The arc of the Western Alps today

Eclogae geol. Helv. 84/3: 631-659 (1991)
0012-9402/91/030631-29 $ 1.50 + 0.20/0
Birkhäuser Verlag, Basel

The arc of the Western Alps today

By Hans Laubscher[1])

ZUSAMMENFASSUNG

Argands Synthese der Westalpen vor 75 Jahren war ein Höhepunkt der Deckenlehre, der brilliante Versuch, die erregenden neuen Entdeckungen in ein zusammenhängendes kinematisches Modell zu fügen. Ein heutiges Modell verlangt demgegenüber die Berücksichtigung von neuen, teilweise revolutionären Daten und Einsichten, z.B. solche der Plattentektonik. Tiefensondierungen mit geophysikalischen Methoden sowie neue Datierungstechniken haben in reichem Masse Informationen erzeugt, die Argand nicht zur Verfügung standen. Das hier vorgeschlagene, grossmassstäbliche Modell versucht, darauf Rücksicht zu nehmen. Es besteht aus diskreten Blöcken in Kartenansicht und basiert auf dem Versuch, eine Flächenbilanz in Kartenansicht aufzustellen, obwohl manche Probleme nur schlecht durch die Daten eingeschränkt sind. Am Anfang steht eine Rückverformung in drei Schritten. (1) Eine Rückschiebung der mittel- bis spätmiozänen lombardischen Phase glättet die stark verstellten Transfergrenzen der adriatischen Platte aus. (2) Die Rückverformung der spätoligozänen bis frühmiozänen insubrisch-helvetischen Phase erzeugt ein einfaches Muster der spätkreatisch-eozänen tektonischen Elemente; dabei müssen die adriatischen Transferzonen mit jungen Scherzonen in den Westalpen (z.B. Canavese-Linie, Penninische Front) verknüpft werden. Für das nördliche Scharnier des Westalpenbogens stellt sich heraus, dass die im Oligo-Miozän aktive Insubrische Linie wahrscheinlich einen weiter nördlich gelegenen Vorläufer hatte im Grenzgebiet zwischen der Margnadecke und der oberostalpinen (nach Schweizer Nomenklatur) Silvrettadecke. Am südlichen Scharnier vermittelt eine Verknüpfung der Bewegungen von Adria mit den ungefähr gleichzeitigen Bewegungen der Toscaniden in den Apenninen und dem Einbruch des Balearen-Ligurien-Beckens ein besseres Bild der Alpen-Apenninen-Beziehungen; sie legt auch die Verwicklungen im orogenen Knoten von Ligurien bloss, wo nicht nur die Alpen im engeren Sinne, die Apenninen und die westmediterranen Einbruchsbecken zusammenstossen, sondern auch der Pyrenäen-Provence-Gürtel (Nordgrenze von Iberia) und die Nordpenninische Kordillere in kaum entwirrbarer Weise verknotet sind. (3) Für das Späteozän wird eine sinistrale Rotation des Penninikums vor dem sinistral-transpressiven Westrand der Adriaplatte postuliert, die sich gegen NW in Europa einbohrt. Für noch frühere Phasen ist eine Rückverformung kaum durchführbar, da korrelierende Strukturen durch die nachfolgenden Bewegungen zu sehr entstellt wurden. Stattdessen wird ein spätjurassischer Anfangszustand angenommen, basierend auf dem frühen plattentektonischen Modell von Dewey et al. (1973). Dieses scheint die alpine Kinematik besser wiederzugeben als spätere Versionen. Schiefe dextrale Konvergenz mit Deckenbildung in grossem Massstab ist in dieser Sicht das Resultat von dextraler Transpression zwischen Afrika und Europa nach 80 Ma. Mit Hilfe dieser Vorwärtsmodellierung gelangt man ohne Komplikationen zum eozänen Zustand, wie er durch Rückverformung erzeugt wurde.

ABSTRACT

Argand's synthesis of the Western Alps 75 years ago was the culmination of nappism, the brilliant attempt to put the exciting new discoveries into a coherent kinematic model. For an updated model, new and partly revolutionary data and insights into orogeny, among them plate tectonics concepts, have to be used. Deep probing by geophysical methods as well as new dating techniques provide a wealth of information not available to Argand. A large-scale map-view model of discrete blocks is proposed that attempts to respect map-view area balance within the still considerable, poorly constrained margin of error. To begin with, retrodeformation is attempted in three steps. (1) Retrotranslation of the middle to late Miocene Lombardic phase straightens out the severely kinked transfer

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boundaries of the Adriatic indenter. (2) Retrotranslation of the late Oligocene-early Miocene Insubric-Helvetic phase, combining these transfer zones with young shear zones in the Western Alps such as the Canavese line and the Penninic Front restores a simpler configuration of late Cretaceous-Eocene tectonic elements. The result at the northern hinge of the Arc of the Western Alps is that the Insubric line, active in the Oligo-Miocene, had a probable forerunner farther north in the boundary zone between the Margna nappe and the upper Austroalpine (Swiss nomenclature) Silvretta nappe. At the southern hinge, combination of these motions of Adria with the approximately contemporaneous Toscanide motions in the Apennines and the collapse of the Balearic-Ligurian sea basins opens a better view of the relation Alps-Apennines and lays bare a new configuration of the orogenic knot of Liguria where not only the Alps sensu stricto, the Apennines and the collapse basins of the western Mediterranean but also the Pyrenees-Provence belt (northern boundary of Iberia) and the North Penninic cordillera are tied in a barely resolvable way. (3) For the late Eocene a counterclockwise rotation of the Pennine realm in front of the sinistrally transpressive western edge of the NW-moving Adriatic indenter is postulated. Farther back, retrodeformation seems hardly feasible as correlative features are too badly deformed by subsequent phases. Instead, an initial late Jurassic configuration is assumed, based on the early plate tectonics model of Dewey et al. (1973) which seems to fit Alpine kinematics better than later versions. Oblique dextral convergence with large-scale nappe development is seen to be the result of dextral transpression between Africa and Europa from 80 Ma on. This forward modeling leads without complications to the Eocene situation arrived at by retrodeformation.

Introduction

Emile Argand was a legend when I was a student at the University of Basel. Most of us had been attracted by geology because of its outdoors activities; it was also said to be something useful. If such brilliant people as that Argand devoted their life to it, it also had to be something of an intellectual challenge. Our professors, however, although acknowledging Argand's brilliance, thought his models (in contemporary parlance) too far removed from observable nature and therefore of doubtful value. This, of course, is one of the eternal problems in geology. Facts, though their number has increased exponentially, remain few in view of the complexity of the geologic systems, and they are often somewhat hazy, ill defined, and their significance depends on uncertain assumptions. Attempts at synthesis are necessarily "speculative" – a word with a negative connotation. However, continuous synthesis on all scales is necessary and done universally. Small is the number of those who delight in isolated, bare figures. Not every synthesis is of the same quality, of course. It is often done unconsciously, without proper thought of the premises. As "speculation" is used in a derogatory sense, I prefer to speak of "attempts at synthesis".

Argand's "Arc of the Western Alps" (1916) was his first attempt at synthesizing the knowledge of his time about the whole of the Western Alps. To do it justice it is necessary to appreciate Argand's position in the history of geology. He began with Lugeon in the heyday of Alpine nappism, and his synthesis was the cumulation of that revolutionary period. At that time, geology was essentially untainted by geophysics and the many physical and chemical properties of rocks with which we are deluged these days. The oceans were practically unexplored. The ambiguous notion of "geosyncline" had been distilled from the observations collected on land. Artistic intuition was called for to combine the facts stored in Argand's prodigious memory. Computers with their memories and modeling power were far in the future. Even nowadays, of course, it is clear that the best computer can only execute what a fertile mind tells it to do. It serves essentially for testing the quantitative implications of mental imagery.

One way of assessing the historic position of Argand's "Arc of the Western Alps" is to compare his with modern images that profit from the vastly increased sets of data and rules, even though these are still insufficient to evolve into a universally accepted model of the geometry, kinematics, and dynamics of the Western Alps. It is the purpose of this paper to offer a series of such images, necessarily somewhat subjective and controversial. My own adventure into Alpine kinematics began about 30 years ago. It was a rather groping attempt and has remained so to this day. Repeated updates and modifications of earlier versions were necessary as new information and new insights became available. This paper is the latest stage in this trial-and-error process.

Argand's fundamental assumptions

The arc of the Western Alps is first of all a problem of three-dimensional kinematics. The approach chosen by Argand for this formidable problem is still that most useful today: to treat cross-sectional and map-view kinematics separately and then try

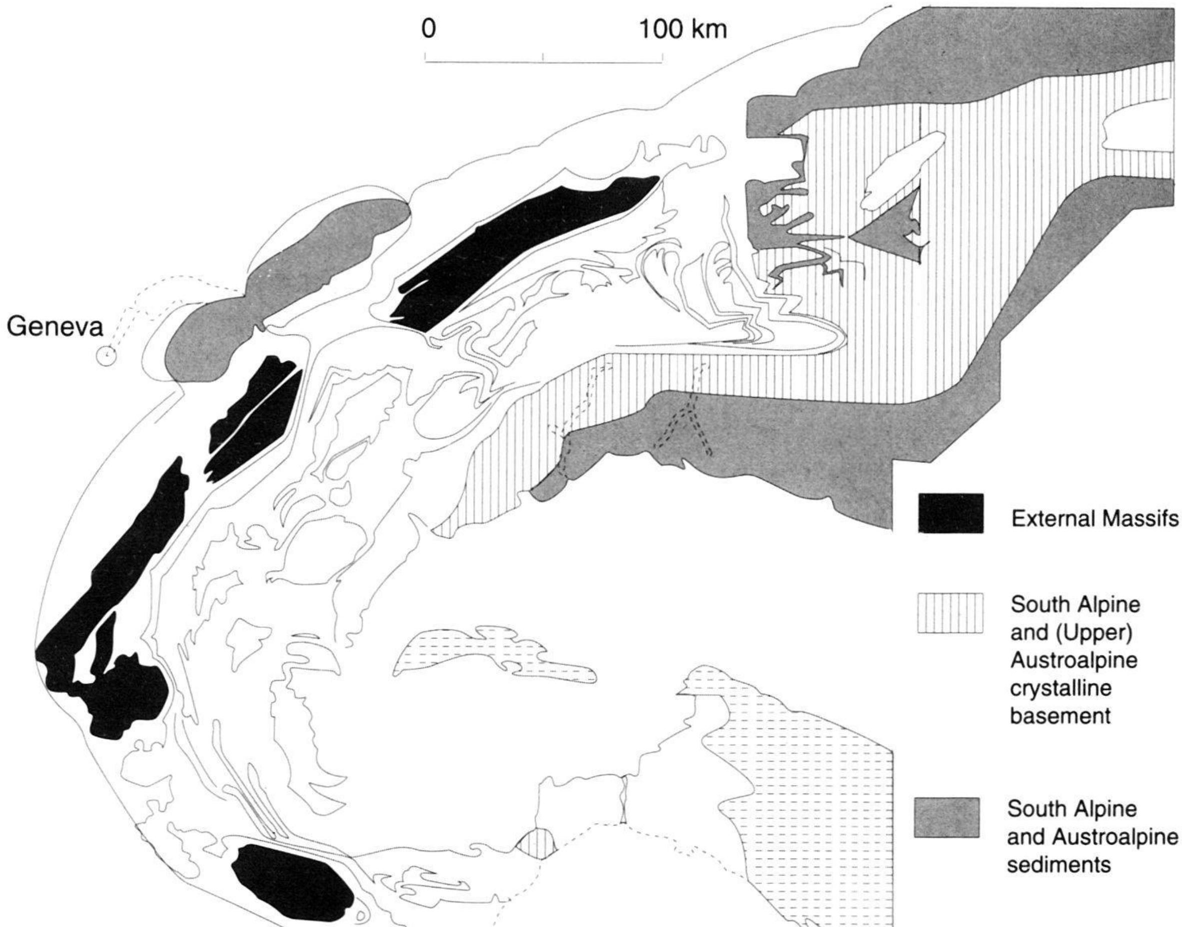


Fig. 1. ARGAND's (1916, Fig. 17) map of the Western Alps, slightly simplified. It serves as the basis for successive retrodeformations (Figs. 3–10) although many of the units would be drawn somewhat differently today. The South Alpine and (Upper) Austroalpine sediments include the Préalpes (not in subsquent Figures), which Swiss geologists at the time thought to be Austroalpine. Note that the Sesia-Dt. Blanche and the Margna nappes for Argand were Penninic and the Savona complex in the Ligurian Alps was Austroalpine. The Apennines were not marked by Argand.

to combine them, at least for some stages of development. In a first step these kinematic pictures are often cartoons rather than quantitatively reliable pictures. Increasingly accurate quantification, however, remains the goal.

Argand used for his synthesis particularly the following fundamental notions:

1. The Alps are cylindrical in essence if not in detail. The deep parts exposed in axial highs can be projected laterally under the higher parts of the nappe edifice preserved in axial lows.

2. The nappe edifice evolved in a series of essentially coaxial phases of virtually S-N directed compression beginning in the late Paleozoic with embryos coinciding with mechanically strong terrains of Variscan granites.

3. A mechanically particularly strong European foreland and a somewhat less strong Adriatic hinterland acted as a vice that squeezed out a plastic domain in between. In map view, the S-N compression of the vice gave rise to diverging flow lines of the plastic material, thus building up the arc by what nowadays would be called "lateral escape". Discrete faults, though present, played no significant role (Fig. 1).

A comparison with modern concepts

The cross-sectional aspect

A comparison of Argand's famous cross-sections with a possible model using modern data reveals a number of important discrepancies.

The first difference is the absence of a crustal root in Argand's profiles. Although gravity measurements had uncovered the fact that mountains generally have such roots, Argand apparently thought they had nothing to do with kinematics. Mohorovicic had postulated his discontinuity already in 1909 (*fide* Toperczer 1960, p. 239) but its geologic significance was unclear, as were the lithospheric subdivions and the distribution of rheologies. In contrast, it is one of the generally known fundamental tenets of modern plate tectonics that tectonics involves the whole lithosphere, of variable thickness (possibly up to 250 km below the older shields) but often assumed to be about 100 km, bearing a continental crust with a standard thickness of 30 km. The lower crust, separated from the mantle – mostly assumed to be of peridotitic composition – by the M-discontinuity, seems to bulge down into the root and only occasionally to participate in orogeny, particularly in nappe formation, at least on surface evidence. The most conspicuous example of lower crust obduction is the Ivrea body, and recently the deep reflection seismic surveys across the Alps have unearthed evidence for a number of deeply hidden lower crust-upper mantle wedges (Bayer et al. 1987, Frei et al. 1989). The nature of the lower crust is still debated. Preference is given to granulitic to eclogitic rocks with large masses of basic intrusives as in the Ivrea zone. The upper crust may be defined by its rheology (Fig. 2). Its base is the brittle-ductile transition. It seems to play a crucial role in intracrustal décollement and the first formation of nappes (e.g. Laubscher 1983a). Material balance demands that the mantle part of the lithosphere and appreciable parts of the crust be subducted into the mantle (Laubscher 1990b, c). Progressive shortening is accompanied by uplift and erosion. Formerly hot deep-seated rocks rise to the surface, become cold and part of the brittle

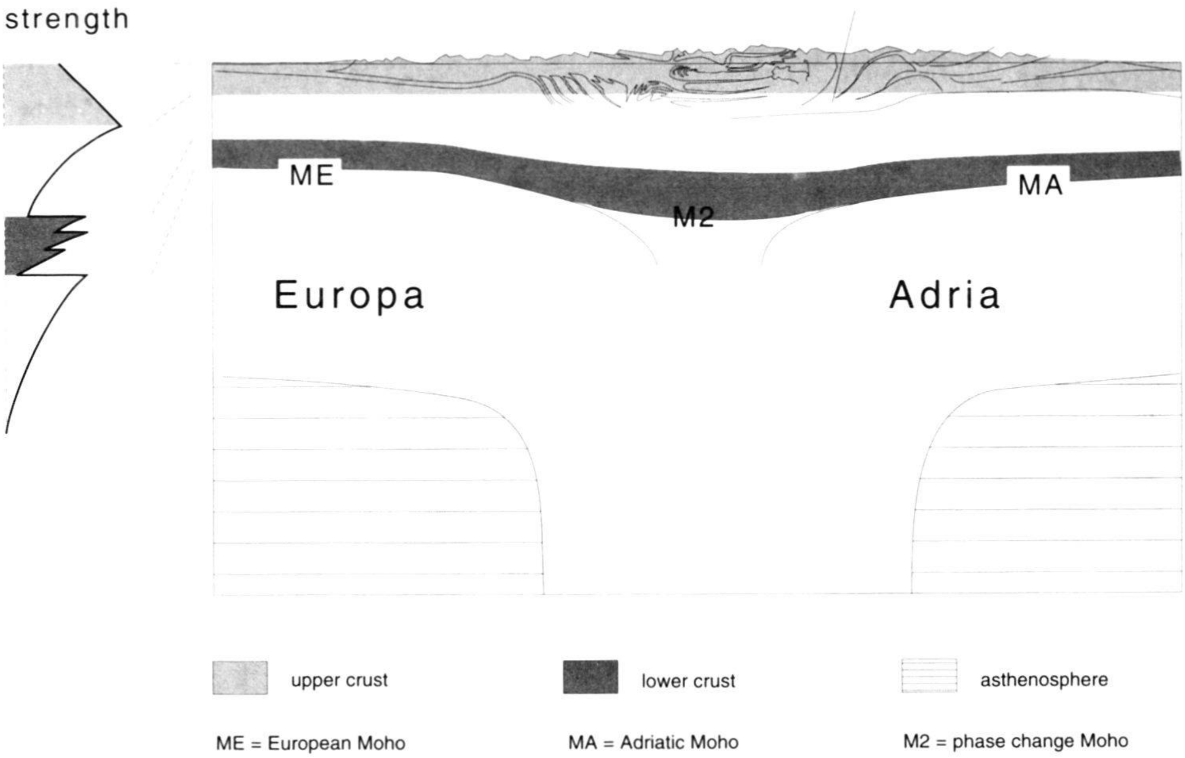


Fig. 2. Schematic rheology for a cross-section through the Swiss Alps. Superimposed on the complex nappe structure (from surface geology) are the approximate domains of the brittle upper crust, the ductile middle crust, and the still controversial lower crust. Position of M approximate, after Müller et al. (1980). Lithosphere and Asthenosphere schematic; they are no issue in this paper.

upper crust or lid. Thus, although the central parts of the Alps had deformed plastically at one time, they had done so disharmonically, under a brittle upper crust now removed by erosion.

Where still present, the upper crust of a former phase of deformation is composed of a mosaic of blocks bounded by faults. It may be conjectured that the same was true for those parts of upper crust now removed. These faults lose definition as they enter the middle crust and may be diffused in broad domains of ductile deformation.

The map view

This brittle aspect becomes particularly important in the map view where strike-slip faults become more clearly visible. Argand's (1916) map (compare Fig. 1) and the inset explanatory figures all avoid strike-slip faults, although divergent motion in a brittle layer requires transcurrent faults such as those observed in smaller arcuate belts. e.g. the Jura (Laubscher 1980). For Argand all was flow with divergent flow lines. For a static picture, trajectories of elastic stress directions have this geometry, but after a small amount of motion rupture takes place, creating a network of faults. In Fig. 3 I have superimposed on a slightly simplified rendition of Argand's map the most obvious large faults in the Neogene Alps. For the brittle lid they seem to have had mainly three functions:

1. They bound a more or less rigid Adriatic subplate (Biju-Duval et al. 1977) or promontory of Africa (Channell & Horvath 1976) that acted as an indenter in the more easily deformable Alpine domain. The reason for this sharp difference in deformational behavior is but imperfectly known, but obviously delamination and subduction of mantle and lower crust under the Alps would play a role.

2. They accommodate divergence of motion, which is quite a problem in a narrow arc such as that of the Western Alps.

3. They accommodate the transition from the deformational domain of the Alps into neighboring domains that are characterized by different deformation. An example is the transition of compressional Alpine tectonics to extensional Pannonian deformation in the middle to late Miocene (Laubscher 1990a).

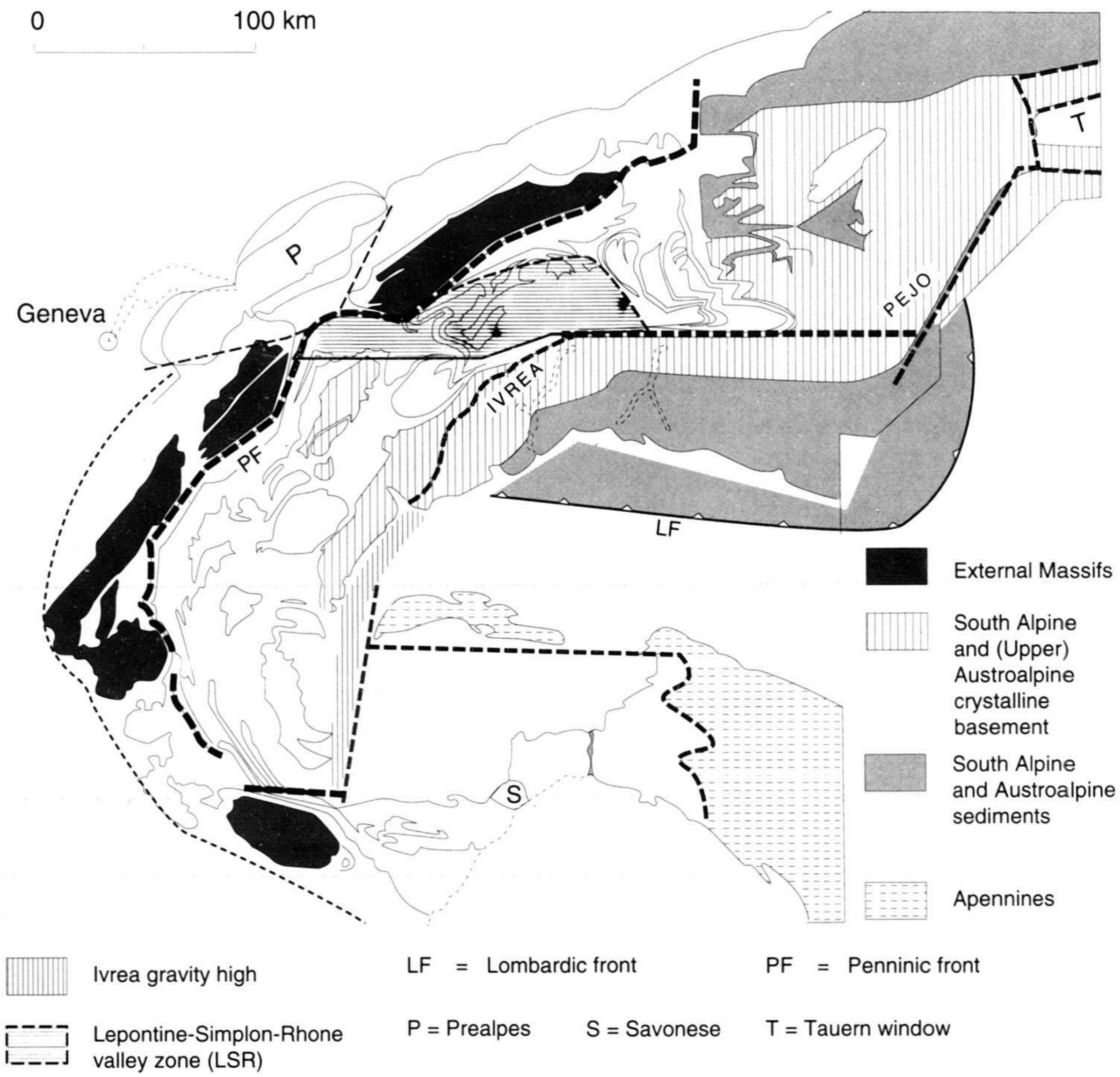


Fig. 3. Addition to the map Fig. 1 of the main tectonic elements that were not considered by Argand. Other modifications: The Préalps and the Savonese (S), assumed to be Austroalpine by Argand, are left blank. Explanations in the text.

Recognition of the important role of strike-slip and other faults does not obviate the role of cataclastic, plastic or viscous flow, but it helps in more clearly defining kinematic necessities. Argand understood the dilemma of the transition from a rigid Adriatic block, capable of transmitting stresses without being seriously deformed itself, and the plastic Alpine domain, but apparently was convinced that it was of minor importance. The all-important tectonic features were the nappes. Many Alpine geologists to almost this day seemed to think likewise, considering, e.g., the Insubric line to be the sole thrust of the Upper Austroalpine nappe (compare, e.g. TRÜMPY 1980) as Argand did, although already in 1930 CORNELIUS & FURLANI-CORNELIUS, who had restudied the line, voiced their doubts. The strike-slip component of the Insubric line, at least qualitatively, today is probably accepted by a majority (compare, e.g. MERLE et al. 1989); nowadays, of course, with plate tectonics holding sway, it takes hardly a revolutionary vision to recognize the role of transfer faulting in tectonics generally and in orogenic belts particularly. it is a kinematics of blocks bounded by transfer faults that appears most useful for a comparison with Argand's kinematics as it offers a well-defined antithesis.

In addition to the main faults I have superimposed, in Fig. 3, essential contributions of geophysics, completely unknown in Argand's time:

1. The gravity high, that reveals the subsurface continuation of the Ivrea body to the southern hinge of the Alpine arc (e.g. NIGGLI 1946, KAMINSKI & MENZEL 1968, VECCHIA 1968);

2. the subsurface Lombardic thrust belt with a front south of Milan, well documented by PIERI & GROPPI (1981);

3. and most recently, the strong, discordant, young reflection band brought to light by the reflection traverses of ECORS-CROP (BAYER et al. 1987) and NFP 20 (FREI et al. 1989) which, at the surface, coincides with the front of the Penninic nappes. It is therefore often identified as the "Penninic front" reflection. However, this is misleading as the reflection band merges with the Miocene boundary zone of the Simplon-Lepontine domain, where a mylonitic to brittle discontinuity dissects the essentially Eocene Penninic system (BEARTH 1956, MANCKTELOW 1985, STECK 1987, 1990). It occupies the position of the base of the brittle lid active during the development of the Helvetic nappes (LAUBSCHER 1991) and connects these kinematically with the coeval activity at the Insubric line.

A map view kinematic model

How do we proceed from the present distribution of tectonic elements to a step-by-step retrodeformation of the western Alps? Age relations are a prerequisite for this performance. And here again, Argand was direly short of data. Micropaleontology had not yet come into its own, and isotopic methods were not even in sight. These age relations, as presently known, though still insufficiently clear, seem to require the following sequence of steps:

The latest motions

The youngest is the belt of external massifs (Fig. 3), a dextral arrangement of crustal en échelon folds, at least from the Belledonne to the Aar massif (LAUBSCHER

1971, 1988). Estimates of their total shortening revolve on the order of 30 km (if Jura décollement is their frontal part, compare GUELLEC et al. 1990) which, compared with the total of Alpine kinematics, is relatively unimportant and is neglected here. At the southwestern end of the Arc of the Western Alps considerable movements took place in Miocene to Quaternary times in the Appennines, with a northward motion of the Padan thrusts (CASTELLARIN et al. 1985) of probably several tens of kilometers. Their kinematic relation to the coeval Umbria-Marche thrusts with possibly several hundred kilometers of ENS-WSW shortening at the front of the Tyrrhenian collapse basin (BALLY et al. 1986) is not understood, and there is no perceivable relation, at this time, to the Western Alps. These Apenninic events are not integrated either in the models of this paper.

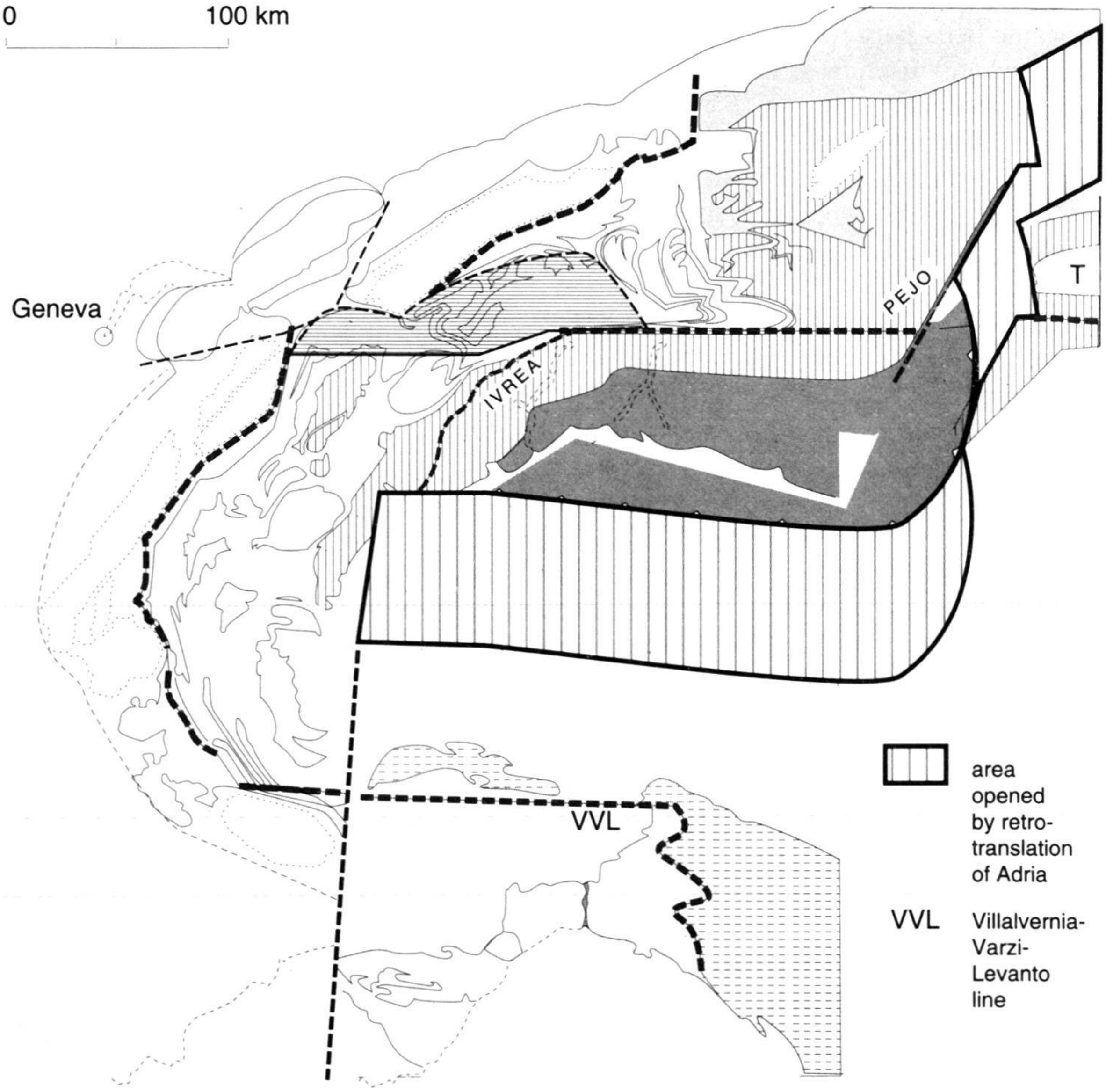


Fig. 4. Retrotranslation of the middle to late Miocene Lombardic phase. In this and the following retrodeformations no attempt is made to smooth out features due to internal deformations such as the Tauern window (T). They are left as markers for easy identification of rigid translations and rotations.

The middle Miocene Lombardic phase

Next youngest are middle to late Miocene motions in the southern Alps and particularly in the subsurface of the Po basin (Fig. 4; see PIERI & GROPPI 1981). There is a divergence of opinion as to the amount of shortening produced in that time interval. This is poorly constrained, as is the beginning of the Miocene motions in the Southern Alps. I have argued for a middle to late Miocene shortening on the order of 100 kms produced by this "Lombardic thrust system" (LAUBSCHER 1990a), compatible with the data set which, however, is insufficient for a unique solution if not complemented by external information. As the eastern end the Lombardic thrust front swings north into the Giudicarie transpressive belt and the western end stops short of the Western Alps, it is seen that this important thrust system is bounded by two sinistral transfer zones. The western one is hidden under Quaternary deposits along with other important boundary disturbances at the eastern margin of the Western Alps. Its existence is a mere conjecture, albeit an apparent kinematic necessity.

Retrotranslation, that is pulling back to the south the Lombardic thrust front by 80 kilometers, has consequences that border on the miraculous: It straightens out the early Miocene boundaries of the Adriatic indenter that in Fig. 3 appeared severely kinked. In the northeast, the Jorio-Tonale segment of the Insubric line now passes straight into the Pustertal-Gailtal segment. In the southwest, the Villavernia-Varzi-Levanto line (ELTER & PERTUSATI 1973), the only Miocene element separating the pre-(latest Eocene to) Oligocene Ligurian Alps from the early Miocene Apennines, lines up with the sinistral shear zone at the southern border of the internal western Alps.

Thus, this first step in the retrodeformation of the Alps is quite successful. Other than that there is no proof that it comes close to what actually happened: the retrodeformation is based on inductive inference from a large but incomplete data set with which it is believed compatible. Its success, however, means encouragement to pursue the matter further and to devise a more complete model *pro tempore.*

The Oligocene-early Miocene Insubric-Helvetic and Toscanide phases

The next older phase of deformation is the (late Oligocene-) early Miocene one (Fig. 5), dated radiometrically across the Insubric line (HURFORD 1986) and stratigraphically at the northern front of the eastern Alps (FUCHS 1980, KRÖLL & WESSELY 1967). I call it, consequently, the Insubric-Helvetic phase (LAUBSCHER 1990c). It is dextrally transpressive at the northern boundary of the Adria plate. Quantification of the normal and the strike-slip components is possible only with some assumptions. Moreover, for the "low-tech" methods employed in this article, it is much easier to treat the normal (Fig. 7) and strike-slip components (Figs. 5, 6) separately, although they were active simultaneously. For the normal components attempts at smoothing out the Helvetic nappes have been published, e.g. by TRÜMPY (1969) and FERRAZZINI & SCHULER (1978). A round figure on the order of 100 km may be inferred. For the strike-slip component, roughly correlative large-scale features may be tentatively used to see how they work out. The pre-Mesozoic crust-mantle boundary in the Ivrea- (BÜRGI & KLÖTZLI 1990) and Pejo (Ultental)-zones (e.g. HAMMER 1902, ANDREATTA

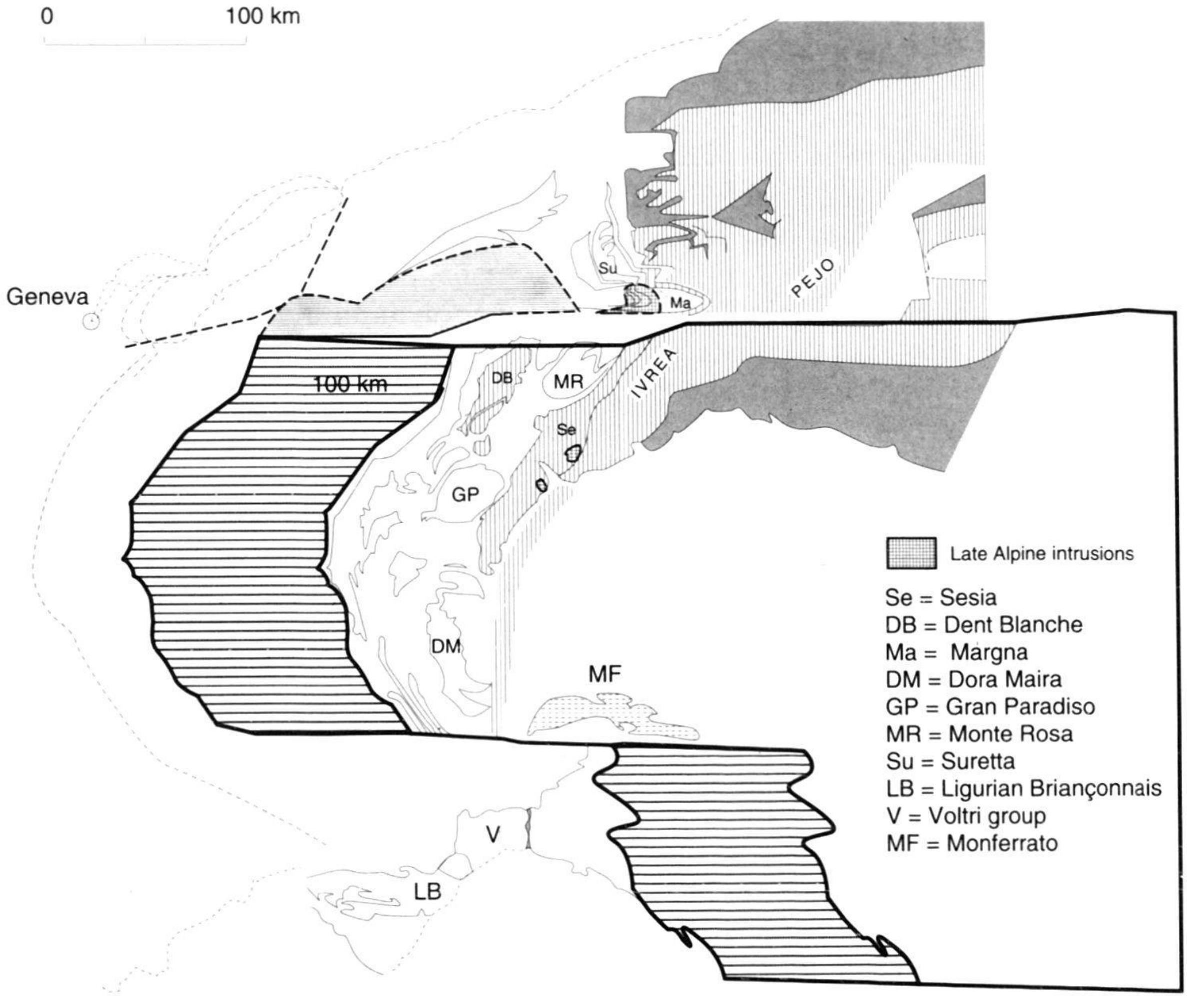


Fig. 5. Partial retrotranslation of the Adria indenter in the late Oligocene (post-30 Ma) to early Miocene (16 Ma) Insubric-Helvetic phase, following the Lepontine-Simplon-Rhone branch of the Insubric line and the "Penninic front" (Fig. 3). For the other partial motions see Figs. 6 and 7. Late Alpine intrusions are about 30 Ma old. Explanations in the text.

1948, 1954, Herzberg et al., 1977) are obvious candidates, with an apparent dextral displacement on the order of 150 km (Fig. 6 and Laubscher 1991). A second pair of correlative features are the Dent Blance and Margna nappes, again with an order of 150 km dextral displacement. This correlation requires that the main motion of early Miocene dextral slip along the Insubric line followed the Lepontine-Simplon-Rhone valley branch rather than the Canavese branch. This is consistent with the observation that the Penninic front joins that branch.

However, there are complications. The first concerns the link with the Toscanide phase in the Apennines (compare Kligfield et al. 1986). This was coeval with the collapse of the Baleares-Provence basin and apparently has to be dated Oligocene-early Miocene (e.g. Rehault et al. 1986, Boccaletti et al. 1990). The Villalvernia-Varzi transfer zone would possibly (though not necessarily) be of the same age, and consequently there would be an Oligocene component for the rest of the system. In fact, the radiometric dating at the Insubric line (Hurford 1986) dates only the compressive component when the Lepontine Alps were squeezed up. It may have been preceded by a transtensive phase during the era of Balearic collapse that extended far into the Alpine domain ("Oligocene lull" of LAUBSCHER 1983b). Along the internal border of the Alps there are suggestive data to this effect: The Piemont-Liguria Tertiary basin (GELATI & GNACCOLINI 1980), the overstepping of Oligocene continental deposits on Sesia basement (ZINGG et al. 1976), and the so-called "late Alpine Intrusions" – all lining up along the Insubric-Canavese fault system (compare LAUBSCHER 1983b). Thus, conceivably, there had been a considerable component of westward transfer of the Adriatic plate in that Oligocene collapse phase (possibly 34 Ma to 26 Ma: Uppermost Eocene Ranzano Sandstone transgressive on the Ligurian Alps, see GELATI & GNACCOLINI 1980 to the beginning of transpression along the Insubric line, see HURFORD 1986).

However, the position of the Bergell granite in the Alpine edifice may be used to constrain the possibilities to a certain extent, if it is assumed that it intruded on the internal side of the Sesia zone in continuation of the coeval Biella and Traversella intrusions (Fig. 5). This line-up is achieved by a post-intrusion dextral translation of 100 km along the Lepontine-Simplon-Rhone valley (LSR, LAUBSCHER 1991) branch of the Insubric line. As may be seen in Fig. 5, this move also lines up quite reasonably

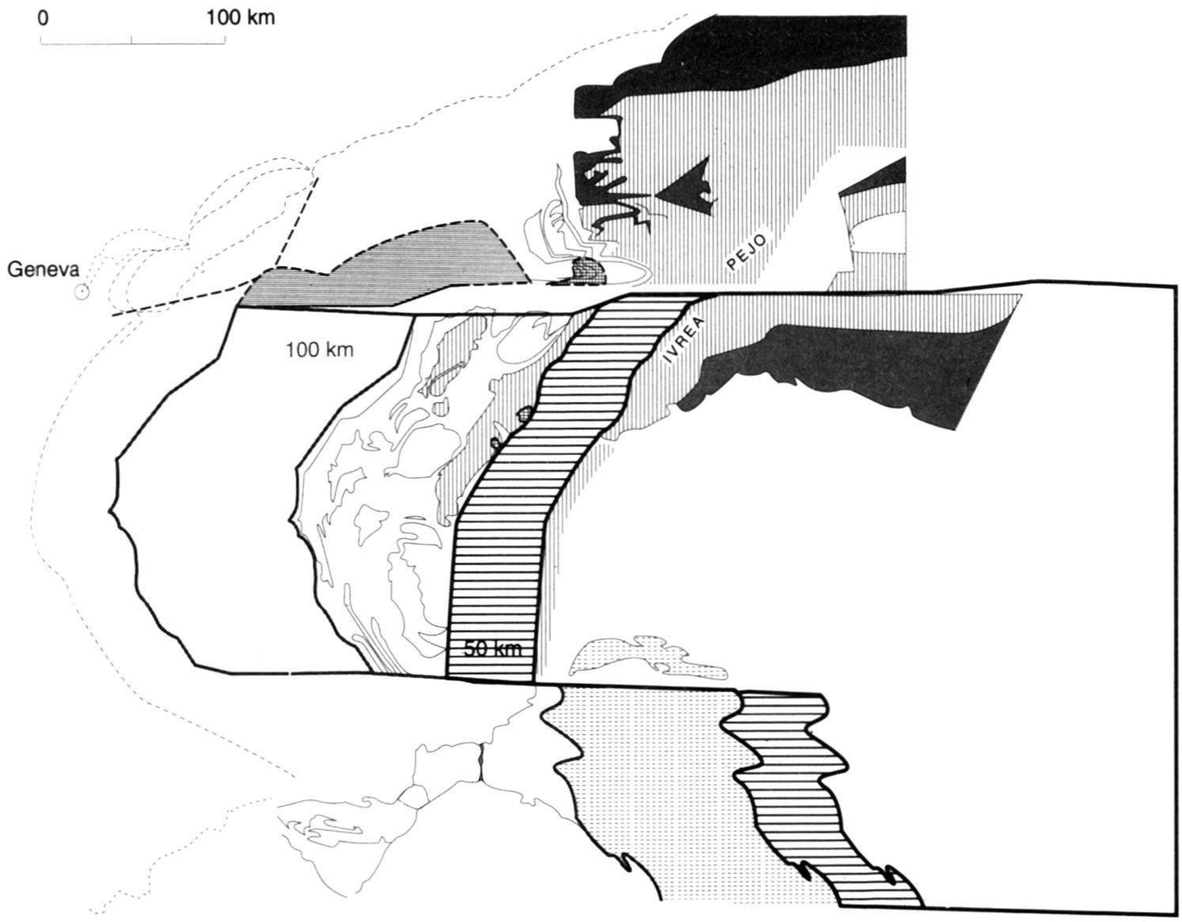


Fig. 6. Partial retrotranslation of the Adria indenter in the late Oligocene (post-30 Ma) to early Miocene (16 Ma) Insubric-Helvetic phase following the Canavese branch of the Insubric line. Explanations in the text.

the front of the Austroalpine nappes and the "Internal Massifs" (DM, GP, MR) with the presumably correlative Suretta nappe (Su). At the SW corner of the Adriatic indenter, the metamorphosed Voltri ophiolites of the Ligurian Alps are in reasonable continuation of the ophiolites of the western Alps. On the other hand, a line-up of both Ivrea-Pejo and Monferrato-Northern Apennines, with correlative lithologies, requires another 50 km of retrotranslation (Fig. 6). This move has to follow the Canavese branch of the Insubric line so as not to destroy the line-ups achieved by the move of Fig. 5. As to timing, we note that at least a part was post-Oligocene: Ivrea and Canavese rocks are in tectonic contact with the discordant Oligocene cover of the Sesia nappe.

Another problem is the extent of Eurasia at the time of the NW translation of Adria. Had the Ligurian domain south of the Villalvernia-Varzi-Levanto line remained

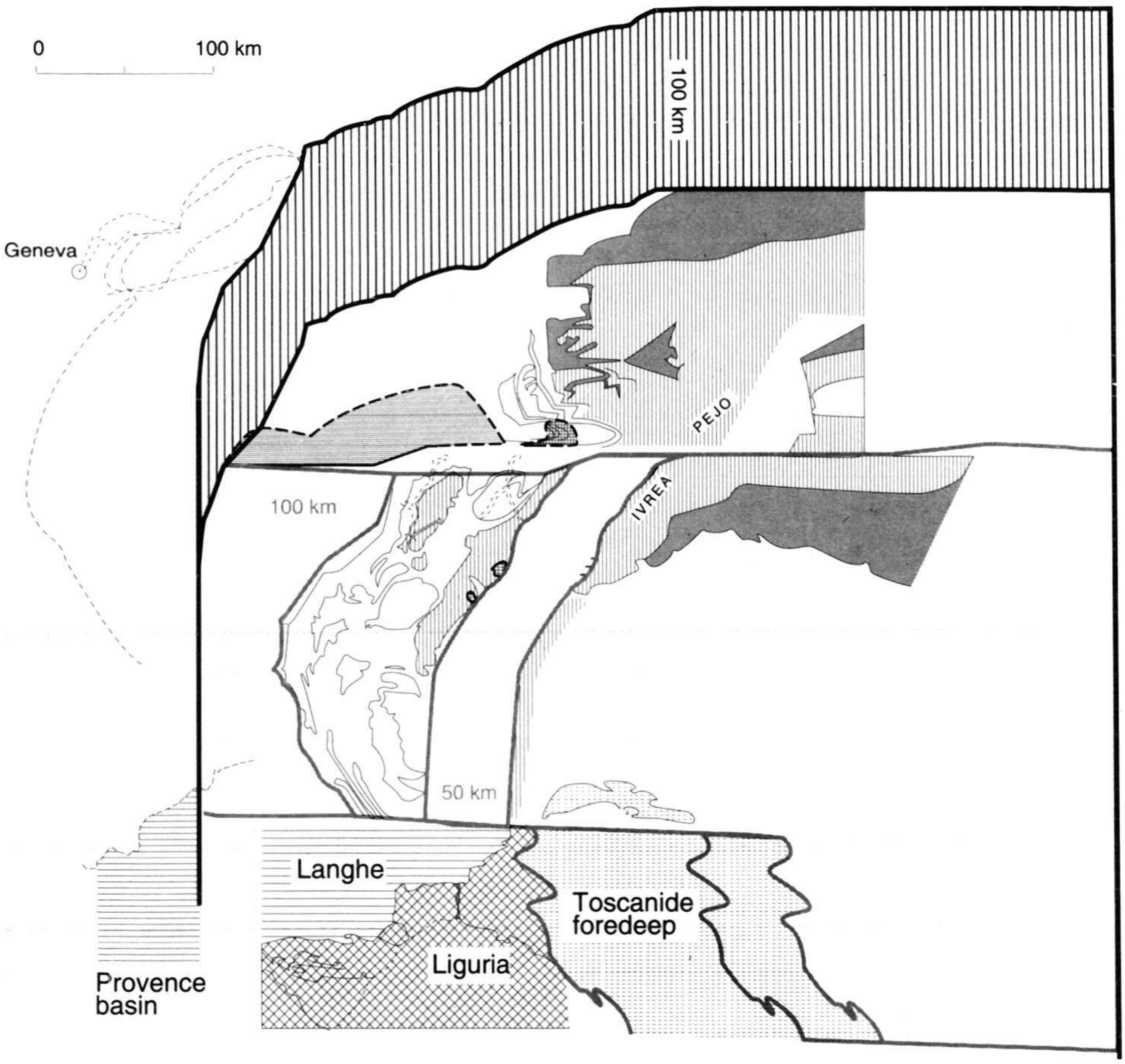


Fig. 7. Retrotranslation of the NS component of the Adria indenter in the late Oligocene (post-30 Ma) to early Miocene (16 Ma) Insubric-Helvetic phase. Note the connection of this component with the Provence collapse basin and the Langhe (Piedmont-Liguria) basin in the southwest. The Liguria block is presumably a part of the Sardinia-Corsica-Liguria continental complex (Fig. 8). The retrotranslations of Figs. 4 and 7 have separated it from the Alps and brought it into approximate continuation of the Provence belt. Explanations in the text.

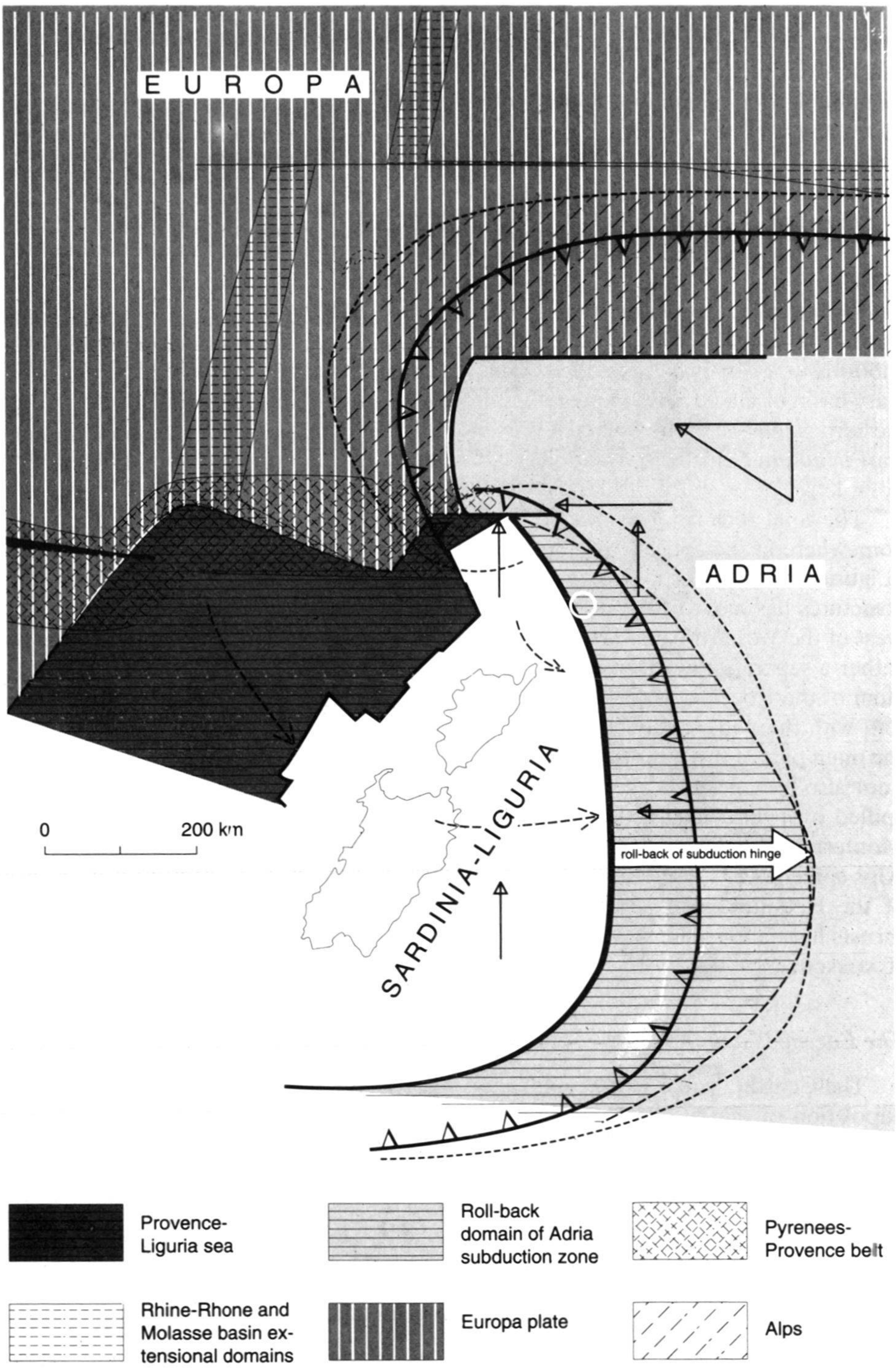
in solid contact with Eurasia as assumed in Fig. 5 and 6, this translation would have created transtension along the Villalvernia-Varzi transfer zone. However, it seems that Liguria was part of a Sardinia-Corsica-Liguria complex of continental blocks that was separated from Eurasia and Iberia by the Baleares-Provence-Ligurian sea collapse (e.g. Boccaletti et al. 1990). This complex acted, in certain ways, as the third block invoked by Laubscher (1971) to account for northward thrusting of the northern Apennines. This implies that the Sardinia-Corsica-Liguria complex moved northward together with Adria, in addition to perpendicularly to the Toscanide front.

Figs. 7 and 8 illustrate the kinematics involved. In Fig. 7 the retrotranslation of the SN-component (Helvetic nappes) of the NW translations is performed. For the reasons set forth above the western boundary of the moved block connects with the Provence basin, west of Liguria. Fig. 8 illustrates the total of Insubric-Helvetic-Toscanide motions in a somewhat extended frame. Note that the Langhe basin (Piedmont Tertiary basin of Gelati & Gnaccolini 1980) of Fig. 7 appears as a sort of shallow northwestern extension of the Baleares-Provence-Ligurian sea collapse basin, if Liguria took part in counter-clockwise rotation of Corso-Sardinia as a part of the Sardinia-Liguria complex.

The total retrodeformation performed thus far results in an interesting situation somewhere at the end of the Eocene phase. One feature of what may be termed the "Ligurian knot" is especially noteworthy: Retrotranslation of the Insubric-Helvetic structures has moved the western part of the Ligurian Alps into a position south and west of the Western Alps. They do not appear now to be their direct continuation but rather a separate branch of the Alpine system. They best fit the junction of the main stem of the Eocene Pyrenees-Provence range whose eastward projection places their join with the Alps somewhere in this area; the Baleares-Provence collapse destroyed the main part of this important link (Fig. 8). Another interesting feature at the Ligurian knot also emerges from Fig. 8: The essentially east-vergent thrusts of the Toscanides spilled over the Villalvernia-Varzi transfer fault at their northern end, producing the Monferrato Apennines. Similarly, the essentially west-vergent thrusts of the Western Alps spilled over to the south of the transfer fault, which may account for the position of the Helminthoid flysch masses in the southwest of the Ligurian Alps. Arcuate thrusts have a tendency of such lateral spilling, compare e.g. the Giudicarie thrust belt (Laubscher 1990a).

The Eocene Penninic phase

The Central Penninic or Briançonnais domain was covered by higher nappes after deposition of the middle Eocene Flysch Noir. It is probable but uncertain that this event was the last stage of SE-NW oblique convergence between Adria and Eurasia that began in the Late Cretaceous (80 Ma; see below) and ended in the complete obliteration of the Piemontese ocean. In this stage the entire (South- to) Ultrahelvetic-North Penninic-Middle Penninic complex of the Central Alps was moved onto the southern part of the Helvetic domain, whereas in the northern part (Diablerets, Gellihorn and Morcles nappes) the lowermost Oligocene (32 Ma, approximately coeval with the late Alpine intrusions; Fischer & Villa 1990) Taveyannaz volcanic sandstones were deposited. The entire depositional width of the Ultrahelvetic to North-


EUROPA
ADRIA
SARDINIA-LIGURIA
0 200 km
roll-back of subduction hinge
Provence-Liguria sea
Roll-back domain of Adria subduction zone
Pyrenees-Provence belt
Rhine-Rhone and Molasse basin extensional domains
Europa plate
Alps

Penninic trough complex (roughly 100 km) and the Subbriançonnais-Briançonnais zone (another roughly 100 km) was eliminated. On the basis of these imprecise numbers the S-N component for this interval may therefore be estimated at about 200 km, perhaps a little more: the farther back in time we go, the larger are the uncertainties (for somewhat larger numbers see below and Figs. 9 and 10). As to the simultaneously active EW-component, the Western Alps appear to demand a sinistral rotation of the Penninic belt of almost 90 degrees average, and this is equivalent to approximately 300 km EW translation (Fig. 9). Based on such a rotation in its front, the SN-component of the Adria indenter turns out to be about 250 km – a little more than that arrived at by estimating the depositional width of the Ultrahelvetic to Middle Penninic belt. The sinistral rotation is compatible with sinistral transpression along the western edge of the NW-moving Adriatic indenter, and it may be conjectured that the total Eocene deformation may have been the sum of the rotation of Fig. 9 and an unspecified NW translation at the front of the Adria indenter (Fig. 10). By this retrodeformation the middle Penninic (Briançonnais) facies zones of the Western Alps acquire an EW-strike in the approximate eastern continuation of the Provence Mesozoic high (compare LAUBSCHER 1971, RICOU & SIDDANS 1986).

We thus arrive at a pre-late Eocene situation that is characterized by a triple point where the Europa, Iberia and Adria plates or blocks join, or even an approximate quadruple point if the Penninic subplate (Penninia) is included (see Fig. 10). The uncertainties in the quantitative estimates used for the restoration of Fig. 9 are augmented by the uncertainties in the relative convergences of both Iberia and Penninia with respect to Eurasia in this area. Within the limits of all these uncertainties the Briançonnais-Provence Mesozoic depositional belt may well have been approximately straight E-W, north of an important regional fracture zone composed of the Pyrenean fault belt at the northern margin of Iberia, and the North Piemontese transfer fault (NPT) at the northern margin of the Piemontese ocean (compare WEISSERT & BERNOULLI 1985). Keeping the various uncertainties in mind, the Briançonnais-Provence belt has been straightened out qualitatively in Figure 10 in order to suggest the simplest possible pre-late Eocene paleogeography. So far as I can see, there are no constraining data for a better resolution of the situation. Whatever the quantities, however, of fundamental qualitative importance is the necessity of a junction of the Pyrenees-Provence suture with the Alps. As shown in Figure 8, the eastern part of this essentially pre-Oligocene suture has largely been destroyed by the Balearic-Ligurian collapse. The Oligo-Miocene motions of the Adriatic indenter had further deformed

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Fig. 8. The kinematic situation in the Oligocene-early Miocene around the "Ligurian knot": the join Alps-Pyrenees-Apennines-(Baleares to Ligurian sea collapse). The relation Adria-Sardinia/Liguria-Baleares/Provence/Ligurian sea collapse basin after BOCCALETTI et al. (1990). Added is the Adria-Europa relation according to this paper. Solid arrows are kinematic vectors and their components of Adria and Sardinia-Liguria with respect to Europa. Superimposed is the rotation (dashed arrows) of Sardinia-Liguria into the roll-back gap of the Adriatic subduction zone. Horizontally ruled are major extensional features: The Provence-Ligurian sea basin and its shallow appendix, the Langhe basin (dark shading), the roll-back gap of the Adriatic subduction zone (light shading), the intra-European Rhone-Rhine graben system (horizontal dashes). Cross-hatched: Pyrenees-Provence branch; diagonally dashed: Alps. Alpine and Apennine thrusting (which eventually reached the dashed line) symbolized with triangles. Explanations in the text.

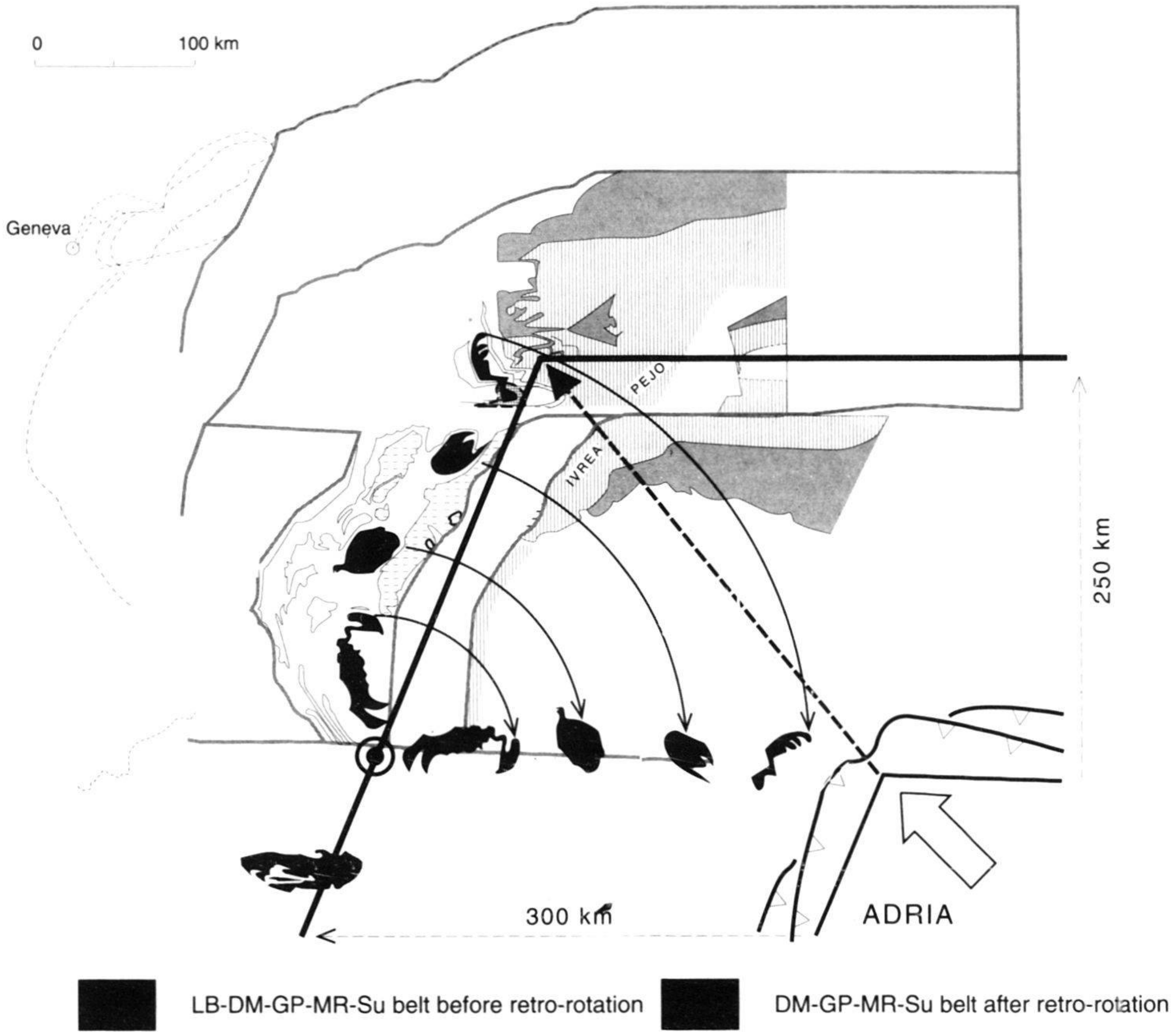

Fig. 9. Partial retrodeformation of the Eocene Penninic phase: Retrorotation around a pivot at the southern end of the Western Alps. For better visualization those "Internal Massifs" south of the LSR branch of the Insubric line (Dora Maira, Gran Paradiso, Monte Rosa) plus the Suretta nappe (DM-GP-MR-Su) (Fig. 5) have been shaded: dark gray before retro-rotation, black after retro-rotation. Their shape was maintained for easy identification. Also black are the basement (including Permian) masses of the Ligurian Alps (LB) (shapes from Fig. 1), that seem to lie outside the Western Alps. Heavy lines: schematic outlines of the NW corner of the Adriatic indenter. Its translation to the NW is conjectured to be responsible for the rotation of the Briançonnais belt. In addition there presumably was some sinistral translation, see Fig. 10. Explanations in the text.

the original Eocene configuration which emerges only after the retrodeformations carried out in figs. 4–9. It has some remarkable features as shown in Fig. 10:

The separation of the Ligurian Briançonnais from that of the western Alps by the retrodeformations of Figs. 4–9, at first sight an embarrassment as it runs counter to apparently well-founded traditional views, may be a blessing in disguise. It is at this site that another important branch of the Alps, hitherto neglected in our kinematics, takes its issue: the North-Penninic cordillera of late Cretaceous and early Eocene times. This cordillera was badly disfigured subsequently but is well documented in several places, e.g. the Pelvoux and Aiguilles d'Arves (Gidon 1979) and the Niesen Flysch (e.g.

Homewood & Caron 1982; compare Laubscher & Bernoulli 1982). Its location was somewhere in the North-Penninic-Ultrahelvetic domain whose pre-deformational position was revealed particularly by the Insubric-Helvetic retrodeformation (Figures 5–7). It is hardly conceivable that this important Late Cretaceous-Eocene zone of motion had a blind ending south of the Pelvoux instead of joining the Provence-Pyrenees branch, and from the reconstructions in this article the most plausible if not only place to do so was near the western end of the Ligurian Briançonnais. Extreme defor-

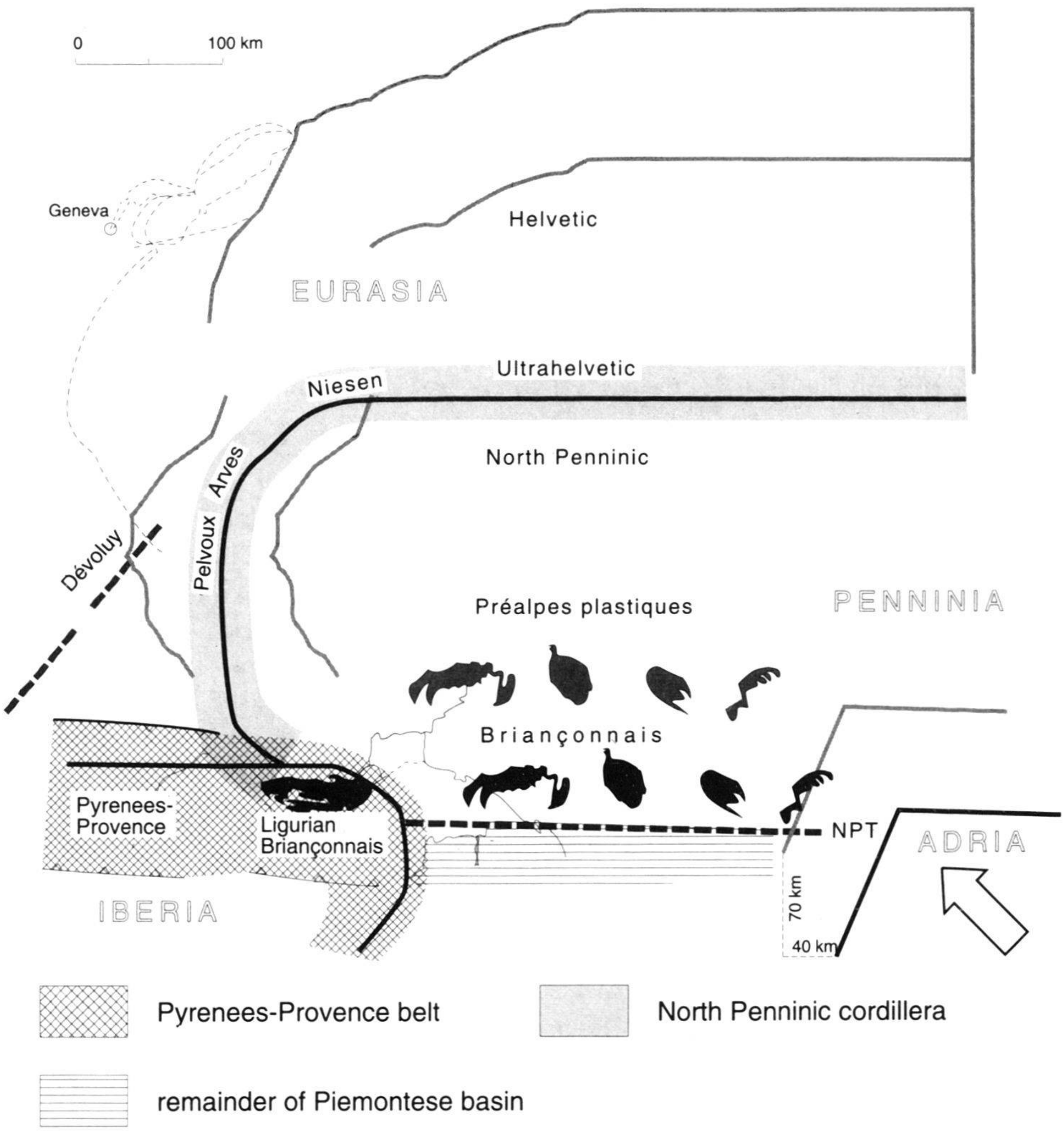

Fig. 10. Retrotranslation in the Eocene phase in addition to the retrorotation of Fig. 9. The most satisfactory line-up would appear to be that of the (Briançonnais)-western Ligurian Alps-Provence belt (compare Figs. 8, 13, 14). Added is the approximate position of the late Cretaceous to Eocene Niesen cordillera. Explanations in the text (NPT = Northern Piemontese transform fault).

mation and even metamorphism of the Ligurian Briançonnais would be due to this position rather than its association with the Briançonnais proper in the present arc of the Western Alps. Furthermore, the conspicuous North-Penninic flysch belt may be visualized as heading into the Imperia-San Remo flysch domain whose abnormal position has always been difficult to explain. It is even conceivable that Piemontese Helminthoid flysch masses there were superimposed on the North-Penninic flysch in the Eocene. However the detailed situation, the general layout of Fig. 10 seems more promising for an understanding of late Cretaceous-Eocene tectonics in what was to become the Western Alps than the traditional views.

It would seem that the Ligurian triple point of Fig. 10 is the forerunner of the Ligurian knot of Figures 3 and 8. It had been an initial boundary condition for Alpine kinematics that originated in Mesozoic block boundaries: the Pyrenean and the North Piemontese transfer faults and the western margin of the Piemontese ocean. It has had a far-reaching influence on Alpine kinematics to the present day.

If the southern hinge of the Eocene arc of the Western Alps has its mysteries and surprises, the northern hinge is not far behind (Fig. 11). Prior to the Oligocene, the northern edge of the Adriatic indenter cannot have used the same transfer fault as the Insubric phase as this would disrupt again the Austroalpine and South-Alpine units which after Neogene retrotranslation now are in juxtaposition (Figs. 6, 7 and 9). Fig. 11 suggests the position of the pre-Oligocene forerunner of the Insubric Line. It had to be north of the Pejo and Margna domains as these had been brought into continuity by Insubric retrodeformation. The area north of the Pejo-Margna is indeed a fundamental discontinuity in the Alpine nappe edifice. In particular, the Middle and Lower Austroalpine units of Switzerland occur only there. They are bounded in the north by the Ortler-Albula sedimentary zone which cuts across the nappe edifice. Upper Austroalpine nappes are found only north of this zone. The adjacent belt in the Upper Austroalpine (Swiss nomenclature) Silvretta nappe is a zone of collapse, with its sedimentary cover in a particularly low position. It is dissected by numerous extensional faults that in part had already been mapped by EUGSTER (1923), EUGSTER & FREI (1927), and EUGSTER & LEUPOLD (1930). LAUBSCHER (1983a) thought that this collapse might be connected with the Oligocene Ortler dikes, but it may also be of Gosau (Late Cretaceous to Eocene) age, in agreement with widespread collapse in the Austroalpine domain. Oligocene extensional faulting at the southern margin of the transverse zone has recently been reported (NIEVERGELT et al. 1991), and an apparently Mesozoic extensional fault has been mapped in the Lower Austroalpine domain (FROITZHEIM & EBERLI 1990). Evidently, there is a superposition of normal faults of different ages which must be dated individually.

The earliest phases of Alpine kinematics

Further retrodeformation of the Alps is hardly feasible as the earlier stages have been too severely distorted to furnish useful correlative features. Instead, a plate tectonics model may be used for an Early Cretaceous starting point, and forward modeling applied in order to see what motions would be necessary for arriving at the situation of Fig. 10. Various plate tectonics models for Africa-Eurasia convergence have been offered since the pioneering work of PITMAN & TALWANI (1972). The dextral compo-

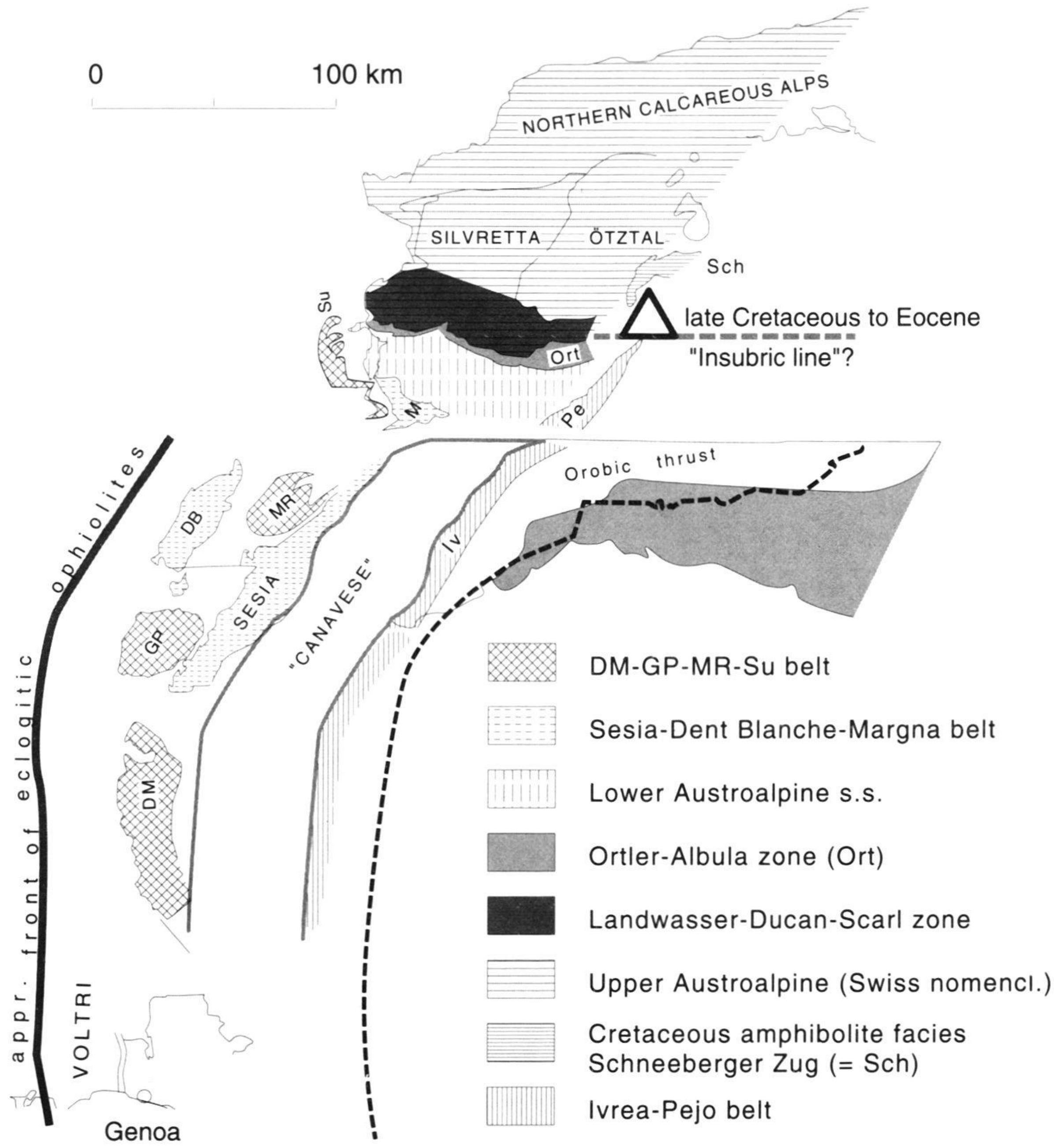

Fig. 11. The location of a Late Cretaceous-Eocene forerunner of the Insubric Line. Situation at the end of the Eocene phase. Wide horizontal ruling: upper Austroalpine nappes (Swiss nomenclature). Narrow horizontal ruling: Cretaceous amphibolite grade metamorphism. Horizontal dashes: Lower Austroalpine elements of the Eocene western Alps (DB = Dent Blance, M = Margna). Vertical ruling: Ivrea (Iv)-Pejo (Pe) zones, obducted lower crust to upper mantle. Vertical dashes: Lower to middle Austroalpine domains at the boundary between the western and the eastern Alps. Cross-hatched: the "Internal Massifs" (DM = Dora Maira, GP = Gran Paradiso, MR = Monte Rosa) and the correlative Suretta nappe (Su). Shaded zones at the Western Alps-Eastern Alps boundary: light shading = Ortler-Albula zone (Ort), dark shading = zone of pronounced extension at the southern border of the Silvretta nappe with preserved sediments (Landwasser-Ducan-Lower Engadine Dolomites). The triangle symbolizes a triple junction of sorts between the Eastern Alps, the Western Alps, and Adria. Explanations in the text.

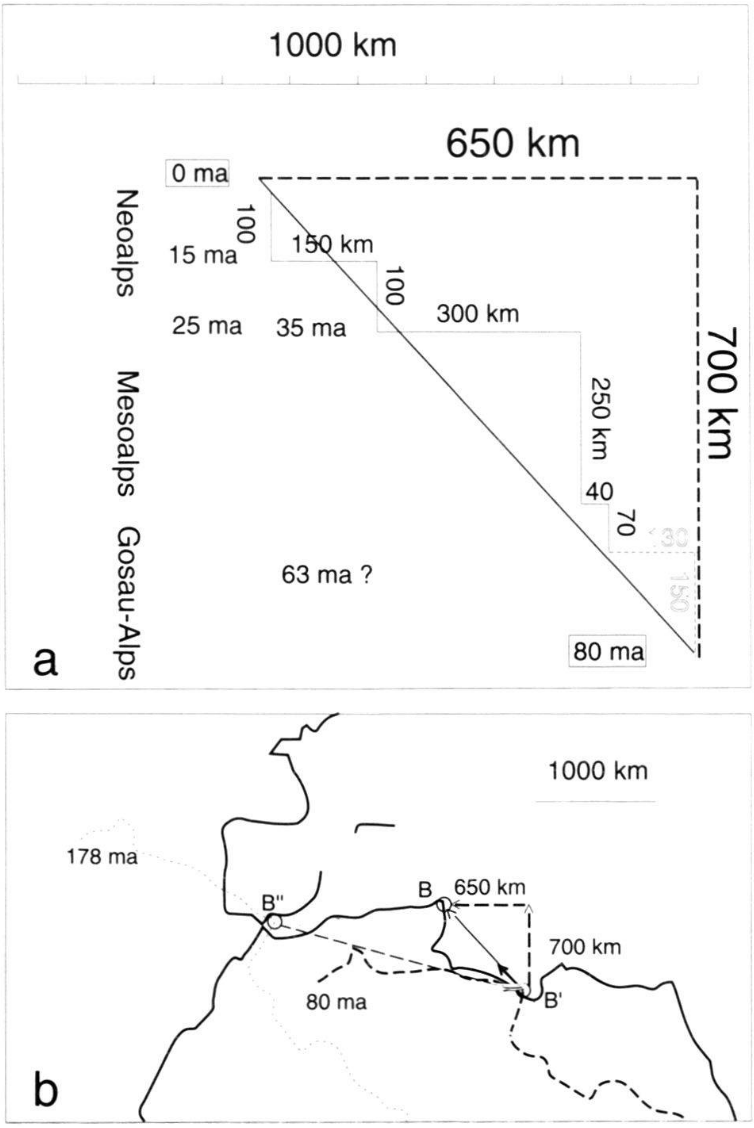

Fig. 12. a) A projection of the NW-SE retrotranslations of Fig. 3–9 to 80 Ma. It coincides quite well with the average translation 80–0 Ma according to DEWEY et al. (1973), see Fig. 12b. However, for the late Cretaceous-Eocene interval only a 200 km NW-translation remains (components are dashed). Compare Figs. 14, 15. b) Average sinistral translation from 178–80 Ma of point B" to B', and average dextrally transpressive translation from 80–0 Ma of point B' to B (Bizerta), according to DEWEY et al (1973). Explanations in the text.

nents apparent in Alpine kinematics seem to be represented best by DEWEY et al. (1973), whereas later models such as those of LE PICHON et al. (1988) and DEWEY et al. (1989) are less satisfactory. All of these models have in common a large sinistral translation in the Mediterranean area until 80 Ma; their greatest divergence is in the kinematics from 80-0 Ma which is the subject of this paper. Whereas an average SE-NW dextrally oblique convergence of 800 to 900 km is implied by DEWEY et al. (1973), an almost pure SN convergence is proposed by LE PICHON et al. (1988). As the DEWEY et al. (1973) average model is close to the linear extrapolation of the Tertiary retrotranslation of this paper (Fig. 12), although arrived at by completely independent means, I prefer that model for the early Alpine motions. On the other hand, the quantities of the two models do not quite agree for the individual stages: e.g., the rest left in Fig. 12 for the late Cretaceous-Paleocene motions is only about half the amount predicted by DEWEY et al. (1973) for that interval; for a discussion see below.

Late Jurassic to Late Cretaceous sinistral kinematics and the Dinaric Alps (148–80 Ma)

After initial rifting mainly in the Early and Middle Jurassic in a sinistral pull-apart scenario that extended from the Caribbean through the central Atlantic to the Africa-Eurasia boundary zone, the Piemontese pull-apart basin entered the spreading, oceanic stage, some time before the Callovian (DERCOURT et al. 1986). This stage seems to have continued till the North Atlantic started to open in earnest in the Late Cretaceous (80 Ma). Fig. 13 depicts this interval. It indicates a maximum width of the Piemontese ocean (not counting its margins) on the order of 1,000 km. At the same time, east of the Piemontese basin the Dinaric segment of the plate boundary had the orientation of a transverse range, and this is indeed intimated by the stratigraphic record (DERCOURT et al. 1986). It is the transitional domain between the pull-apart

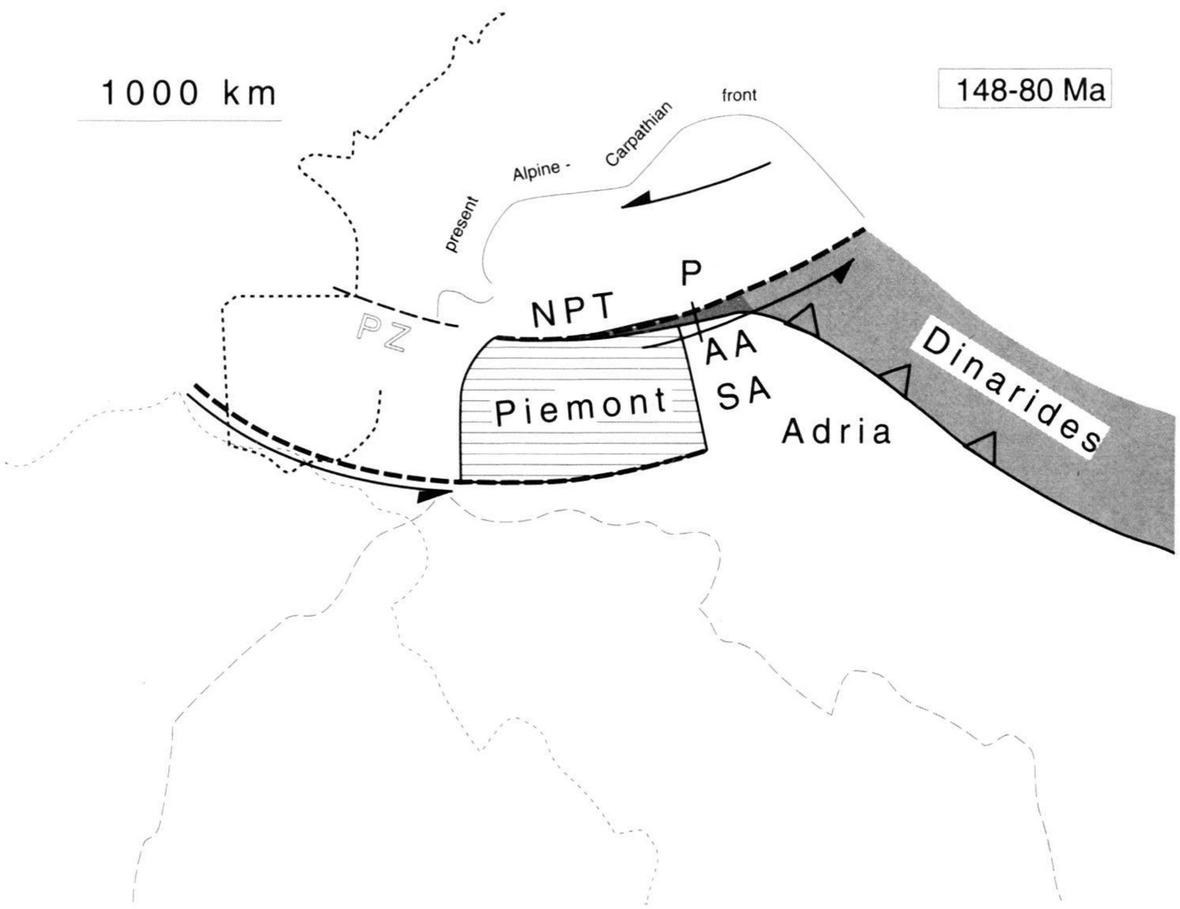

Fig. 13. Position of the Dinaric Alps in a system of sinistral rotation for the Interval 148–80 Ma, according to DEWEY et al. (1973). The Piemont ocean basin (horizontal ruling) is still in extension as a pull-apart basin, while the Dinarides are in compression as a transverse range (shaded). The Dinaric Alps are postulated to have been located somewhere in the sinistrally dragged northwestern tail (P) of the Dinarides (AA = Adria-Austroalpine, PZ = Pyrenean zone, NPT = Northern Piemontese transform fault, SA = Southern Alps).

basin and the transverse range that is of crucial importance for the development of the Alps.

A sinistrally transpressional drag (STD) of the Dinarides along the North Piemontese transfer fault (NPT) is postulated in Fig. 13. It occupies the site where subsequently the Austroalpine nappes developed (Fig. 14, 15). Although such a situation seems quite plausible in view of the tremendous strike-slip, it is more directly intimated by stratigraphic, radiometric and structural data. For instance, the early Cretaceous orogenic Rossfeld beds with their ophiolitic debris (Faupl & Tollmann 1979) suggest an association with contemporaneous ophiolite obduction in the Dinarides; radiometric dating of mylonites in some Austroalpine structures gives definite pre-80 Ma dates. This is particularly true for those at the base of the Ötztal nappe (Thöni & Hoinkes 1987) which around 90 Ma was thrust in a westerly direction (Schmid & Haas 1988) and subsequently rode piggyback on the Silvretta nappe to the north. Quite generally, pre-Coniacian tectonics, or deformations sealed by the transgression of the Gosau beds, belong to this phase.

The Late Cretaceous-Paleocene dextrally transpressive interval (80–63 Ma)

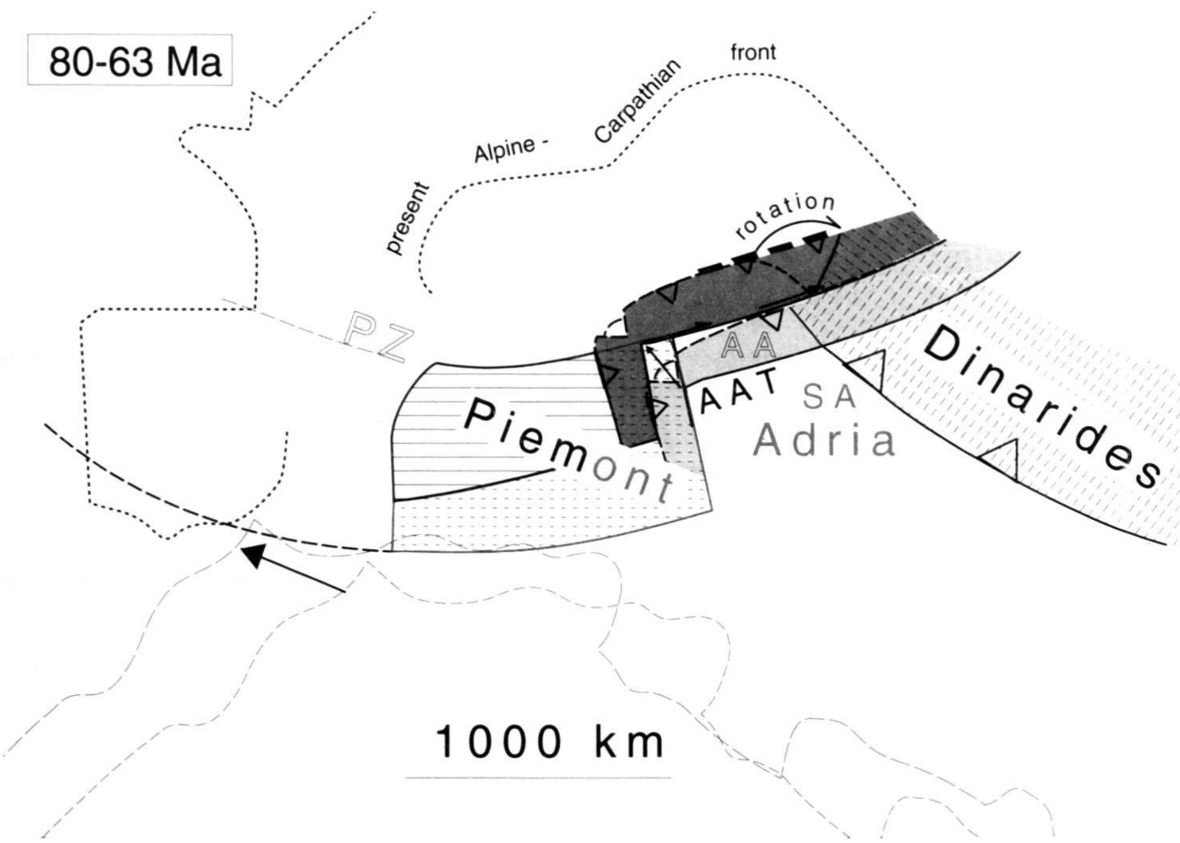

Fig. 14. Minimum 200 km dextral transpression in the Gosau Alps (80–63 Ma), based on Fig. 12. SA = Southern Alps, AAT = Adria-Austroalpine transform fault, PZ = Pyrenean zone. The black, partly interrupted band north of AA symbolizes possible elements of NPT dragged along on the front of the Austroalpine nappes. Horizontal ruling: The remainder of the Piemont trough at 63 Ma. Explanations in the text.

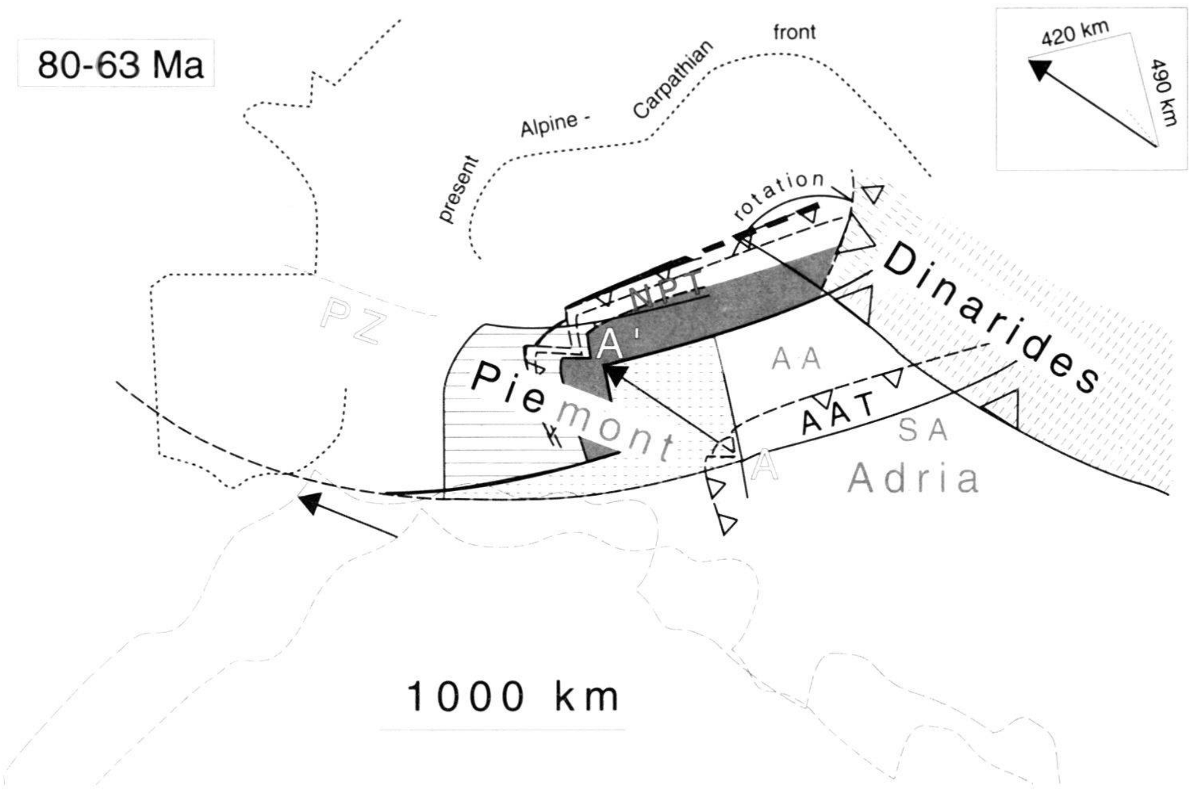

Fig. 15. Maximum 630 km dextral transpression (A-A') in the Gosau Alps (80–63 Ma), based on Dewey et al. (1973). Compare Fig. 14. (AA = Austroalpine, AAT = Adria-Austroalpine transform fault, NPT = Northern Piemontese transform fault, PZ = Pyrenean zone, SA = Southern Alps).

Intra- and post-Gosau motions in the Austroalpine domain are, in the plate tectonics model by Dewey et al. (1973), characterized by large-scale dextral transpression. The Silvretta-Lechtal nappe which is the important upper Austroalpine nappe (in the sense of Swiss geologists) in Switzerland is believed to be a product of that phase. Stratigraphically, nappe emplacement seems to be post-Gosau (Prey 1980), while radiometrically the pseudotachylites apparently associated with mylonites at the base of the nappe are only poorly dated (50 to 65 Ma, Thöni 1981). It has been mentioned above that there is some discrepancy between the plate tectonics and the retrodeformation models. In order to illustrate the range of possibilities I have constructed a minimum (Fig. 14) and a maximum translation (Fig. 15) model. The scenario of Fig. 14 is interesting in various respects:

– In order to separate the Austroalpine nappes from the South-Alpine strata that remained on the Adriatic plate, a more or less EW trending Austroalpine-Adria transfer boundary (AAT) seems required. Its exact position would be hard to fix at this time, but it would have to be some distance south of the Dinaric Alps, transverse to both Dinarides and eastern margin of the Piemont ocean basin. It may be considered an early forerunner of the Insubric line with a similar kinematic function, but in a different location. While it accommodated the dextral EW strike-slip component, the post-80 Ma Austroalpine thrusts accomplished the NS shortening. An interesting position in this scenario is that of the probably Cretaceous Orobic thrusts in the northern part of the Lombardic Southern Alps (Laubscher 1985). This system shows dextral en échelon features which suggest a possible association with AAT.

– Elements of the Austroalpine nappes were rotated clockwise (dextrally) by about 90 degrees according to paleomagnetic data (Channell et al. 1990a). Such a rotation is also suggested by the fact that Jurassic-Early Cretaceous isofacies lines, and particularly the eastern border of ophiolitic sea floor, originally had been SN-oriented (Fig. 12) whereas Austroalpine and Piemontese thrusts are more nearly EW. Such rotations are often found associated with strike-slip faults, compare e.g. Channell et al. (1980), Channell et al. (1990b), Oldow et al. (1990) and Laj et al. (1982), although their detailed kinematics are a puzzle still to be solved.

– Such a rotation of that part of the Dinarides N of AAT, coupled with dextral translation, would produce an exotically looking Dinaric fragment in the Pannonian region, as indicated in Fig. 14. It would fit the Dinaric elements found in Hungary in the Transdanubian Central Range-Bükk Mountains belt (Kazmer & Kovacs 1989) although large additional displacements are required to explain their special position.

– The highly idealized NW corner of the Adriatic indenter would produce two entirely different types of Austroalpine nappes, one type along the northern edge as described above, and one at the western edge with distal continental margin characteristics (Canavese, lower Austroalpine, Bernoulli et al. 1991) rather than extensive and thick sediments. It has been noted above that there is a striking discrepancy between the Austroalpine nappes in the eastern Alps and those of the central and western Alps.

– As the Adriatic indenter moved to the NW it successively piled up more and more external nappes in its front. The flysch masses of the Piemont basin were sheared off and converted into decollement nappes shoved ahead of the Austroalpine nappes, with the youngest developing in westernmost portions of the Piemont basin. This is where the slightly if at all metamorphosed flysch and ophiolite nappes of the eastern Ligurian Alps may be thought to have had their origin in Eocene times. Those Liguride nappes east of the Varzi-Levanto line probably developed in a similar fashion but were reactivated in the Oligocene and thrust on the Toscanide foredeep.

Whereas the minimal 200 km NW translation of Adria in Fig. 14 is based on the retrodeformation model Fig. 12, the maximum 630 km NW translation of Adria in Fig. 15 is taken from Dewey et al. (1973). AAT in this model would be near the southern transfer margin of the Piemontese ocean, and in Fig. 15 it was placed exactly there in order to emphasize the possibility that this transfer zone may have been reactivated as AAT. I do not consider this probable, however. The convergence rate in Fig. 15 would be about three times the average of Fig. 12, whereas in Fig. 14 it would be close to average. I consequently prefer a scenario that is not too far from the minimum translation shown in Fig. 14.

An early Eocene link

In such a way – no more than a sketch is possible at this time – a link between the backward kinematics (retrotranslations) of Figs. 4–10, and the forward kinematics of Figs. 13 and 14 may be arrived at. It has some interesting features (compare Figs. 11 and 14):

– with continued SE-NW convergence the Austroalpine-Adria transfer fault (AAT) approaches the North Piemontese transfer fault (NPT) and finally merges with it. This is conceivably the time when rotation of the Briançonnais elements into the Arc of the Western Alps set in (Figs. 9, 10). The eastern part of the merged AAT and NPT at this stage constituted the northern edge of the Adria indenter. The idealized NW corner of Adria may now be positioned approximately at the vague domain where the eastern and central Alps join (Fig. 11), with a pronounced change in the character of the Austroalpine nappes, and a less pronounced change of the Penninic nappes. As noted above, this domain is characterized, furthermore, by a conspicuous extension of the nappe edifice that is typical for the divergence of motion at the corner of an indenter (compare, e.g., LAUBSCHER 1990a). The superimposed Oligocene extension was probably more widespread in the Alpine domain, and it was during this interval that the modern Insubric line was installed. Its position was a little farther south, and the NW corner domain of Adria now is found at the present "northern hinge of the Arc of the Western Alps" (LAUBSCHER & BERNOULLI 1982), in the area between the Lepontine dome and the Prealpes depression (Fig. 5) that is characterized by widespread Neogene extension (LAUBSCHER 1991).

Conclusion

In the 75 years since Argand's publication of the "Arc des Alpes Occidentales" the earth sciences have acquired a huge set of new data and new insights into the nature of deformations on all scales. His was the synthesis at a time when nappism was at its culmination, and his achievements are to be viewed in this context. At present, the starting point for a synthesis is quite different. Apart from plate tectonics and its reinterpretation of the concept of geosynclines as essentially ocean basins and margins, deep geophysical sounding, p-T-t developments and the corresponding rheologies, and particularly timing of events are essential new elements. Material balance considerations are most easily satisfied by following the motions of an idealized system of rigid blocks bounded by shearing planes. Based on these notions, a new attempt at synthesis may be made. However, although greatly increased, the sets of both data and rules for tectonic development are still insufficient for a unique model of the kinematics of the Western Alps. A modern kinematic synthesis is only achievable, as it was in Argand's times, by weighing the importance of the data and the plausibility of motions at each stage. Observational data and fundamental rules of kinematics still leave a wide margin of error. As is usually the case in the geosciences, models cannot be built on first principles but are a trial-and-error adventure whose usefulness is judged in hindsight by the apparent solution it brings to unsolved problems or controversial issues.

In this perspective, the modernized model of the kinematics of the Western Alps presented in this article is believed useful. The straightening out by the late (middle Miocene) Lombardic phase of such fundamental transfer faults as the Insubric Line and the Villalvernia-Varzi fault, which seem hopelessly kinked and unfit for their function as transfer faults, is a first success of the model. These straightened transfer faults then may be combined with the "Penninic Front" shearing surface and with the Helvetic nappes to perform the retrodeformation of the late Oligocene-early Miocene Insubric-Helvetic phase. Thereby older structures which had been torn apart by this phase, may be restored into a much simpler geometrical pattern, and this is a second success. Simultaneous consideration of Oligo-Miocene motions in the Apennines, coupled with collapse in the Balearic-Ligurian domain, explains more easily than before the main features of the Alps-Apennines link. This too may be seen as a success of the model. However, the farther back the retrodeformation is pursued, the more uncertain it becomes. Thus the Eocene phase contains some new thorny problems which can be dealt with only on the basis of the success of combined movements. These problems occur particularly at the hinges of the arc. In particular, the Ligurian Briançonnais is a recalcitrant entity for retrodeformation. If the Helvetic-Insubric motions which are so successful for the reconstitution of other elements are accepted, then the Ligurian Briançonnais turns out to lie outside, to the west of the Eocene arc of the Western Alps. However, this apparent embarrassment may be a blessing in disguise: it opens a new vista on the relations of the Pyrenees-Provence belt, the North Penninic (Niesen) cordillera, and the Western Alps sensu stricto, which before these retrodeformations are completely obscured. Whether this view is accepted or not, it offers new solutions to old and unsolved problems. At the northern hinge of the Eocene Western Alps another thorny problem reveals itself in a new light. The boundary zone of the Austroalpine nappes s.s. ("upper Austroalpine nappes" in Swiss terminology) and the "Austroalpine" units of the Western Alps (Sesia-Dent Blanche to Margna nappes) becomes the prime candidate for an Eocene (to probably late Cretaceous) forerunner of the Insubric line. Here, the model offers answers to two questions: What is the reason for this fundamental hiatus in the Alpine nappe edifice? How old is the Insubric line as a northern boundary of the Adriatic plate?

Retrodeformation of even more remote stages of Alpine development is hardly feasible without recourse to some plate tectonics data. Forward modeling from an assumed late Jurassic situation then leads in two generalized steps to the Eocene configuration arrived at before by retrodeformation. The incisive event between the two steps is the opening of the North Atlantic in the late Cretaceous which in all plate tectonics models abruptly changed the direction of convergence between Africa and Eurasia. Alpine kinematics favors the early model by Dewey et al. (1973), which postulates a change from essentially sinistral strike-slip to dextral transpression, over more recent models, which prefer near perpendicular convergence from the late Cretaceous on.

The model suggests that Jurassic-early Cretaceous fault zones were fundamental initial mechanical boundary conditions for the deformation of convergent stages in the Alps. In particular, the northern boundary of the Iberian block (Pyrenees-Provence) seems to have lined up with the North Piemontese transfer zone that bounded the Piemontese ocean in the north. In the perspective of the model, the triple junction Iberia-Eurasia-Piemont ocean developed into the Ligurian knot- a unit that is particularly hard to disentangle. However, this development was not straightforward as old shearing zones were inactivated and new ones developed. A particular role outside the actual Alpine nappes was played by the late Cretaceous to Eocene North Penninic (Niesen) Cordillera which, in the perspective of the model, joined the Pyrenees-Provence belt in the Ligurian knot.

Acknowledgements

I wish to thank Daniel Bernoulli for many years of fruitful collaboration in regional geology, particularly in the Alpine-Mediterranean belt.

REFERENCES

Andreatta, C. 1948: La «Linea di Peio» nel massiccio del Ortles e le sue miloniti. Acta geol. alpina 1, 1–63.

Andreatta, C. & Pirani, R. 1954: Analisi strutturale di rocce metamorfiche. VIII: compagini di parascisti di catazona (Val di Peio, gruppo del Ortles). Per. di Mineral. 23, 125–145.

Argand, E. 1916: Sur l'arc des Alpes Occidentales. Eclogae geol. Helv. 14, 145–191.

Bally, A.W., Burbi, L., Cooper, C. & Ghelardoni, R. 1986: Balanced sections and seismic reflection profiles across the Central Apennines. Mem. Soc. geol. ital. 35, 257–310.

Bayer, R., Cazes, M., Dal Piaz, G.V., Damotte, B., Elter, G., Gosso, G., Hirn, A., Lanza, R., Lombardo, B., Mugnier, J.-L., Nicolas, A., Nicolich, R., Polino, R., Roure, F., Sacchi, R., Scarascia, S., Tabacco, I., Tapponnier, P., Tardy, M., Taylor, M., Thouvenot, F., Torreilles, G. & Villien, A. 1987: Premiers résultats de la traversée des Alpes occidentales par sismique réflexion verticale (Programme ECORS-CROP). C.R. Acad. Sci. Paris, t. 305, Série II, 1461–1470.

Bearth, P. 1956: Geologische Beobachtungen im Grenzgebiet der lepontinischen und penninischen Alpen. Eclogae geol. Helv. 49, 279–290.

Biju-Duval, B., Dercourt, J. & Le Pichon, X. 1977: From the Tethys ocean to the Mediterranean seas: a plate tectonic model of the evolution of the western Alpine system. In: Int. Symposium Structural History of the Mediterranean Basins (Ed. by Biju-Duval, B. & Montadert, L.), 143–164. Editions Technip, Paris.

Boccaletti, M., Ciaranfi, N., Cosentino, D., Deiana, G., Gelati, R., Lentini, F., Massari, F., Moratti, G., Pescatore, T., Ricci Lucchi, F. & Tortorici, L. 1990: Palinspastic restoration and paleogeographic reconstruction of the peri-Tyrrhenian area during the Neogene. Paleogeography, Paleoclimatology, Paleoecology 77, 41–50.

Bürgi, A. & Klötzli, U. 1990: New data on the evolutionary history of the Ivrea zone (northern Italy). Ver. Schweiz. Petrol. Geol. Ing. 56/130, 49–70.

Castellarin, A., Eva, C., Giglia, G. & Vai, G.B. 1985: Analisi strutturale del fronte appenninico padano. G. Geol. 47, 47–76.

Channell, J.E.T. & Horvath, F. 1976: The African (Adriatic) promontory as a paleogeographical premise for Alpine orogeny and plate movements in the Carpatho-Balkan region. Tectonophysics 35, 71–101.

Channell, J.E.T., Catalano, R. & d'Argenio, B. 1980: Paleomagnetism and the deformation of the Mesozoic continental margin of Sicily. Tectonophysics 61, 391–407.

Channell, J.E.T., Oldow, J., Catalano, R. & d'Argenio, B. 1990a: Paleomagnetically determined rotations in the western Sicilian fold and thrust belt. Tectonics 9, 641–660.

Channell, J.E.T., Brandner, R., Spieler, A. & Smathers, N.P. 1990b: Mesozoic paleogeography of the Northern Calcareous Alps – evidence from paleomagnetism and facies analysis. Geology 18, 828–831.

Cornelius, H.-P. & Furlani-Cornelius, M. 1930: Die Insubrische Linie vom Tessin bis zum Tonalepass. Denkschr. Akad. Wiss. Wien math.-naturw. Kl. 102.

Dewey, J.F., Helman, M.L., Turco, E., Hutton, D.H.W. & Knott, S.D. 1989: Kinematics of the western Mediterranean. Geol. Soc. (London) Spec. Publ. 45, 265–283.

Dewey, J.F., Pitman, W.C., Ryan, W.B.F. & Bonin, J. 1973: Plate tectonics and the evolution of the Alpine system. Geol. Soc. Amer. Bull. 84, 3137–3184.

Elter, P. & Pertusati, P. 1973: Considerazioni sul limite Alpi-Appennino e sulle sue relazioni con l'arco delle Alpi occidentali. Mem. Soc. geol. ital. 12, 359–375.

Eugster, H. 1923: Geologie von Mittelbünden, III. Abteilung: Geologie der Ducangruppe (Gebirge zwischen Albula und Landwasser). Beitr. geol. Karte Schweiz N.F. 49.

Eugster, H. & Frei, F. 1927: Geologische Karte von Mittelbünden 1:25 000, Bergün. Geol. Spezialkarte 94F, Schweiz. Geol. Kommission.

Eugster, H. & Leupold, W. 1930: Geologische Karte von Mittelbünden 1:25 000, Landwasser. Geol. Spezialkarte 94D, Schweiz. geol. Kommission.

Faupl, P. & Tollmann, A. 1979: Die Rossfeldschichten: Ein Beispiel für die Sedimentation im Bereich einer tektonisch aktiven Tiefseerinne aus der kalkalpinen Unterkreide. Geol. Rdsch. 68, 93–120.

FERRAZZINI, B. & SCHULER, P. 1979: Eine Abwicklungskarte des Helvetikums zwischen Rhone und Reuss. Eclogae geol. Helv. 72, 439–453.

FISCHER, H. & VILLA, I.M. 1990: Erste K/Ar und 40Ar/39Ar-Hornblende-Mineralalter des Taveyannaz-Sandsteins. Schweiz. mineral. petrogr. Mitt. 70, 73–75.

FREI, W., HEITZMANN, P., LEHNER, P., MÜLLER, ST., OLIVIER, R., PFIFFNER, A., STECK, A. & VALASEK, P. 1989: Geotraverses across the Swiss Alps. Nature 340, 544–548.

FROITZHEIM, N. & EBERLI, G.P. 1990: Extensional detachment faulting in the evolution of a Tethys passive continental margin, Eastern Alps. Switzerland. Geol. Soc. Amer. Bull. 102, 1297–1308.

FUCHS, W. 1980: Die Molasse und ihr nicht helvetischer Vorlandanteil am Untergrund einschliesslich der Sedimente auf der Böhmischen Masse. In: Der geologische Aufbau Österreichs (Ed. by OBERHAUSER, R.). Springer-Verlag, Wien, 144–176.

GELATI, R. & GNACCOLINI, M. 1980: Significato dei corpi arenacei di conoide sottomarina (Oligocene – Miocene inferiore) nell'evoluzione tettonico-sedimentaria del Bacino terziario ligure-piemontese. Riv. ital. Paleont. Strat. 86, 167–186.

GIDON, M. 1979: Le rôle des étapes successives de déformation dans la tectonique alpine du massif du Pelvoux (Alpes occidentales). C.R. Acad. Sci. (Paris) (D); 288, 803–806.

GUELLEC, S., MUGNIER, J.L., TARDY, M. & ROURE, F. 1990: Neogene evolution of the Alpine foreland: a review from ECORS data and balanced cross sections. Mém. Soc. géol. France 168, 165–184.

HAMMER, W. 1902: Die kristallinen Alpen des Ultenthales. I. Das Gebirge südlich des Faltschauer. Jb. k.k. geol. Reichsanst. 52, 105–134.

HERZBERG, C., RICCIO, L. CHIESA, S., FORNONI, A., GATTO, G.O., GREGNANIN, A., PICCIRILLO, E.M. & SCOLARI, A. 1977: Petrogenetic evolution of a spinel-garnet-lherzolite in the Austridic crystalline basement from Val Clapa (Alto Adige, northeastern Italy). Mem. Ist. Geol. Mineral. Univ. Padova 30, 1–28.

HOMEWOOD, P. & CARON, C. 1982: Flysch of the Western Alps. In: Mountain Building processes (Ed. by HSÜ, K.H.), 157–168. Academic Press, London.

HURFORD, A.J. 1986: Cooling and uplift patterns in the Lepontine Alps South Central Switzerland and an age of vertical movement on the Insubric fault line. Contrib. Mineral. Petrol. 92, 413–427.

KAMINSKI, W. & MENZEL, H. 1968: Zur Deutung der Schwereanomalie des Ivrea-Körpers. Schweiz. mineral. petrogr. Mitt. 48, 255–260.

KAZMER, M. & KOVACS, S. 1989: Triassic and Jurassic oceanic/paraoceanic belts in the Carpatho-Pannonian region and its surroundings. In: Tectonic evolution of the Tethyan region (Ed. by ŞENGÖR, A.M.C.), NATO ASI, C, 259, 77–93.

KLIGFIELD, R., HUNZIKER, J., DALLMEYER, R.D. & SCHAMEL, ST. 1986: Dating of deformation phases using K-Ar and 40Ar/39Ar techniques: results from the Northern Apennines. J. struct. Geol. 8, 781–798.

KRÖLL, A. & WESSELY, G. 1967: Neue Erkenntnisse über Molasse, Flysch und Kalkalpen auf Grund der Ergebnisse der Bohrung Urmannsau 1. Erdöl-Erdgas-Z. 83, 442.

LAJ, C., JAMET, M., SOREL, D. & VALENTE, J.P. 1982: First paleomagnetic results from the Mio-Pliocene series of the Hellenic sedimentary arc. Tectonophysics 86, 45–68.

LAUBSCHER, H.P. 1971: The large-scale kinematics of the western Alps and the northern Apennines and its palinspastic implications Amer. J. Sc. 271, 193–226.

— 1980: Die Entstehung des Faltenjuras – Daten und Vorstellungen. N. Jb. Geol. Paläont. Abh. 160, 289–320.

— 1983a: Detachment, shear and compression in the Central Alps. Geol. Soc Amer. Mem. 158, 191–211.

— 1983b: The late Alpine (Periadriatic) instrusions and the Insubric Line. Mem. Soc. Geol. It. 26, 21–30.

— 1985: Large-scale, thin-skinned thrusting in the southern Alps: Kinematic models. Geol. Soc. Amer. Bull. 96, 710–718.

— 1988: Material balance in Alpine orogeny. Bull. geol. Soc. Amer. 100, 1313–1328.

— 1990a: The problem of the deep structure of the Southern Alps: 3-D material balance considerations and regional consequences. Tectonophysics 176, 103–121.

— 1990b: Seismic data and the deep structure of the central Alps. In: Proceedings of the Sixth Workshop on the European Geotraverse (EGT) Project: Data compilations and synoptic interpretation (Ed. by FREEMAN, R. & MUELLER, St.), 149–156. European Science Foundation, Strasbourg.

— 1990c: Deep seismic data from the central Alps: mass distributions and their kinematics. Soc. Géol. Suisse Mém. 1, 335–344.

— The Alps – a transpressive pile of peels. In: Thrust tectonics (Ed. by MCCLAY, K.). Unwin Hyman, London, in press.

LAUBSCHER, H.P. & BERNOULLI, D. 1982: History and Deformation of the Alps. In: Mountain Building processes (Ed. by HSÜ, K.H.), 169–180. Academic Press, London.

LE PICHON, X., BERGERAT, F. & ROULET, M.-J. 1988: Plate kinematics and tectonics leading to the Alpine belt formation; a new analysis. Geol. Soc. Amer., Spec. Pap. 218, 111–132.

MANCKTELOW, N. 1985: The Simplon Line: A major displacement zone in the western Lepontine Alps. Eclogae geol. Helv. 78, 73–96.

MERLE, O., COBBOLD, P.R. & SCHMID, S. 1989: Tertiary kinematics in the Lepontine dome. Geol. Soc. Spec. Publ. 45, 113–134.

MUELLER, St., ANSORGE, J., EGLOFF, R. & KISSLING, E., 1980: A crustal cross section along the Swiss Geotraverse from the Rhinegraben to the Po plain. Eclogae geol. Helv. 73, 463–483.

NIEVERGELT, T., LINIGER, M., FROITZHEIM, N. & FERREIRO-MAEHLMANN, R. 1991: The Turba mylonite zone: an Oligocene extensional fault at the Pennine-Austroalpine boundary in eastern Switzerland. Terra Abstracts 3, 248.

NIGGLI, E. 1946: Über den Zusammenhang der positiven Schwereanomalie am Südfuss der Westalpen und der Gesteinszone von Ivrea. Eclogae geol. Helv. 34, 211–220.

OBERHAUSER, R., (Ed.) 1980: Der geologische Aufbau Österreichs. Geologische Bundesanstalt, Springer-Verlag, Wien.

OLDOW, J., CHANNELL, J.E.T., CATALANO, R. & D'ARGENIO, B. 1990: Contemporaneous thrusting and large-scale rotations in the western Sicilian fold and thrust belt. Tectonics 9, 661–682.

PIERI, M. & GROPPI, G. 1981: Subsurface geological structure of the Po plain, Italy. Cons. Naz. Ric. Prog. finalizzato Geodin. 414, 1–13.

PITMAN, W.C. & TALWANI, M. 1972: Seafloor spreading in the North Atlantic. Geol. Soc. Amer. Bull. 83, 619–646.

PREY, S. 1980: Die Geologie Österreichs in ihrem heutigen geodynamischen Entwicklungsstand sowie die geologischen Bauteile und ihre Zusammenhänge. In: Der geologische Aufbau Österreichs (Ed. by OBERHAUSER, R.), 79–117. Geologische Bundesanstalt, Springer-Verlag, Wien.

REHAULT, J.P., MASCLE, J. & BOILLOT, G. 1986: Evolution géodynamique de la Méditerranée depuis l'Oligocène. Mem. Soc. geol. ital. 27, 85–96.

RICOU, L.E. & SIDDANS, A.W.B. 1986: Collision tectonics in the Western Alps. Geol. Soc. Spec. Pap. 19, 229–244.

SCHMID, S.M. & HAAS, R. 1989: Transition from near-surface thrusting to intrabasement décollement, Schlinig thrust, eastern Alps. Tectonics 8, 697–718.

STECK, A. 1984: Structures de déformations tertiaires dans les Alpes centrales (transversale Aar-Simplon-Ossola): Eclogae geol. Helv. 77, 55–100.

— 1987: Le massif du Simplon – Réflexions sur la cinématique des nappes de gneiss. Schweiz. mineral. petrogr. Mitt. 67, 27–45.

— 1990: Une carte des zones de cisaillement ductile des Alpes Centrales. Eclogae geol. Helv. 83, 603–627.

THÖNI, M. 1981: Degree and evolution of the Alpine metamorphism in the Austro-Alpine unit W of the Hohe Tauern in the light of K/Ar and Rb/Sr age determinations on micas. J. Geol. Bundesanst. 124, 111–174.

THÖNI, M. & HOINKES, G. 1987: The southern Ötztal basement: Geochronological and petrological consequences of Eoalpine metamorphic overprinting. In: Geodynamics of the Eastern Alps (Ed. by FLÜGEL, H.W. & FAUPL, P.), 200–213.

TOPERCZER, M. 1960: Lehrbuch der allgemeinen Geophysik. Springer-Verlag, Wien.

TRÜMPY, R. 1969: Die helvetischen Decken der Ostschweiz. Versuch einer palinspastischen Korrelation und Ansätze zu einer kinematischen Analyse. Eclogae geol. Helv. 62, 105–142.

— 1980: An Outline of the Geology of Switzerland. In: Geology of Switzerland: a guide-book. 1–110. Schweiz. Geol. Kommission (Ed.), Wepf & Co. Publ., Basel/New York.

VECCHIA, O. 1968: La zone Cuneo-Ivrea-Locarno, élément fondamental des Alpes. Géophysique et géologie: Schweiz. mineral. petrogr. Mitt. 48, 215–226.

WEISSERT, H. & BERNOULLI, D. 1985: A transform margin in the Mesozoic Tethys: evidence from the Swiss Alps. Geol. Rdsch. 74, 665–679.

ZINGG, A. & HUNZIKER, J.C. 1990: The age of movements along the Insubric Line west of Locarno (northern Italy and southern Switzerland). Eclogae geol. Helv. 83, 629–644.

ZINGG, A., HUNZIKER, J.C., FREY, M. & AHRENDT, H. 1976: Age and degree of metamorphism of the Canavese zone and of the sedimentary cover of the Sesia zone. Schweiz. mineral. petrogr. Mitt. 56, 361–375.

Manuscript received 25 April 1991
Revision accepted 27 June 1991