fig. 2), the frontal parts of the thrusts are exposed to the south, instead of disappearing below the younger sediments as equivalent thrusts do further east (e. g. in the Valtorta transect).

Two 4 to 5 km thick basement slivers are involved in the sections, the upper usually called "Orobic basement", the lower "Orobic anticline" (Figs. 2, 3 and 5). This is somewhat confusing because the lower unit also consists of Variscan basement, is also located in the Orobic Alps and only its southern part is deformed as an anticline, if this anticline is interpreted as a ramp-fold. Therefore the following terms for these two units are used in this article: "San Marco unit" for the upper unit above the Orobic thrust, bordered in the east by the Porcile line (Fig. 1) and in the north by the Insubric line. The western termination of the unit in the Ticino area is rather complex and being studied by Schumacher (1990). The term "Mezzoldo unit" is used for the lower unit, the Orobic anticline sensu stricto (in the sense of de Sitter 1963) and its northern continuation below the Orobic thrust.

The Orobic thrust is an important thrust of basement onto basement, Permian and lowermost Triassic. These sediments on top of the Mezzoldo unit, included for better clearness in the basement in Figs. 2 and 3, are lying parallel beneath the sharp thrust-

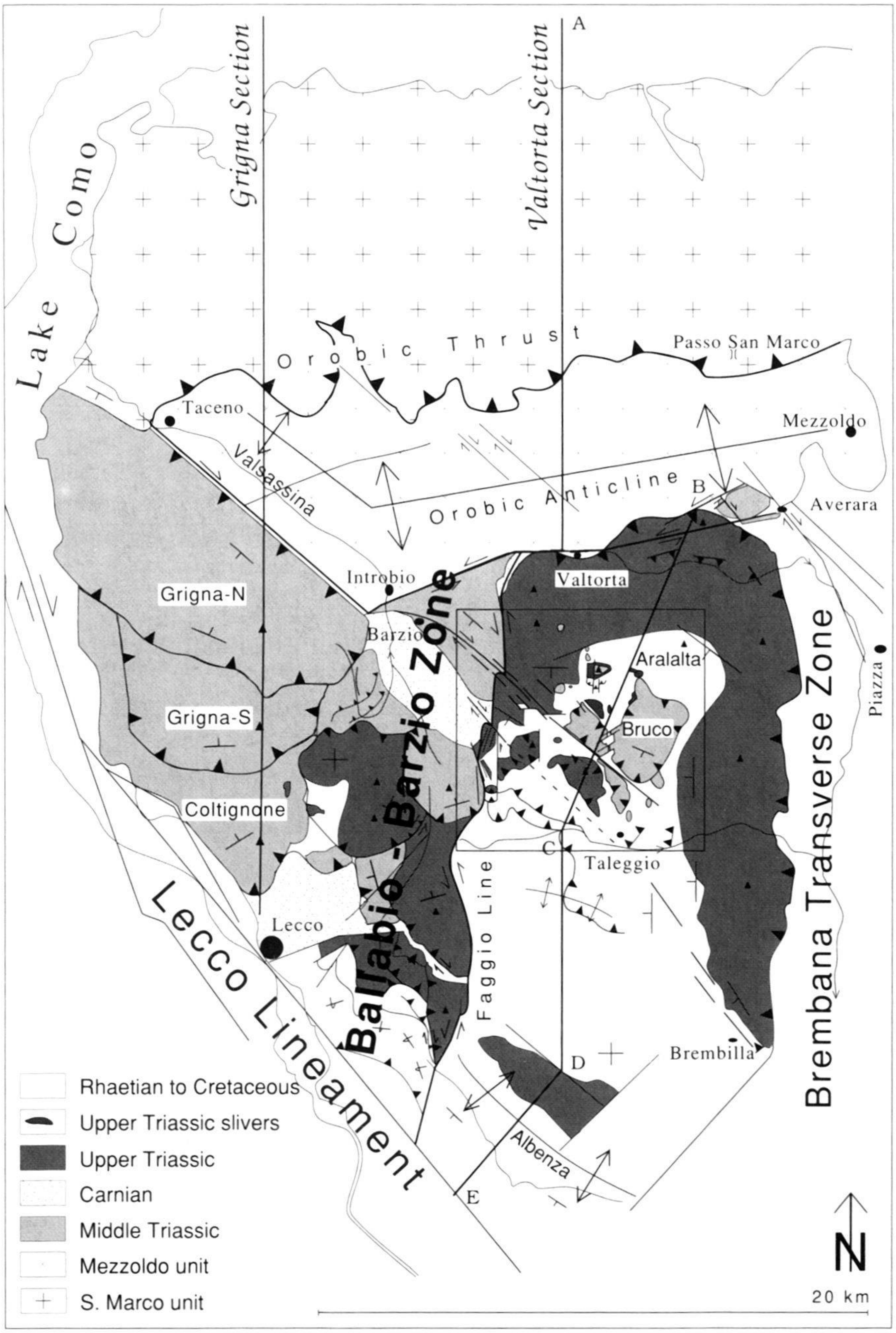
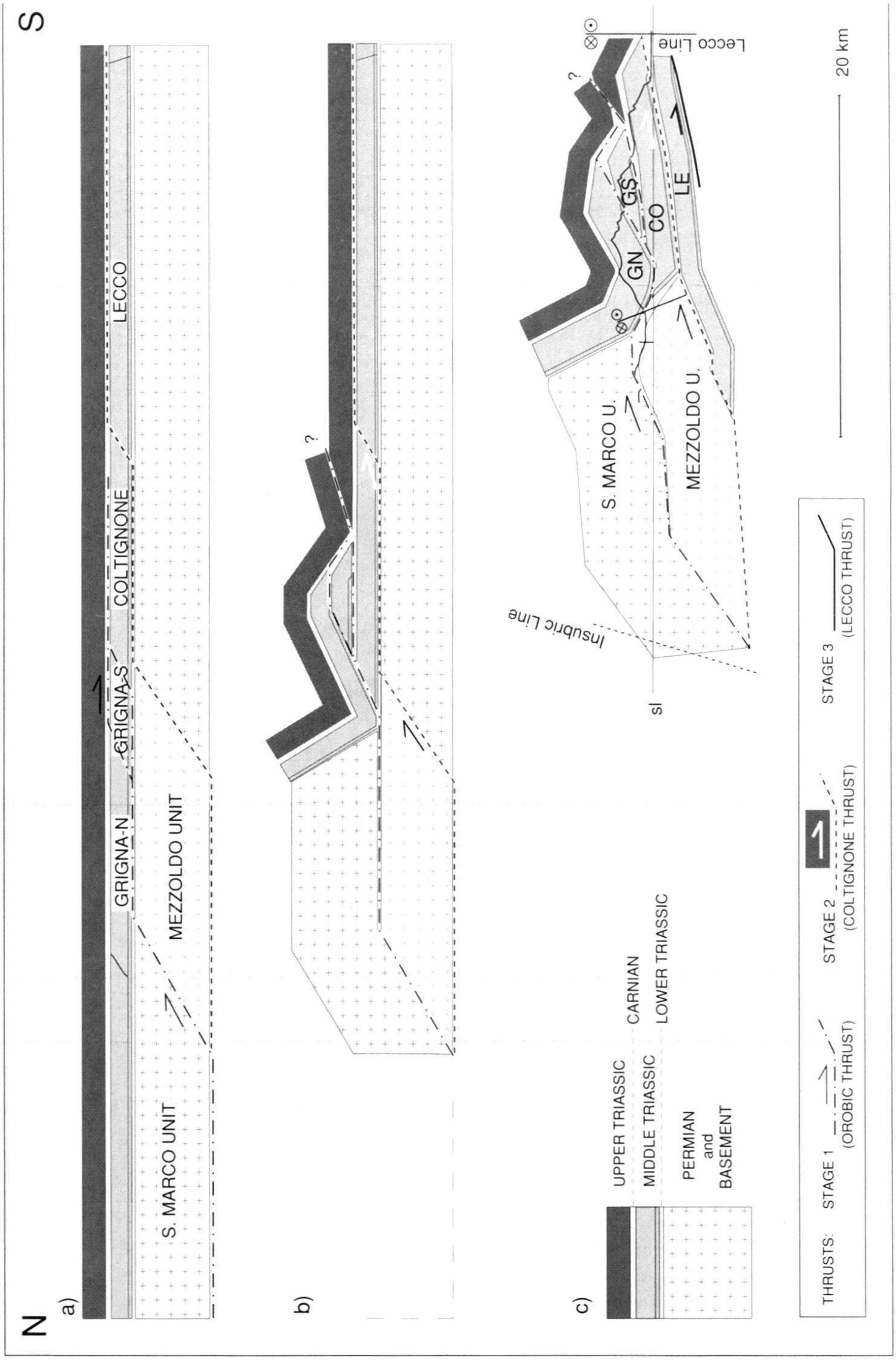


Fig. 2. Simplified geological map of the Grigna-Valtorta region. The irregularly deposited Permian and the lowermost Triassic are included in the basement. For reasons of better clearness the Zorzino Formation (Norian basinal facies) is indicated like the Rhaetian, except the sheared off thin slivers beneath the Middle Triassic klippen. The rectangle indicates the location of Fig. 4.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STAGE 1
(OROBIC THRUST)
STAGE 2
(COLTIGNONE THRUST)
STAGE 3
(LECCO THRUST)

plane, dipping 20° to 35° north. This means that the Orobic thrust is folded by the subsequent Orobic anticline. Of particular interest is the area of Taceno, where the Orobic anticline is plunging west. There the Orobic thrust splits into several branches, causing different overturned basement imbrications (SCHÖNBORN & LAUBSCHER 1986; see DALLAGIOVANNA et al. 1986 for another view) and then connects with the Grigna-N thrust, forming the Valsassina halfwindow. The situation is further complicated by the Valsassina line, a dextral strike-slip fault bordering the Orobic anticline to the SSW, dragging the imbrications of Taceno. West of Taceno, the sediments are in stratigraphic contact with the basement (GAETANI 1982; GIANOTTI 1968), only minor faults can be mapped. Therefore the northern part of the Grigna-N must be the sedimentary cover of the frontal part of the San Marco basement. The Lower Triassic Servino Formation shows a triple junction at Taceno: one Servino branch leads below the Orobic thrust to the NE, one to the WNW and one follows the south side of the Valsassina to the SE. This pattern is diagnostic for the tip of a fault-bend fold where its base joins the décollement horizon. The steeply (60°–70°) south dipping Permian between Taceno and Lake Como indicates the dip of the underlying frontal limb of the ramp-fold of the San Marco basement.

Grigna kinematics

Fig. 3a shows the restored version of the kinematic model, where the units of Lecco, Coltignone, Grigna-S and Grigna-N are restored to their original position and geometry. Fig. 3b depicts the situation after stage 1 (activity of the Orobic thrust), 3c today. A better constrained cross-section through the Orobic anticline some kilometers east (Bobbio-Val Biandino) reveals a thickness of 4150 m for the basement, interpreting the anticline as a ramp-fold. Including the middle Permian Collio Formation (about 700 m) and the upper Permian Verrucano Lombardo (100 m) the Mezzoldo unit is nearly 5000 m thick. The thickness of the San Marco unit is assumed to be 5000 m also (including the irregularly deposited Permian), the ramp angles in the basement 30°. The thickness of the Esino Formation changes from 1100–1150 m in the Grigna-N, -S and Lecco sheets to 1400 m in the Coltignone sheet. As later on the Grigna-N was folded during the second stage with an axis parallel to the Valsassina line oblique to the profile, the Esino Formation gets an apparent thickness of 1850 m. The Anisian Angolo Limestone, the lower part of the Middle Triassic, is drawn with a constant thickness of 150 m.

During the first stage (Fig. 3b), the upper basement unit, Grigna-N and then Grigna-S were moved south along the Orobic thrust. The amount of displacement of the basement must be the same as the displacement of the sediments and the internal shortening by folding in the basement and the sediments. So the model can be tested.

Fig. 3. A kinematic model of the Grigna mountains after own observations and the model of LAUBSCHER (1985). In a first stage (b) the San Marco unit ("Orobic basement"), the Grigna-N and then the Grigna-S sheet are displaced along the Orobic thrust (shortening is 16.9 km). In a second stage (c) the Mezzoldo unit ("Orobic anticline") and the Coltignone sheet are thrust on top of the Lecco unit (shortening is 25.4 km). The geometry of the Dolomia Principale is unknown. GN = Grigna-N, GS = Grigna-S, CO = Coltignone, LE = Lecco.

The shortening of the sediments is 2550 m (Grigna-N thrust) + 8100 m (Grigna-S thrust) + 1000 m (shortening consumed in the ramp-fold, caused by the climbing on the Grigna-S sheet, compare SUPPE 1983) + 1100 m (idem for the climbing on the thicker Coltignone ramp) + 4200 m (shortening in the basement ramp-fold) = 16950 m.

The shortening of the basement (Fig. 3b or 3c) is 16800 m (distance between the foot of the basement ramp and the northern end of the frontal limb of the ramp-fold on the thrust). Considered the scale, these two values fit remarkably well.

During the second stage (Fig. 3c), the Orobic anticline is thrust onto the Lecco unit. The thrust (called Coltignone thrust by LAUBSCHER 1985) follows the base of the Coltignone sheet, which again lies in its northernmost part in normal position above the tip of the Mezzoldo basement. A substitution of the cover is possible, because the contact is not exposed. But there are no indications leading to a different interpretation than in the analogous geometries of the tip of the San Marco unit or of the southwestern flank of the Trabuchello anticline, an equivalent of the Orobic anticline further east (north of Piazza Brembana in Fig. 2). The shortening is 25300 m in the sediments and 25500 m in the basement (analogous calculations as for the Orobic thrust).

The Valsassina strike-slip fault affects the southern border of the Orobic anticline. It is, however, of minor importance as compared to thrusting and is not expected to influence balancing in an important way. But it testifies to the existence of lateral mass transport in the area (Fig. 2).

The Lecco sheet on Fig. 3c is cut obliquely by the Lecco line. The Dolomia Principale is just projected above to indicate that all observed tectonics occurred below the Upper Triassic, that has to be shortened in a similar manner. The only outcrop possibly showing part of this Dolomia Principale is out of the section on top of the Coltignone sheet (Corni del Nibbio).

The kinematic model implies 42.3 km of shortening, 16.9 km for the first stage, 25.4 km for the second. These values approximately agree with those of LAUBSCHER (1985). They are conservative, as the Grigna-N, the Grigna-S and the Coltignone sheet are eroded frontally, and extending them would increase shortening.

In the Ballabio-Barzio transverse zone the different tectonic levels are hard to trace, as blocks of Middle and Upper Triassic formations are thrust and rotated in a complex way and some younger-over-older thrusting took place. Work on 3-D kinematic modelling of this area is in progress.

The Valtorta section

East of this transverse zone the structural geometry changes. Instead of Middle Triassic thrust sheets there is an undulating Upper Triassic plateau with some klippen on it. However, as the transverse zone dies out both in the north and in the south, no large-scale mass transfer beyond the studied sections is observable, and consequently overall shortening in the two sections has to be the same.

One of the key features of this segment is the "Valtorta fault" (Fig. 4). Detailed mapping has revealed, that it is a composite feature with the following elements: 1: The Dolomia Principale borders directly on the Orobic anticline, the Middle Triassic is

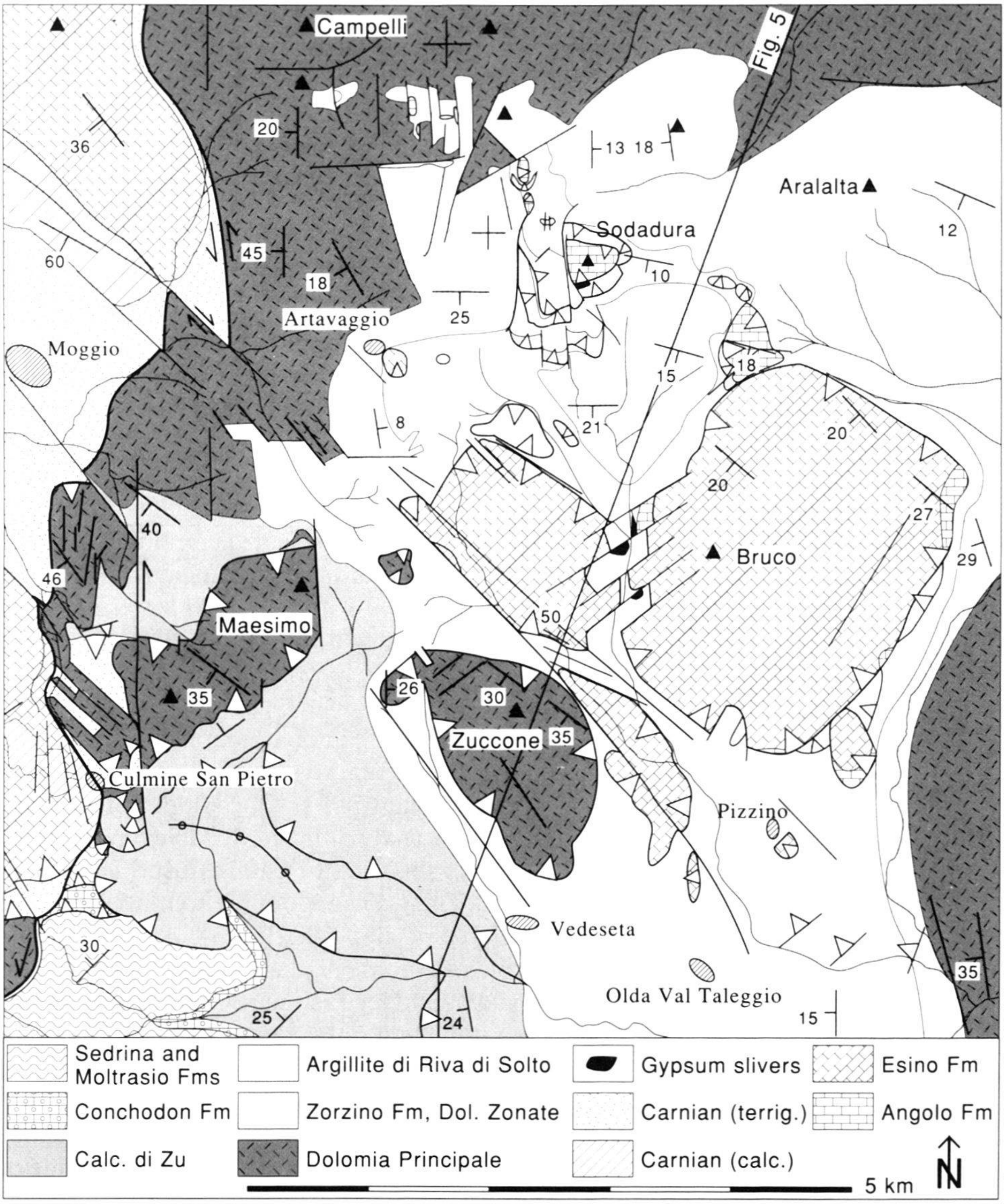


Fig. 4. Geological map of the Aralalta-Taleggio area.

missing. Near the village Valtorta (Fig. 2), Dolomia Principale and basement are separated by steeply south dipping Permian and Lower Triassic imbricates. This has been interpreted in terms of a normal fault by DE SITTER & DE SITTER-KOOMANS (1949) and called Valtorta fault. However, this fault is bounded east and west by transverse zones and thus embedded in the 3-D aspects of thrust kinematics. 2: Further east this fault runs inside the Dolomia Principle dipping there gently south and splits into several branches, one of them trending ENE along the northern flank of Pizzo di Cusio (Fig. 5). South of it numerous north-verging thrusts, dipping about 25° SSE to SW are observed along road cuts. They form an arc inside the Dolomia Principale which is about parallel to its northeastern border (compare Figs. 2 and 4). Their north-vergent character is documented by striations and steps, supporting LAUBSCHER's (1985) interpretation of the Valtorta fault as a north-vergent backthrust. 3: Along some branches, particularly in the western part where the fault is dipping with 80° towards 350°, clear sinistral striations dip 10° towards 070° (outcrops east of Introbio).

The enigmatic Bruco klippen (DE WIT 1941; GAETANI et al. 1981; JADOUL & GAETANI 1986) consist of Middle Triassic Angolo and Esino Limestone in the northeastern and Upper Triassic Dolomia Principale in the southwestern part. Because Angolo Limestone is lying on top of Upper Triassic slivers (e. g. at the M. Sodadura in Fig. 4), a thrust of Middle Triassic onto the Dolomia Principale klippen was assumed by all authors. But in fact, the Middle Triassic is not situated on top of the Dolomia Principale, but above small slivers of sheared off Upper Triassic beds in basinal facies (Zorzino Limestone and Dolomie Zonate, see JADOUL 1985 for the sedimentology of the Norian basin). Their detachment can be studied in detail at the southern flank of M. Sodadura. These thin slivers may not be confused with the much larger Dolomia Principale klippen of M. Zuccone and M. Maesimo with no Middle Triassic on top (Fig. 4). Some outcrops of Carnian evaporites between Middle Triassic Angolo Limestone and slivers of the Zorzino Formation indicate the main thrust.

Mapping of this area is hindered by recent slope creep of the whole klippen, giving impressive proof of the aptitude of the lower Rhaetian Argillite di Riva di Solto as a detachment horizon. As an effect of this motion, many parts of the klippen are disintegrated into small blocks and measuring of dips is made difficult. Reliable dips SW of a line Artavaggio-Pizzino make an angle of 20° to 40° with the basal thrust (Fig. 5). This can be observed best at the Maesimo klippe (Fig. 4). Therefore the southwestern part of the klippen is interpreted as the frontal limb of a ramp-fold (Fig. 5).

Outcrops along the Esino/Dolomia Principale boundary inside the klippen unit are not easy to interpret. Additionally to gravitational creep, an important fault zone follows the contact. Layered limestone along this fault has been described as Anisian Angolo Formation (DE WIT 1941) or Ladinian Buchenstein Formation (JADOUL 1985), but also an interpretation as Carnian Raibl Beds is possible.

Still some problems remain unsolved: the basal thrust of the klippen climbs continously towards SW from the base of the Argillite di Riva di Solto at the northern side of the M. Sodadura- and the Bruco klippe to the Calcare di Zu (middle Rhaetian) beneath the Maesimo klippe. The map view aspect of Upper Triassic formations to the SW, Middle Triassic formations to the NE also suggests a SW-vergent thrust. But at least till now, large-scale SW-vergent compression is not documented in this part of the Southern Alps.

A net of SE-striking dextral and WSW-striking sinistral strike-slip faults covers the region (Fig. 2). This system, partly consisting of reactivated Late Permian faults (KELLER et al. 1986; DE SITTER & DE SITTER-KOOMANS 1949; DOZY 1935), defines boundary conditions, along which the Orobic anticline developed. Also the Aralalta-Albenza unit is influenced, as the dextral offsets of its sinistral (SCHÖNBORN in press)

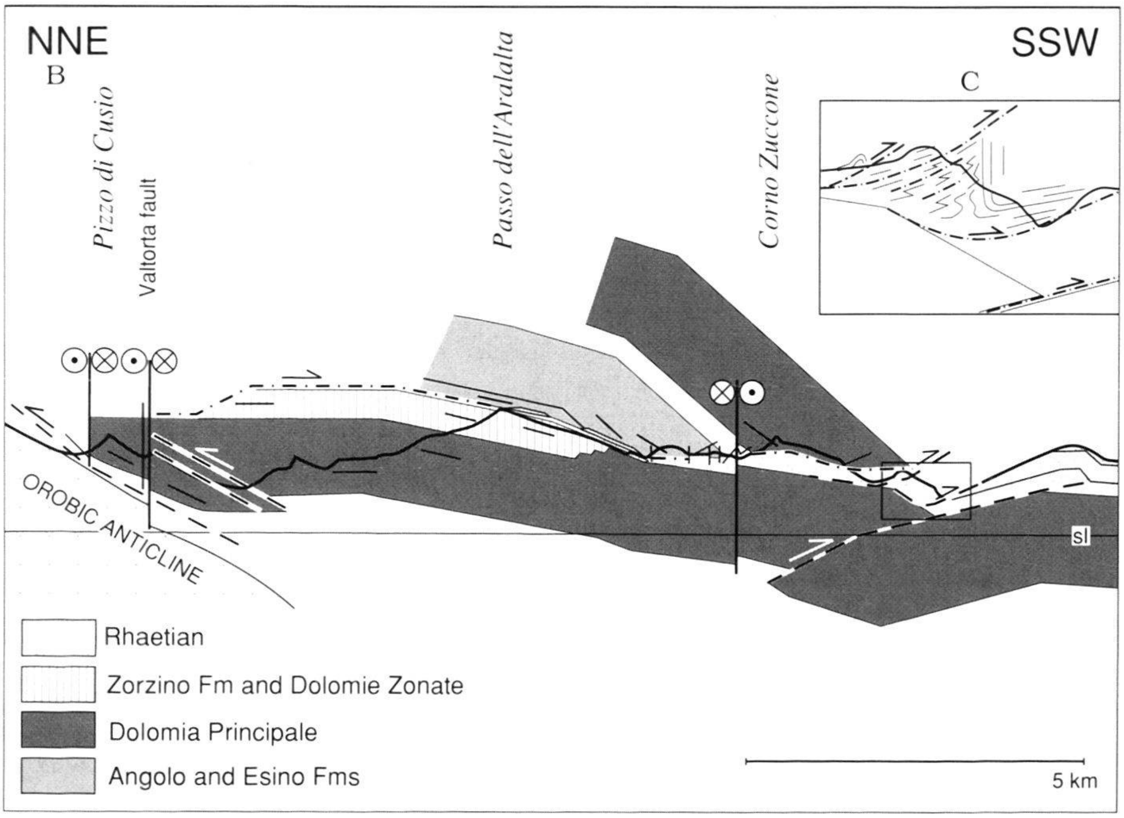


Fig. 5. Cross-section through the Valtorta-Taleggio region. The SW part of the klippen is interpreted as the frontal limb of a ramp-fold. Small slivers of Zorzino Limestone and Dolomie Zonate are sheared off below the Middle Triassic klippen. The Valtorta fault consits of a backthrust and sinistral strike-slip faults with a normal fault component. For location of B and C see Fig. 2.

western border-fault (Faggio line) show (see ZANCHI et al. 1988 for an other view). These dextral strike-slip faults are obvious in the Middle Triassic blocks of the transverse zone and in the Dolomia Principale, but are more difficult to trace in the Argillite di Riva di Solto. They cut the whole plateau and connect to the east-vergent thrusts of the Dolomia Principale onto the Brembana transverse zone. Dextral strike-slip in the south and sinistral strike-slip along the Valtorta fault in the north leads to a relative eastward motion of the Valtorta-Taleggio block (Fig. 6). This is compatible with the observed extension in the northern Ballabio-Barzio zone or pull-aparts (post-stage 1) NW of the M. Sodadura and the east-vergent thrusting in the Brembo valley. Eastward movement is combined with southward thrusting and some backthrusting (see Fig. 7 for kinematics).

The maximum value for the sinistral offset along the Valtorta fault is 6 km, because the fault ends SW of Introbio. The dextral offset along the NW-striking faults is about 1.5 km. If the rotation point is located near Culmine San Pietro, a maximum clockwise rotation of 35° results. Remembering the fact, that the southwestern part of the klippen is inside the swarm of dextral strike-slip faults, this rotation would be big enough to pretend SW-vergent mass transport during stage 1.

Projecting the Dolomia Principale below the Rhaetian on the right part of Fig. 5, a narrow syncline is obtained with large bedding plane slip that the massive Dolomia

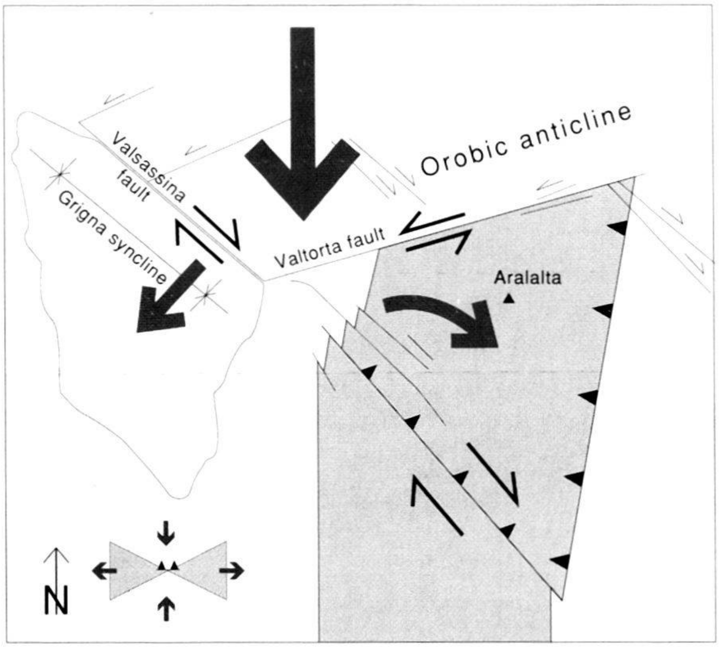


Fig. 6. Scheme for the eastward motion and clockwise rotation of the Aralalta unit between sinistral and dextral transpressional faults during stage 2. Although larger, the south component of the movements is not shown. The angles between the sinistral and dextral faults developed due to inherited weaknesses and do not reflect the Mohr criterion. Compare Fig. 2. Not to scale.

Principale probably cannot account for. This slip is absorbed in the model by a SSW-vergent thrust of some 650 m. In fact, such a thrust is needed in order to explain an anticline in the Rhaetian and the Lower Liassic (interpreted as a fault-propagation fold on the right side of Fig. 5). This thrust folded other SSW-vergent thrusts, which generated at the northern margin of the Dolomia Principale flexure. They caused an intriguing picture (inset Fig. 5) of vertical Rhaetian strata beside Z-folds (fold axis generally dipping <15° towards W to WNW), thrusts and normal faults. All those thrusts are correlated with the dextral strike-slip faults and take up the compressional part of this transpressive system. The Dolomia Principale flexure, the dextral strike-slip faults and the SW- as well as SE-vergent thrusts are exposed also near the eastern border of the Aralalta-Albenza unit, NE of the village Brembilla.

The southern part of the investigated area (Fig. 7c, right side) is dominated by the Albenza anticline and its very steep southern limb. The SE-trend of the anticline indicates transpression along the Lecco line. The northern limb is disturbed by a SE-striking fault, downthrowing the northeastern side. The large masses of Argillite di Riva di Solto in the hills north of this fault may have been accumulated during Alpine thrusting (detachments within this formation are exposed at many places) or they may additionally represent a primarily thicker formation, indicating an early Rhaetian age of this fault. South of this frontal range folded Cretaceous is exposed (see also Bersezio & Fornaciari 1988). The narrow folds and the thrusts indicate a very shallow detachment, possibly in the Marne del Bruntino. This is the most incompetent horizon of the Cretaceous and older sediments, e. g. the Lower Cretaceous Maiolica Formation, do not appear at the surface. Northwards the detachment has to step down below the Dolomia Principale because it is not exposed. That leads to the interpretation of the Albenza anticline as a ramp-fold (fault-bend fold, second mode after SUPPE 1983) or a fault-propagation fold with a fault that broke through the steep limb (compare SUPPE 1990).

Valtorta kinematics

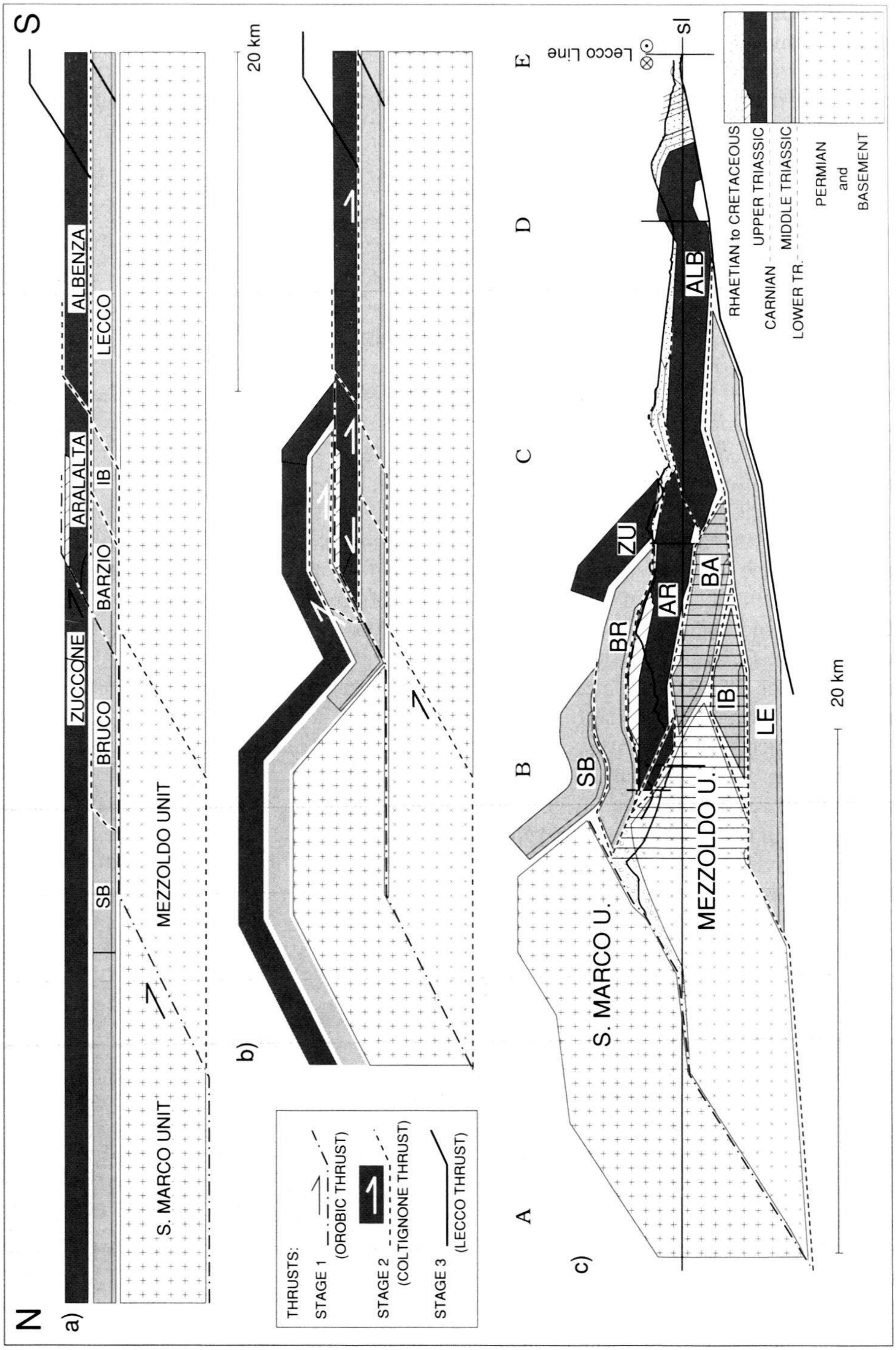
Fig. 7 depicts a kinematic model of the Valtorta section that is compatible with local observations as well as with the shortening of the better constrained Grigna section some 10 km west (Fig. 3). This model differs significantly from LAUBSCHER's interpretation (1985, Figs. 7 and 8) for various reasons. E. g. the size of the Orobic anticline makes it difficult for its basal thrust to rise to the level of the base of the Dolomia Principale, as assumed by LAUBSCHER (1985), and so the thrust sheet underlying the klippen is the Coltignone rather than the Lecco sheet. Furthermore his model doesn't account for different features of the klippen unit.

Cross sections have to run parallel to the mass transport vector to be balanceable. The Valtorta section strikes SSW-NNE in the Valtorta-Taleggio area (Fig. 2), to account for the mentioned presumable rotation of the Aralalta block (Fig. 6).

The basement units in in the Valtorta transect (Fig. 7) are similar to those of the Grigna transect, adapted to local geometries. The Middle Triassic Bruco unit is equivalent to the Grigna-N and Grigna-S sheets. In contrast to the west, it is thrust on top of the Upper Triassic Aralalta unit. The Zuccone unit lies both in the deformed and restored version on top of the Bruco unit (Figs. 7a and 7c).

The Bruco unit was thrust some 4650 m on top of the Upper Triassic, or 700–800 m more than the equivalent Grigna thrusts would require. The Orobic thrust is assumed to cut through the Middle and Upper Triassic in one ramp, without an intervening flat in the Carnian, as otherwise shortening would considerably exceed the one in the Grigna section. This assumption is compatible with observations in the klippen: the frontal limbs in both Middle and Upper Triassic are on the same regular thrust.

The Middle Triassic of Barzio is projected below the Aralalta unit. The Barzio unit, the northernmost unit of the Ballabio-Barzio transverse zone, lies on top of the Mezzoldo basement and is folded by the Orobic anticline. It is therefore interpreted as the continuation of the Coltignone sheet which occupies the same position in the Grigna section. Its relation to the basement, however, is modified by the sinistral Valtorta fault system which here has an important normal fault component, downthrowing the southern side. Obviously (Figs. 2 and 7) shortening in the Barzio unit is smaller than that of the Coltignone sheet extending further south. Consequently an other Middle Triassic unit beneath the Barzio unit, called here "Infrabarzio", is called for to ensure the same amount of shortening. These two units and the Mezzoldo basement unit form a wedge below the backthrust Dolomia Principale (vertical lines in Fig. 7c). The length of the Lecco sheet, not constrained by direct observation, is assumed equal to that in the Grigna section. Because of the necessity to assign shortening of about 25 km to the Coltignone equivalent in the Valtorta section, LAUBSCHER (1985) has equated the Bruco klippen with the Coltignone. In the new model, this shortening is achieved


N
S
a)
ALBENZA
LECCO
ARALALTA
IB
BARZIO
ZUCCONE
BRUCO
SB
MEZZOLDO UNIT
S. MARCO UNIT
20 km
b)
THRUSTS:
STAGE 1
(OROBIC THRUST)
STAGE 2
(COLTIGNONE THRUST)
STAGE 3
(LECCO THRUST)
c)
A
B
C
D
E
Lecco Line
sl
ZU
AR
BA
BR
ALB
IB
LE
SB
MEZZOLDO U.
S. MARCO U.
20 km
RHAETIAN to CRETACEOUS
UPPER TRIASSIC
CARNIAN
MIDDLE TRIASSIC
LOWER TR.
PERMIAN
and
BASEMENT

below instead of above the Upper Triassic sheet, what in several respects simplifies kinematics.

Fig. 7a depicts the restored version of the model. During the first stage (Fig. 7b), the Orobic thrust was active with 16.9 km of basement displacement. After some 18 km of detachment in the Lower Triassic, the thrust ramps at the precise lateral continuation of the Grigna-S thrust through Middle and Upper Triassic. There is no equivalent of the Grigna-N thrust.

The kinematics of the second stage (from Fig. 7b to 7c) are complicated by the backthrust of the Dolomia Principale. After ramping through basement and Middle Triassic, the latter in two in-sequence thrusts (first the Barzio thrust, then the Infrabarzio thrust, similar to, though at a lower level than the Grigna-N and Grigna-S thrust in the first stage of Fig. 3), shortening is split into a south-vergent thrust (12 km), internal thrusting and bending of the Dolomia Principale (1.5 km, Fig. 5 right side) and backthrusting (about 5.5 km, Fig. 5 left side).

In the model, Fig. 7, the Bruco thrust sheet of stage 1 (Fig. 7b) is dissected in stage 2 by an out-of-sequence thrust, in order to accomodate internal shortening and backthrusting of the Aralalta unit, with the creation of a "Superbruco" unit (SB in Fig. 7). But also more complex structures like backthrusts or folding are possible. In addition, the basal thrust of the klippen is reactivated by a small amount (<1 km) in order to obtain a close fit to the map view aspect of the klippen. Thrusting was contemporaneous with the sinistral displacement along the Valtorta fault and therefore somewhat oblique to stage 1, so the NW-SE striking faults (Figs. 2 and 5) served as dextral transpressional boundaries. Detailed calculations of the models will be given in the authors PhD thesis.

The southernmost thrust beneath the Albenza anticline is younger than stage 2. The term "Lecco thrust" is used here, as it is the basal thrust of the Lecco sheet and as it may be observed SE of Lecco. Although of great importance, it is not visible in the Grigna section, because there the Lecco sheet is cut obliquely by the Lecco line. The kinematics are complicated by 3-D aspects. The shortening along this thrust is at least 20 km (Schönborn in press).

Timing

The timing of the tectonic events in the Bergamasc Alps has to rely on regional evidence, as it is poorly constrained locally. The Adamello intrusions (43–30 my) seal the

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Fig. 7. A kinematic model of the Valtorta section. Tectonic elements from top to bottom: SB = Superbruco, BR = Bruco, ZU = Zuccone, AR = Aralalta, ALB = Albenza, BA = Barzio, IB = Infrabarzio, LE = Lecco. Dashed lines are thrusts active in the subsequent stages. The Permian is simplified and included in the basement, except the large imbricates below the Orobic thrust (small circles). 7a: Palinspastic configuration before thrusting. 7b: Situation after initial deformation: The Bruco unit is thrust on top of the Upper Triassic by the Orobic thrust. Arrows indicate the relative movements during the next stage: First the Barzio, then the Infrabarzio Middle Triassic unit is thrust. In the Carnian beds, motions are split into a south-vergent and a north-vergent flat as well as into a south-vergent ramp through the Dolomia Principale. The tip of the Mezzoldo unit, the Barzio and Infrabarzio units form a wedge below the Dolomia Principale of the Aralalta unit (vertical lines). The north-vergent backthrust deforms the Bruco unit: It is thrust internally (Bruco and Superbruco) and its basal thrust is reactivated. 7c depicts the geometry today after the deformation of stage 3. The shortening in stage 1 and 2 corresponds to that in the Grigna section (Fig. 3).

Gallinera line, an approximate eastern equivalent of the Orobic thrust (Fig. 1). Consequently, stage 1 is pre-Adamello, possibly Cretaceous (compare Doglioni & Bosellini 1987; new data on Cretaceous flysch in Bernoulli & Winkler 1990). For stage 2, there are arguments for pre- as well as for post-Adamello activity: the Coltignone thrust below the Orobic anticline is linked either with the thrust below the Cedegolo anticline, which predates the intrusions, or with the Val Trompia thrust, which postdates them. Even a combination is possible: pre-Adamello array and post-Adamello reactivation of the Coltignone thrust (compare Laubscher 1990). In this case, stage 2 would be split into stages 2a and 2b with a considerable time span in between. Post-Oligocene activity may more safely be assumed for the thrust below the frontal range (during stage 3), which is possibly linked with the Miocene tectonics in the southernmost Ticino area (Bernoulli et al. 1989). The Mid to Late Miocene thrusts (Milan belt) below the Po plain (Pieri & Groppi 1981; Cassano et al. 1986) have to be kinematically linked to the Lecco thrust or, more probably, to other thrusts below, not depicted in Figs. 3 and 7 (compare Roeder in press).

Conclusions

The fault-bend fold model (Suppe 1983) is applied to construct balanced cross-sections and to forward modelling of sediment sheets and basement units. The combination with the development of kinematically viable models helps unraveling complex, multi-phase, brittle thrust belts with basement and sediment thrust sheets, especially if there is a lack of conventional structural information.

It is possible to transfer the kinematics of the Grigna mountains across the Ballabio-Barzio transverse zone to the Valtorta-Albenza region. Detailed mapping and computer-aided section balancing permit the construction of a new kinematic model for this region. This transfer involves the following changes:

Stage 1 (Orobic thrust): Whereas in the Grigna section the Orobic thrust ramps through the Middle Triassic at two separate points, in the Valtorta-Albenza section there is only one ramp, leading however through Middle and, unlike in the other section, Upper Triassic.

Stage 2 (Coltignone thrust): In contrast to stage 1 it is now in the Grigna section that the Coltignone sheet remains undeformed internally, while in the Valtorta-Albenza section it is split into two units (Barzio and Infrabarzio), which form a wedge below the backthrust Upper Triassic. This requires a sinistral displacement in the transverse zone. Eastward motion of the Aralalta unit causes extension in the northern part of the transverse zone and E-W compression in the Brembo valley.

Stage 3 (Lecco thrust): The whole edifice is transported south.

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