# A CONTINENT REVEALED

## The European Geotraverse

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subsequently warped by the updoming of the Aiguilles Rouges and Mont Blanc massifs during the northwest oriented late convergence.

In summary it follows that the Tertiary collision in itself represents a polyphase and complex interplay of crustal scale normal, thrust and strike-slip faulting which continues to the present. Recent crustal movements expressed by vertical uplift along the EGT transect reach a maximum value of 2 $mma^{-1}$ near Chur (in Figure 6-27, see also Chapter 5.3.3). In plan view this maximum extends along the basement uplifts of the external massifs (e.g. Aar massif, Figure 6-27). Does this mean that this recent uplift is at least partially triggered by presently continuing collision and associated decoupling of upper crust? The data on recent seismicity is not in conflict with this idea. We explore the possibilities further in Chapter 7.2.2.

## 6.5 THE FRAGMENTED ADRIATIC MICROPLATE: EVOLUTION OF THE SOUTHERN ALPS, THE PO PLAIN, AND THE NORTHERN APENNINES

P. Giese, D. Roeder, and P. Scandone

This section of the EGT extends from the topographic backbone of the Alps to the north tip of Corsica. It is only 430 km long, but it displays a spectacular architecture of plate interaction. The suture between Europe and the Adriatic microplate is crossed twice by this segment; once in the Alps with a deep subduction slab, and again in the Apennines with a Moho overlap at shallower depth. This EGT section contains the Adriatic microplate warped under subduction load and the thrust loads of the Alps and the Apennines. At its southern end, it contains the tip of the Ligurian rift which functioned during orogeny-related lithospheric extension, but had already evolved during the separation of Laurasia and Gondwana.

### 6.5.1 TECTONIC SETTING

The crustal silhouettes of the two opposed thrust fronts of the Alps and Apennines are strikingly different and demonstrate two orogenic regimes. Both orogens are in a post-collisional state, and they face each other head on.

The Alps are still largely in a compressional regime with thickening crust, but in the Central Alps, rising topography is already counteracted by the beginnings of extensional tectonics. Fold belts at the Alpine north front record the latest supracrustal trace of the Europe-vergent collisional suture which intersects the Moho a short distance north of the Alpine south front. The latter is a south-vergent backthrust antithetic (conjugate) to the collision suture. It breaks through the Alpine crust too far to the north to show a Moho overlap.

The Apennines are clearly in the extensional stage, with mid-crustal and deeper detachments, metamorphic core complexes, and with new oceanic crust being formed within the the main body of the orogen. Its north front shows a magnificent Adriatic-vergent Moho overlap in the footwall of the original collision suture. It is not older than Pliocene and is oriented synthetic (parallel) to the older suture. Seismicity and Neogene stratigraphy show that the north front of the Apennines is in active compression, as shown in Chapter 5.3.

The common foreland of the orogens is the Adriatic microplate. This cratonic terrane has been part of the field of transtension between Europe and Africa since the Jurassic, when Atlantic opening reactivated the east-facing Tethyan passive margin. Its cover of Mesozoic sediments is now deeply buried beneath Neogene clastic foredeep fill, shed from the rising Alps and Apennines, and its lithosphere is deflected into an antiformal ridge by the thrust loads and, mostly on the Apennine side, by subduction hinge retreat. Near the EGT section line, the northwest spur of the Adriatic microplate has been indenting the European crust since the late Eocene collision.

### *Southern Alps*

Three structural elements comprise the topographic south slope of the Alps. Furthest to the north, a belt of steeply dipping layers is composed of a stack of north-vergent basement nappes above the ophiolite-lined Penninic (Tethyan) collision suture. During Neogene backthrusting, this stack was tilted backward to form the steep zone. Near its southern edge, the steep zone is truncated along the Insubric line, which is a major terrane boundary with a complex history of dip slip and strike slip. Its kinematics and its considerable depth extent are recorded in mylonite fabrics and contrasting cooling histories. South of the Insubric line, a south-Alpine crustal block and its sediment cover contain south-vergent polyphase compression. Seismic data show that a detachment at a mid-crustal level merges with the Insubric line at 15–20 km depth. It transports the south-Alpine crustal body southwards over the load-warped Adriatic lithosphere, displacing the Po Valley basin fill, and forming a classical fold-thrust belt which involves upper crust, Tethyan-margin sediments, and foredeep fill. The south-Alpine fold-thrust belt is being tilted southwards by the Apennine subduction. Therefore, its northern, internal zones are being eroded while its southern front is buried beneath the braided, oxbowed, and swampy gravels of the Po River and its Alpine tributaries.

South Alpine thrusting includes Paleogene, Miocene, and Plio-Pleistocene spasms. Recent thrust tectonics is demonstrated in devastating earthquakes (1976 near Gemona in the Tagliamento valley and possibly 1348 near Villach in the Gail valley) for the extreme eastern part, but so far, the area of the EGT section appears quiet. Figure 6-27 shows the structural style in a representative cross section. A compressionally emplaced thrust sheet involves 10 km of pre-tectonised crust intruded by arc magma, 5–7 km of Mesozoic passive-margin sediments, and 3–7 km of Oligocene to Pleistocene foredeep fill. Its frontal part is a blind thrust within the Miocene section. Its foreland imbrications contain several of Italy's major oil and gas fields.

The south Alpine bulk-strain estimate, of about 100 km, is made from a mix of published data and speculation. It consists of 70 km of main-thrust overlap and 30 km of combined foreland and main-thrust imbrication. Unknown subsurface details may widen the range to between 80 and 150 km, but is still consistent with the EGT Moho data shown in Figure 3-13.

### *Po basin*

The crust of this double foredeep is known from numerous refraction seismic experiments, as indicated in Figure 6-28. Its supracrustal details are known by petroleum exploration. Elastic load flexural models of the basement top have been used to emulate the Moho at its shallowest depth of 28 km and at its antiformal flanks, deepening beneath both thrust fronts.

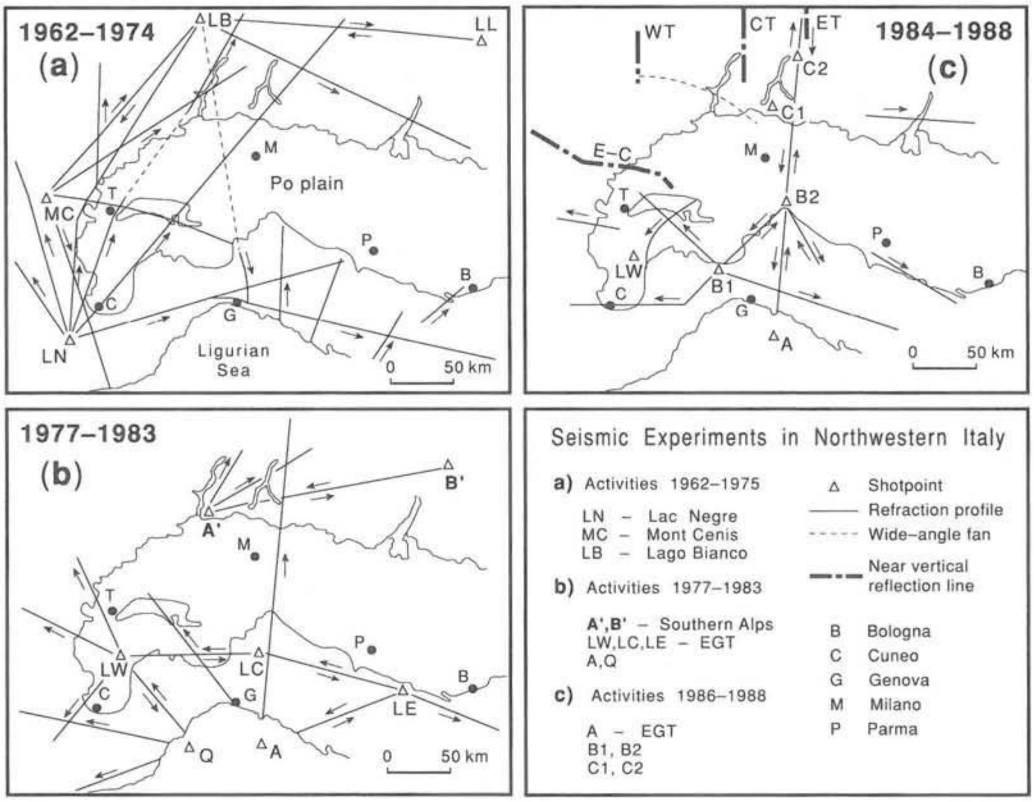

*Figure 6-28. Map of seismic experiments across the Southern Alps and northern Apennines.*

The sediment cover of the Adriatic crust is composed of the same elements as known from both fold-thrust belts. There, as well as in the Po basin, E–W extension of Jurassic age has generated rifts and has reduced the net crustal thickness to about 20 km.

The south slope of the Po basin contains an Apennine foothills fold belt forming three subsurface lobes or promontories (Pieri and Groppi 1981). These syndepositional folds are of Pliocene age, blind-thrusted and buried beneath undeformed cover sediments, and are displayed in superb detail on reflection seismic profiles.

### *Apennines*

Along the EGT section, the Apennine orogen is composed of four geodynamic units. Polyphase thrust imbrication during the Tertiary has assembled three pre-orogenic paleogeographic units, from top to bottom and from south to north:

(a) the Liguride ophiolites and associated marine sediments of Mesosoic age,

(b) the Tuscanides, a pre-Mesosoic basement with thin Mesozoic cover rocks derived from the stable edge of the Tethyan passive margin and fragmented off Pangea during the Jurassic,

(c) the central Adriatic microplate and its Mesozoic sediment cover.

The latter sequence is a northern correlative of the outcropping and strongly detached Umbrian series, but is known only from wells drilled into mildly detached structures (Pieri and Groppi 1981). The thrust imbrication of the northern Apennines also includes an Upper Cretaceous and Tertiary polyphase accretionary wedge. It covers the three lower units unconformably, it contains their erosional products, shows evidence of repeatedly cannibalizing perched basins, and is progressively involved in the thrusting and folding. In this polyphase flysch wedge, stratigraphy and sedimentology document the tectonic assemblage of the Apennine stack of thrust sheets (Giannini and Lazzarotto 1975, Bally *et al.* 1988, Patacca and Scandone 1989).

Flysche deposits date a NE-vergent collision or obduction of the oceanic Liguride units with the Tuscan part of the Adriatic plate as Oligocene. NE-vergent thrust stacking continued by successively piggybacking the stack. The present front of Apennine deformation involves Pliocene strata and meets the buried Alpine foothills front head-on near the Po river (Cassano *et al.* 1986). In at least one cross section (Pieri and Groppi 1981, section 6), the Alpine detached units are overridden by an Apennine thrust front.

### *Ligurian Sea*

In the Ligurian hinterland of the Apennines, polyphase extension has accompanied and superposed Apennine thrusting since the Oligocene. Offshore, the European continental crust is progressively thinned southward toward the oceanic crust of the Provençal basin. Its top shows articulation into several basins filled with Neogene sediments. The crustal profile of the EGT shows a complex rift zone with thinned crust and a field of magnetic bodies which can be traced southeastwards into the Tyrrhenian Sea. Onshore, the tectonics of this margin is beginning to be understood as synkinematic backarc spreading. Tortonian and younger extension is affecting at least the middle crust, and probably the entire lithosphere, of the Adriatic microplate. Deep detachments form antiformal viscous pillows or metamorphic core complexes in the Cordilleran sense. Carmignani and Kligfield (1990) describe the Alpi–Apuane as an example. The extended supracrustal material is the thrust belt itself. Compression and thrust overlap near the front and extension in the main orogenic body are contemporaneous. The domain boundary migrates outward and generates complex superpositions of compressional and extensional strain.

### *Corsica*

This relatively thick continental crust (Figure 3-15) with Variscan granites carries a cap of Alpine rocks emplaced westward during the Eocene collision. The cap documents it as a fragment of the European foreland, rotated anticlockwise away from a site adjacent to the coastal Provence (SE France) during the Oligocene and Lower Miocene.

## 6.5.2 GEOPHYSICAL CONSIDERATIONS

### *Bouguer gravity*

The Bouguer anomaly profile shown in Figure 6-29 (see EGT Atlas Map 9) portrays the lateral variations in crustal thickness interpreted in terms of a density model which has been constrained by the seismic data of Figure 3-12. A gravity low along the crest of the Alps is consistent with 50 km of composite crustal thickness. A gravity high follows the Southern Alps and fringes the curved west edge of the Po basin. It is the potential field expression of the celebrated Ivrea body whose sparse outcrops support the idea of a crustal slab exposed to near the base of the crust. The Apennine foredeep, its low-density fill, and its doubled crust are reflected in another of the deeper gravity minima of the EGT profile. The Ligurian coastal

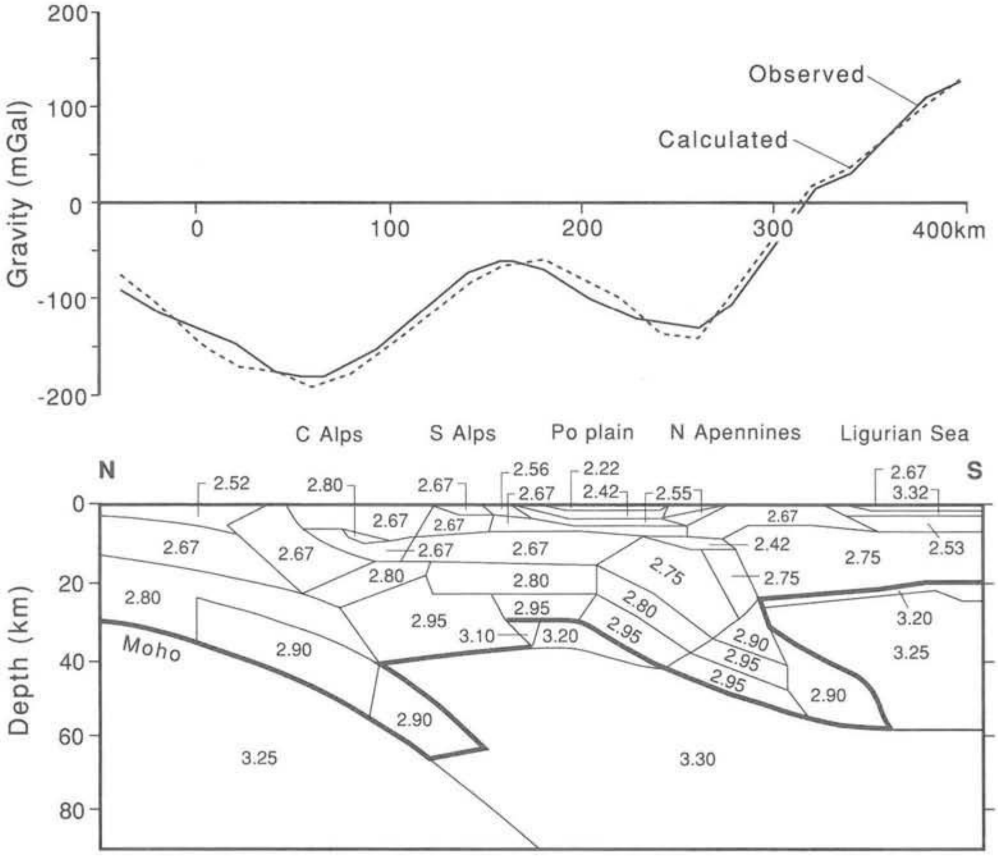

*Figure 6-29. Density model for the Alps to Ligurian Sea based on the seismic profile given in Figure 3-12, showing fit of calculated gravity to observed. Numbers show densities in $gcm^{-1}$.*

zones and their extensional structures are associated with intermediate gravity values grading into the oceanic gravity range of the Ligurian and Provençal seas. The continental block of Corsica and Sardina shows a zero level of Bouguer anomaly.

### *Seismic data*

About 6000 km of deep refraction seismic lines recorded since 1956 (Figure 6-28) provide a solid data base for modelling the lithosphere in the Po basin and its Alpine–Apennine frame. Following a number of experiments of both local and international scope, the EGT projects described in Chapter 3.2.3 included a composite N–S line from the Alpine north front to the coastal waters of Corsica, E–W lines in the Apennine region, and fans across the Po basin and the Southern Alps. Deep events recorded in many of these lines can be interpreted as coming from the Moho, and our accumulated wealth of Moho data shows the base of the crust in an unsuspected degree of complication, as illustrated in Figure 3-13.

### *Rheological stratification of the lithosphere*

The seismic data base of dipping and stacked Moho segments can be interpreted tectonically by applying to the lithosphere the model of a rheological stratification with a strong upper crust, a weak middle and lower crust, and a strong upper mantle, as suggested in Chapter 4.2 by the lithospheric composition and the geotherm (Meissner 1986). By analogy with supracrustal compressional tectonics (Suppe 1985 and many others), thrusts

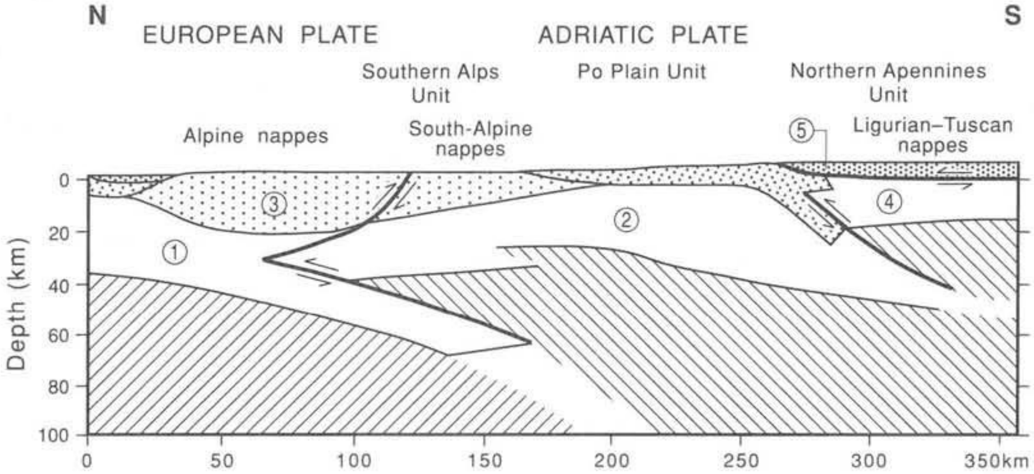

*Figure 6-30. Cross section along EGT from the Alps to the northern Apennines showing five separate plate units; 1: European unit, 2: Po Plain unit, 3: Alpine unit, 4: northern Apennines unit, 5: sub-Monferrato unit.*

cutting the stratified lithosphere can be expected to show ramped segments in the strong layers and flat detachments in the weak layers.

Intracrustal thrusts cannot generally be seen on seismic data. However, for ramped thrusts within a stratified lithosphere, the finite cutoff angle should be much lower than the expected Coulomb shear angle. Figure 6-30 shows that in 25 km thick stratified crust, we can expect thrust fronts at the basement top to be located up to 150–200 km ahead of the Moho break, instead of 60–80 km as predicted for homogeneous crust.

### 6.5.3 STACKED SLABS OF LITHOSPHERE

The discussion of Alpine lithospheric imbrication started when seismic studies suggested that the Ivrea zone contains mantle thrust over the European crust (Giese 1968). During the following decade, the discussion became organised in plate-tectonic terms of Benioff (B-type) subduction and quickly dominated the field of geodynamics (Dewey *et al.* 1973). However, the complexity of slabs twisted and stacked in three dimensions is not predicted by the classical plate tectonic model. Its full understanding required a new theory (Pavoni 1961, Tapponnier 1977) and another decade of seismic surveys. The Moho data from scores of seismic surveys were patiently mapped, correlated, and interpreted in several incremental syntheses (e.g. Giese *et al.* 1982). At present, and based on much unpublished work, we can recognise five crustal and lithospheric units and their tectonic interaction. For several of them, we can map the configuration of the Moho (Figure 3-13). For all of them, we can also describe the configuration at the top of the crust. From the bottom up, the stack includes (1) the European unit, (2) the Po Plain unit, (3) the Alpine unit, (4) the northern Apennines unit and (5) the sub-Monferrato unit. Figure 6-30 schematically locates these units relative to each other and relative to the geography. Some degree of paleogeographic and plate tectonic coherence is suggested for the Adriatic microplate since the Jurassic opening of the Atlantic. However, the Alpine collision and indentation since the late Eocene fragmented the Adriatic microplate into separate units (2), (3), (4), and (5).

### *European unit*

This unit, shown as (1) in Figure 6-30, is the foreland and lower plate of the Tethyan and Alpine collision suture. The present southern edge of its Moho, seismically documented beneath the Po Valley, is the limit of observation at a depth of more than 70 km. Its Moho structure is dominated by a nearly circular depression below the west-Alpine arc, clearly related to the overlap on the Alpine subduction suture, closely reflecting the elastic end-load configuration, and thus of Alpine age. Eastwards it extends into an elastic line-load depression shoaling toward the Pannonian basin. Along the Ligurian coast and in the EGT section, the southward rising Moho reflects thinning at an extensional margin.

### *Po Plain unit*

This unit, shown as (3) in Figure 6-30, forms part of the upper plate of the Alpine subduction, but it is fringed by crustal complexities and additional subductions. The southwest and northeast flanks of the Po Plain unit are downwarped and form lower plates of Neogene subduction zones beneath the Apennines and the Dinarides–Hellenides (Moretti and Royden 1988). The crestal line of this double downwarp, not everywhere documented by Moho data, extends from Milano along the Adriatic median high and ends with the south cape of Apulia at the heel of the boot of Italy, where present deep water and thick sediments suggest oceanic crust of Mesozoic age.

Moho stacking in the Po Valley–Ligurian area suggests a subduction-related overlap of at least 100 km beneath the northern Apennines. This overlap may continue northwestward into the Piemont area, but a decrease to zero overlap near the trace of the EGT has also been suggested (Moretti and Royden 1988). Subduction beneath the Dinarides is not yet supported by data on Moho stacking. However, both the Apennine subduction and the Dinaride subduction can be traced southeastwards into seismically active Benioff zones below the Tyrrhenian sea and the Aegean sea.

Mesozoic sedimentary facies belts in the Dinarides and the Apennines suggest that both of these overlaps are located within continental crust. However, the overlaps may also have developed at the sites of Mesozoic failed rifts with thinned or even oceanic crust within the Adriatic microplate.

### *Alpine unit*

Shown as (2) in Figure 6-30, this unit includes the crustal core of the Alps assembled from the original north front of the Po Plain unit or the Adriatic microplate, but it also incorporates substantial parts of the European crust. Its base is defined by shears rather than outlined by Moho segments. Its conceptual definition is largely based on the geological interpretation of Alpine basement complexes, as expressed in the previous section, 6.4, but seismic data clearly outline its shape.

Along the EGT profile, the present base of the Alpine unit is outlined by the south-Alpine backthrust and the Insubric line, and by a segment of the collision suture in its late-Alpine position. Under the Alpine body proper, the base is not particularly visible, but ambiguous seismic data still allow interpretation, including detachments at the base of the Aar massif and below internal foreland units. If geologically real, these elements collectively form an active detachment which is absorbing the present trans-Alpine convergence. It is broadly synclinal in shape and 23–30 km deep. Surface geology would suggest that this detachment cuts discordantly through an assemblage of crustal units, suture segments, and sediments. At its southern tip beneath the Piemont area, the Alpine unit may or may not continue into the Apennines.

### *Northern Apennines unit*

This unit constitutes the crustal underpinning of the Apennine orogen as a mappable area with coherent Moho events. It is distributed between the Apennine crest and the Ligurian coast, with a nearly flat Moho at about 24 km depth. From its leading edge below the Apennine crest, the sub-Moho wedge of material with mantle velocities thickens to about 18 km at the coastline. The upper crust and sediment cover of this segment contain stacked thrust sheets and are affected by late Miocene and younger crustal extension. The supracrustal northward extension of the Moho overlap displays the north-vergent architecture of subsurface thrust lobes and folds explored for oil and gas (Pieri and Groppi 1981). The structural assemblage produced during the supracrustal thrust succession and the Moho stacking suggests that all thrust imbrications on top of the northern Apennines unit are older than the documented Moho overlap and must have been powered by lithospheric thrusts further south or west. It also suggests that the documented Moho overlap is dated by the subsurface foothills folds as Pliocene.

### *Sub-Monferrato unit*

This lithospheric slab is similar to the northern Apennine unit, and both may either be coherent or separated by a fault contact of unknown structure. The Moho of the sub-Monferrato unit is documented along a line of dip of at least 50 km extent, at a depth between 20 and 32 km. Its surface expression is the Monferrato complex of deformed Neogene accretionary wedge. Its thrust emplacement is recent enough to deviate the Po River northward by about 15 km. The sub-Monferrato unit describes an Apenninic crustal slab, presumably emplaced upon European crust during the Pliocene and Pleistocene. Its relationship to the Alps of Piemont immediately to the west is not understood. Apparently the sub-Monferrato unit is separated from the Piemont Alps by a N–S striking fault mapped at the surface as the Sestri–Voltaggio line.

### 6.5.4 PLATE PATHS, OROGENIES AND LITHOSPHERIC MASS BALANCE

To gain insight into the dynamics of the lithosphere, we are restoring structural cross sections to the depositional state of their sediment cover. In the central Mediterranean area, three problematic topics can be approached by using restorations. First, why are the overthrust vectors of the Neogene orogenic belts not all parallel to the independently obtained direction of convergence between Europe and Africa? Smith (1971) has shown that the documented pattern of intra-Mediterranean small-plate motions cannot be resolved by Eulerian vector addition, a fundamental assumption of the plate tectonic theory. Instead they form a self-contained system. This topic is part of a newly emerging geodynamic model to be discussed in Chapter 7.2.

Secondly, why is the amount of Neogene convergence between Europe and Africa, measured across the Alps as the predominant site of indentation, two or three times greater than the documented and dated Alpine bulk strain? A partly satisfactory answer is that the

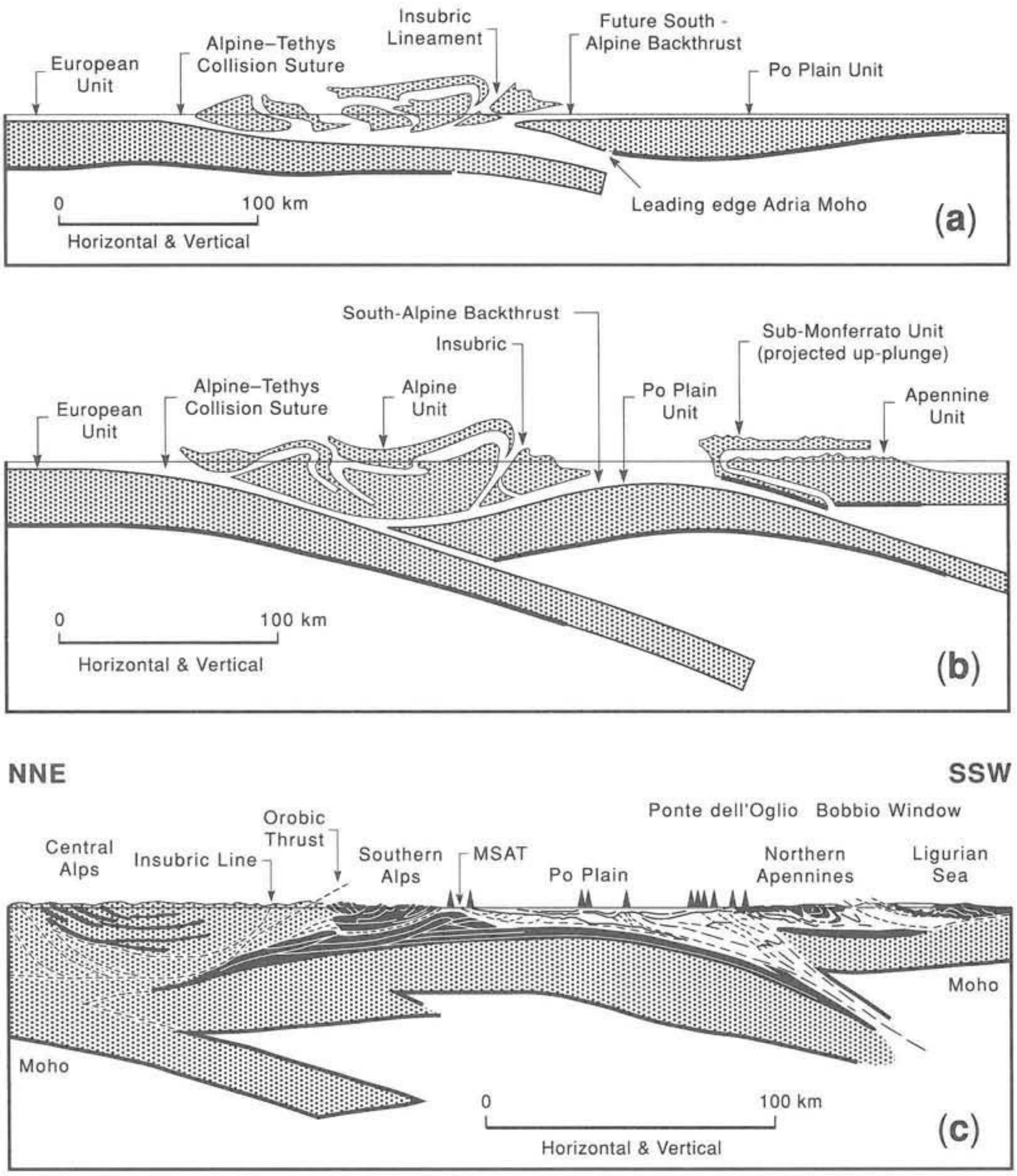

*Figure 6-31. Schematic cross sections to illustrate the evolution of the Adratic microplate in relation to the Alps. (a) pre-collision stage, (b) collisional stage, (c) present day.*

Adriatic microplate, serving as one jaw of the vice of Alpine convergence, is performing non-Eulerian movements independently of Africa. As another partial answer, the Alpine convergence mismatch suggests that there have been unrecognised oceanic basins contained in the convergence path. These basins have been subducted without geophysical or petrological trace.

Thirdly, where is the disposal site of the lithospheric surplus generated when trans-Alpine convergence is applied to normally thick, thermally defined lithosphere? This problem can be partially solved since seismic Moho mapping has confirmed an asymmetric model of subduction. Thermally defined lithosphere in the lower (European) plate of the Alpine subduction can be eliminated by thermal assimilation dependent on the thermal constants, its thickness, and the convergence rate (Oxburgh and Turcotte 1970) although this may not be sufficient. More likely, lower lithosphere becomes detached and sinks, as explained in Chapter 7. As is shown schematically in Figure 6-31, the base of the upper (Adriatic) plate is a northward and westward rising tectonic surface cutting successively through mantle, crust, and sediment cover. The upper mantle in the upper plate is affected neither by the Alpine subduction nor by the associated compression and backthrusting, because the south-Alpine backthrust merges with, and intersects, the base of the upper plate north of, and above, the leading edge of the (Adriatic) Moho. Therefore, no upper mantle is participating in the south-Alpine convergence. Figure 6-31a shows a restoration, in cross section, of the Adriatic microplate to pre-collisional state after deposition of its cover sediments. To make this restoration, we have assumed that the convergence acted in the plane of section, and we have used the abundant data on supracrustal tectonics (Castellarin *et al.* 1985, Cassano *et al.* 1986, Bally *et al.* 1988, Roeder 1989a). We have matched this restoration against the available seismic and depth converted Moho data. The match between both types of palinspastic data is imperfect, but it does support the tectonic interpretation of stacked Moho segments. In the Apennines, crustal data are strongly affected by insufficiently charted extension, but the base of the crust does show significant tectonic overlap. In the Alps, crustal compression is better understood, but the original base of the crust is incomplete. The regular wedge shape of the north Alpine crustal front suggests that it originated in Mesozoic time as an extensional detachment, although it became modified during a long history of convergence between Europe and the Adriatic microplate, subduction, wedge compression, and mechanisms of blueschist re-emergence.

## 6.6 SARDINIA CHANNEL AND ATLAS IN TUNISIA: EXTENSION AND COMPRESSION

D. Roeder

At its southern end, the EGT intersects for a third time the Neogene plate boundary between Europe and Africa. A composite fold-thrust belt with detached foothill folds and with docked exotic fragments of the Penninic accretionary wedge overlies a crustal wedge which resembles a passive extensional margin. Although there is neither trench nor Benioff zone nor magmatic arc, this convergent margin is consistent with the Mediterranean orogen model if we appreciate that major parts are not intersected by the EGT profile, and if we make allowance for some shortcomings in our documentation.

Figures 3-19 and 4-19 reveal little evidence of a N-dipping slab of seimic high-velocity lithosphere beneath Tunisia and the Sardinia Channel which could represent a subduction zone. Yet parallel sections of seismic tomography both east and west of the EGT transect (Spakman 1986, 1990a) show such a feature clearly. There is the suggestion in Figure 3-19 of a N-dipping high-velocity slab at greater depth that has become detached from the lithosphere above. Figure 6-32 shows in more detail the P-wave velocity variations in this section of the EGT taken from an earlier model by Spakman (1986). It indicates that asthenosphere or very thin lithosphere may be in contact with the Moho of the Atlasian foreland or Sahara platform. It shows that the possible break between surface lithosphere and the detached, sinking slab is very shallow, perhaps less than 150 km depth. This leads to the intriguing conclusion that the downgoing slab may not be Alpine in age but possibly Variscan or Caledonian. The Atlasian system must have the Mediterranean type of architecture with spreading just behind the thrust front.