Lithospheric wedging in the western Alps inferred from the ECORS-CROP traverse

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ABSTRACT

The ECORS-CROP traverse integrates vertical and wide-angle seismic-reflection, gravity, and magnetic studies along a 190 km profile across the western Alps. The combination of geophysical and geologic data constrains the deep structure along the traverse. Although alternative models are not excluded, the model that best fits the data of crustal accretion implies that, after the consumption of the Piemontese ocean, continental collision proceeded by lithospheric wedging of the subducting European continental foreland. In the Internal zones, further shortening may have been achieved by an unknown amount of penetrative deformation and by back thrusting.

INTRODUCTION

Although geologically the Alps are the most intensively studied mountain chain in the world, their deep structure and collisional history are still poorly understood. Geophysical investigations in the 1960s showed that the Moho deepens below the chain and abruptly shallows in the Ivrea body (Berckhemer, 1968). A geophysical traverse across the entire belt, mainly based on vertical seismic-reflection profiling, was conducted between 1985 and 1987. The joint French-Italian 190-km-long ECORS-CROP profile (Figs. 1 and 2) is the eastern part of a 350-km-long traverse that extends from the stable European foreland to the tilted hinterland of the south Alpine microplate. The profile intersects at high angles the main Alpine structures and the Bouguer anomaly and magnetic isolines (Bayer et al., 1989) in a domain where they are relatively cylindrical (Fig. 1), thus allowing a two-dimensional geometrical analysis. These structures have been induced by west-northwest-directed thrusting (Choukroune et al., 1986); thus, the ECORS-CROP profile is parallel to the mean west-northwest transport direction.

The geophysical traverse consists of a vertical seismic-reflection profile, a gravity survey centered on the seismic line, an aeromagnetic profile flown at 4000 m, and a wide-angle reflection study conducted to obtain a cross section of the crust-mantle interface in the vicinity of the vertical seismic-reflection line. Some of the results of these experiments have been published (Bayer et al., 1987, 1989; ECORS-CROP Deep Seismic Sounding Group, 1989; Hirn et al., 1989; Rey et al., 1990); the remainder will be published in a special volume of the French, Italian, and Swiss geological societies. Herein we summarize these results and present a model that implies lithospheric wedging during collision.

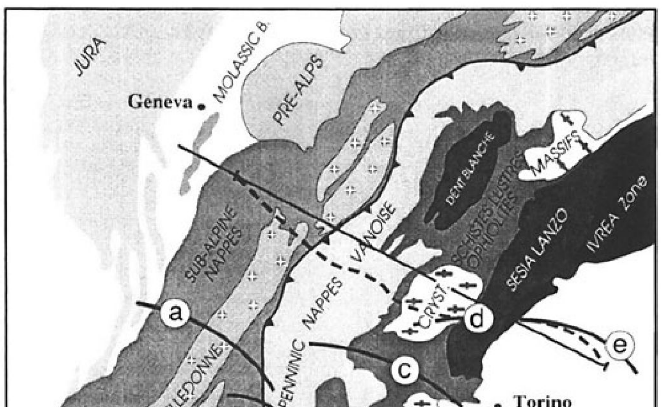

Figure 1. Location of ECORS-CROP traverse (dashed line) through western Alps. *a–e*: Curved segments represent fans of midpoints of wide-angle reflection experiment; straight continuous line is projection of gravity cross section shown in Figure 4.

REGIONAL GEOLOGY AND EVOLUTION OF THE WESTERN ALPS

The cross section in Figure 2 illustrates the three main paleogeographic domains crossed by the profile. They are described from northwest to southeast.

1. Foreland of the paleo-European margin. To the west, the basement of the foreland is concealed by Mesozoic and Cenozoic sedimentary formations of the Jura, Molassic basin, and Subalpine nappes. It emerges in the external crystalline massifs (Belledonne massif) and farther east in the internal crystalline massifs (Gran Paradiso). Between the external and internal massifs, the Vanoise is a Paleozoic metamorphic synform. The Gran Paradiso and Vanoise internal basement units have been overthrust by the Piemont ophiolitic nappes, which have an internal origin.

2. Schistes Lustrés nappe and ophiolite suture—remnants of the Piemontese ocean (incorporated into the Penninic nappes).

3. Promontory of the south Alpine (also called Austro-Alpine or Apulian) continental plate, whose Moho and lower crust have been tilted upward and crop out in the Ivrea zone. The plate dips southeastward below the Po Plain sediments.

The European and south Alpine passive margins were stretched and separated at 200 Ma by a rift that evolved (ca. 165 Ma) into the Piemontese ocean (Lemoine and Trumpy, 1987). Reversal from extension to convergence at 130 Ma during the Cretaceous resulted in oceanic subduction below the south Alpine plate and possibly crustal imbrication within this plate (Gillet et al., 1986). The ocean was completely consumed at 110 Ma, and there was continent-continent collision. The edge of the European margin was then subducted beneath the south Alpine plate

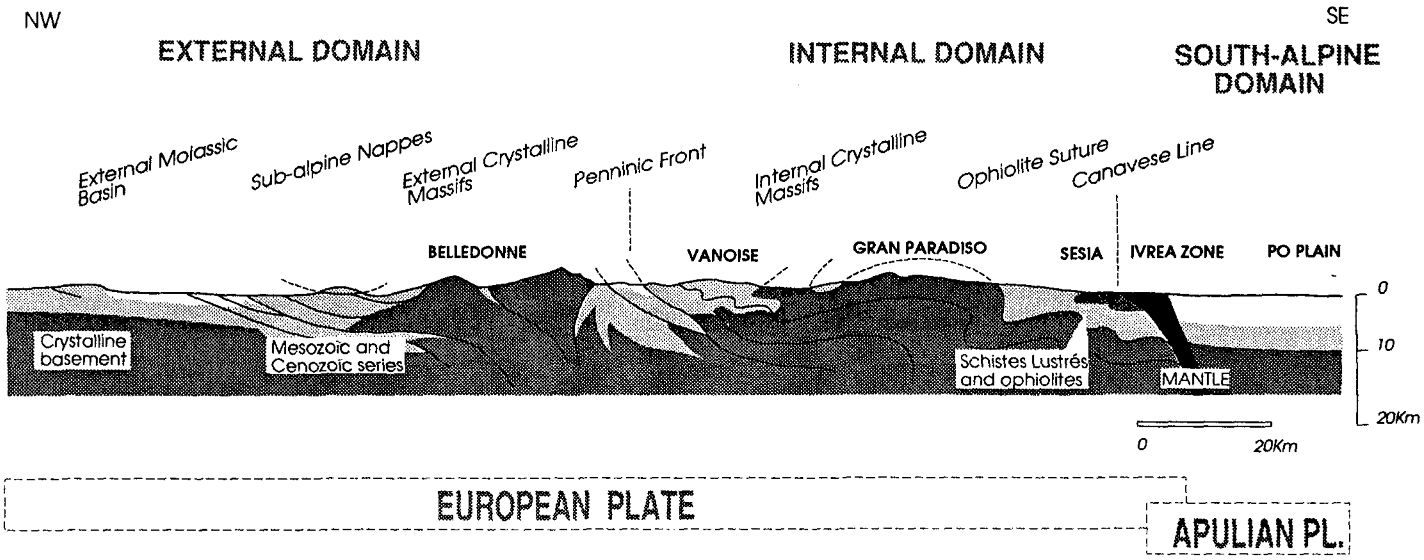

Figure 2. Simplified geologic cross section along ECORS-CROP geophysical traverse (after P. Vialon, *in* ECORS-CROP, 1986).

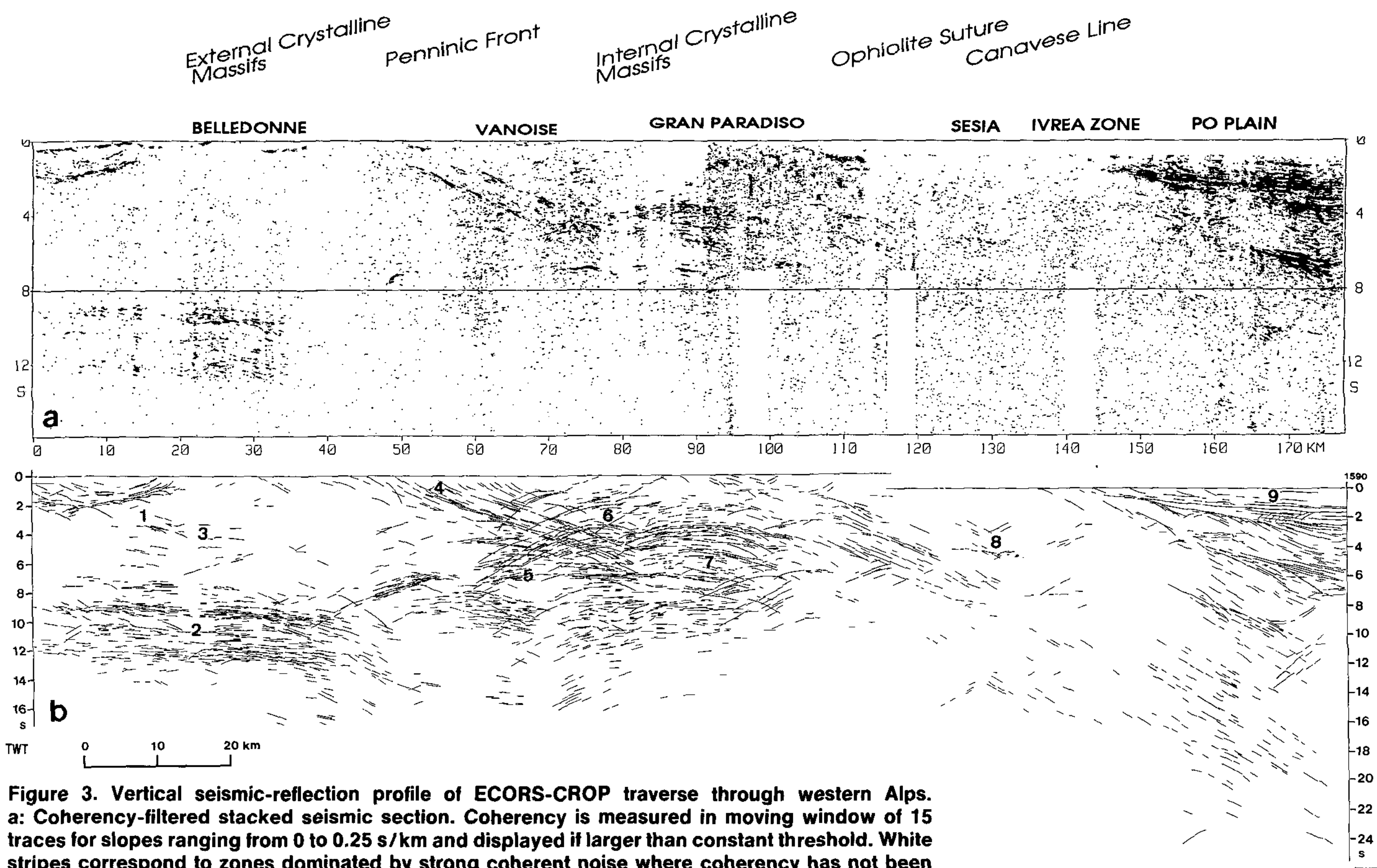

Figure 3. Vertical seismic-reflection profile of ECORS-CROP traverse through western Alps. a: Coherency-filtered stacked seismic section. Coherency is measured in moving window of 15 traces for slopes ranging from 0 to 0.25 s/km and displayed if larger than constant threshold. White stripes correspond to zones dominated by strong coherent noise where coherency has not been displayed (Marthelot, 1990). b: Line drawing of most prominent reflectors (Damotte et al., 1990). See text for explanation of numbered reflectors.

to depths of 90 km, as indicated by the eclogitic metamorphism in the internal massifs (3 GPa; Chopin, 1984). During the next 100 m.y., thrusts migrated westward, rupturing the external crystalline massifs during Oligocene time (40–20 Ma) and eventually reaching the most external zones during Neogene time, generating the Jura belt.

VERTICAL SEISMIC REFLECTION PROFILE

The vertical seismic-reflection profiling was done with combined vibrators and dynamite shooting, described technically in Bayer et al. (1987). Because it preserves most of the stack information and can be published at a reduced scale, a coherency-filtered stack is presented (Fig. 3A), together with an unmigrated line drawing (Fig. 3B). A depth-migrated version of this line drawing is shown in Figure 4. Detailed descriptions of these line drawings and their relation to geologic markers (Nicolas et al., 1990) are not presented here; we emphasize a few general observations.

1. Most reflectors have a moderate dip toward the east. Three main domains (1, 5, and 6 in Fig. 3B) dip westward. The high-energy reflectors (1) dipping to the northwest beneath the sub-Alpine nappes mark the basement on which the sedimentary cover of the Belledonne massif slid westward.

2. A clearly layered lower crust (2 in Fig. 3B) is nearly continuous in the western extremity of the profile and beyond (Bergerat et al., 1990). It deepens eastward before disappearing below the Penninic front. The base of this layered section seems to coincide with a wide-angle seismic reflector (I in Fig. 4) interpreted as the Moho below the crust of the European foreland (Hirn et al., 1989).

3. The ophiolite suture and the Ivrea zones are transparent with the exception of a flat reflector (8, Fig. 3B) that coincides with a wide-angle seismic reflector (III in Fig. 4), representing the top of the mantle. The virtual absence of reflectors above reflector 8 may be explained by the steep dip of structures in the ophiolite suture and the Ivrea zone. The same applies to the Belledonne massif and its median high-angle thrust (Fig. 2). In contrast, the Penninic front (4 in Fig. 3B) is marked by two high-energy reflectors, which on the migrated section (Fig. 4) flatten at depth and merge into a highly reflective zone (7, Fig. 3B).

4. The east-dipping reflectors (9, Fig. 3B) are ascribed to the Miocene-Pliocene infilling of the Po Plain.

WIDE-ANGLE SEISMIC REFLECTION, GRAVITY, AND MAGNETIC MODELING

The fan shooting of the wide-angle seismic reflection experiment was described by Hirn et al. (1989). Midpoints used to construct the profile are shown in Figure 1. The a, b, c, and d wide-angle reflectors have been projected onto the vertical seismic reflection profile (white lines in Fig. 4) from as far away as 50 km (for fan b). Surface geology and the Bouguer gravity map (Rey et al., 1990) suggest that, in this part of the Alpine belt, the deep structures can be reasonably extended along strike, a necessary assumption to project the wide-angle data to the plane of Figure 4. Seismic modeling of the wide-angle reflectors implies a *P*-wave velocity discontinuity of 1 km/s or more (Thouvenot et al., 1990). Also because these deeper reflectors grossly follow the crust-mantle interface determined by the 1960s seismic-refraction experiments (Berckhemer, 1968), they have been ascribed to this interface (Hirn et al., 1989). Reflector II (Fig. 4) is, however, discussed further below.

New gravity measurements (more than 0.1 stations/km^2), yield a new Bouguer anomaly map and profile along the traverse (Bayer et al., 1989). Several gravity models have been tested, taking into account the wide-angle and vertical seismic reflection data. In the model of Figure 4, it is assumed that Alpine metamorphism has fully reequilibrated the lower crust of the deepened European foreland to a uniform granulite density (2900 kg/m^3). The question of eclogites is discussed below. *The presence of a heavy slab is necessary above the subducted European foreland in all models tested.* These models are also sensitive to the total extension of the European crustal slab below the Internal Alps, which is estimated at 80 ±15 km (Bayer et al., 1989).

An aeromagnetic map, based on French and Italian surveys of the western Alps (Rey et al., 1990), covers the region of the profile and shows negative anomalies in the external domains and positive ones in the Ivrea zone. On the basis of magnetization measurements made in lower-crust rocks from the Ivrea zone, and assuming that the Curie isotherm is a surface uniformly located at 26 km depth, the magnetic anomalies can be explained by the geometry of the lower crust shown in Figure 4.

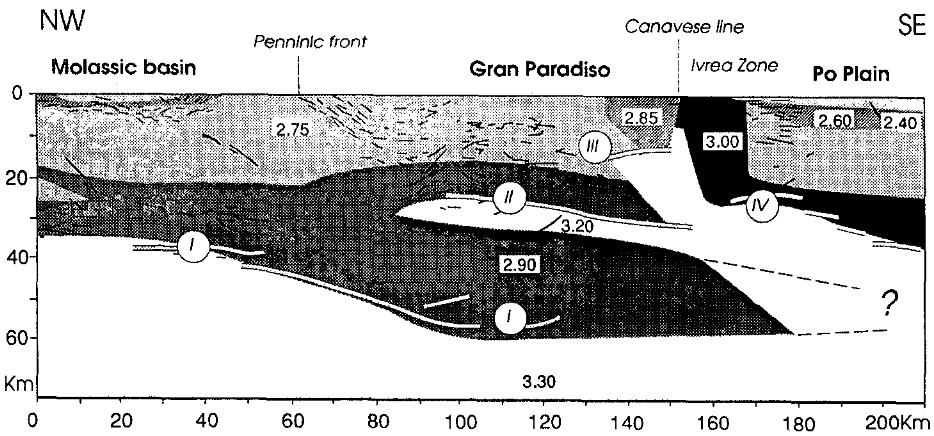

Figure 4. Gravity model along straight line in Figure 1 fitting Bouguer anomaly profile and based on densities (numbers in white boxes) superimposed on gravity profile. Thin black lines are depth-migrated line drawing (Guellec et al., 1990), and white lines are wide-angle P wave reflectors (Hirn et al., 1989). Possible eclogitic tail of deep European crust below Po Plain is shown (dashed lines and question mark; modified from Bayer et al., 1989).

DISCUSSION

The model shown in Figure 4 gives the favored gravity interpretation and the main seismic reflectors used for its elaboration. This is a good starting point for discussion of models of the western Alps.

Problem of Eclogized Deep Crust

Mafic eclogites cannot be distinguished from periodotites by gravity (same density) and conventional seismology (same compressional velocity). The question of eclogite occurrence arises mainly about the nature of reflector II (Fig. 4) and about the possible eastward extension below the Po Plain of the deep slab of European crust (Butler, 1986), an issue which is discussed elsewhere (Nicolas et al., 1990).

Reflector II is a crust-mantle or a granulite-eclogite interface. The granulite-eclogite transition from felsic to mafic granulites is spread over more than 10 km (Ringwood, 1975); therefore, in a supposedly felsic-mafic layered crust, as suggested by the nature of the Ivrea body deep sections, this transition would not be sharp enough to generate a wide-angle seismic reflection signal. Unless the contact is tectonic or the rocks are monotonously mafic, making a sharper transition possible, the interface should be the Moho reflector.

Cross-Section Balancing

The amount of shortening in this part of the western Alps, estimated from paleogeographic reconstructions, may range from 130 (Laubscher, 1988) to 385 km (Butler, 1986). Shortening in the internal zones is not constrained. Cross sections that can be balanced only west of the

Penninic front yield 40 to 50 km of shortening (Mugnier et al., 1990). This 40 to 50 km estimate should be compared with the 80 ±15 km of underthrust European crust measured in Figure 4, which is a minimum value if eclogized crust extends farther toward the east. The discrepancy between the two sets of data suggests that the main underthrusting surface for the European slab emerges east of the balanced section and might correspond to the Penninic front itself.

Early Collision Models

Many evolutionary models can fit the results of the geophysical data (Fig. 4). Mechanically, these models all derive from a limited number of starting situations, once subduction has caused continental collision. These situations depend on the level of the main decoupling within the subducting lithosphere. If the decoupling level is within the mantle, at the mantle-crust interface, or above, the collision will lead to the accretionary wedging of slabs involving either the lithosphere (Fig. 5C) or the crust (Fig. 5B). After the initial wedge formation, further thrusting is controlled by local and temporary situations of mechanical weakness, using preexisting decoupling levels or creating new ones. In keeping with this analysis, the most striking feature of Figure 5 is the presumed occurrence of a mantle wedge within the thickened crust of the internal domain, indicating that the primary decoupling level was located within the mantle, thus involving lithospheric accretion.

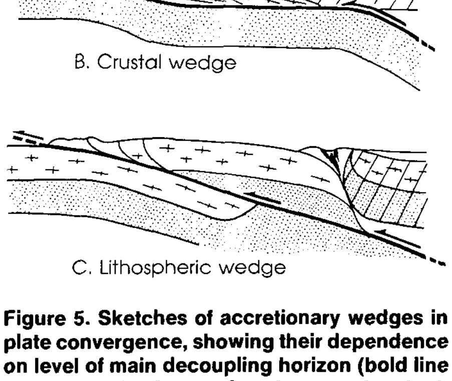

Figure 5. Sketches of accretionary wedges in plate convergence, showing their dependence on level of main decoupling horizon (bold line with arrows). Upper plate is cross-hatched. A: Sedimentary accretion in oceanic subduction zone. B: Continental-crust accretion in collision belt (inspired from Mattauer's [1986] interpretation of Himalayas). C: Lithospheric accretion in collision belt (this study).

Lithospheric Accretionary Wedging

The lithospheric wedging occurred after subduction of the Piemontese ocean and collision between the facing continental plates, which is responsible for upward tilt of the Moho of the south Alpine plate promontory (Fig. 5C). In this model, the foreland of the European plate has been sliced by a major lithospheric thrust rooting eastward and doubling the lithosphere below the internal Alps. The lithospheric rupture within the European plate was possibly facilitated by the existence of the Valaisan trough, interpreted as a narrow oceanic rift parallel to the Piemontese basin (Lemoine and Trumpy, 1987); in this case, the main thrust should emerge on the site of this former trough—i.e., in the vicinity of the Penninic front. Splays of this thrust could also merge toward the west, within and at the base of the Belledonne massif, allowing for the cover shortening recorded in the Subalpine nappes and for the Jura decollement. In this evolutionary model, the role of back thrusts is underplayed (Roure et al., 1990).

REFERENCES CITED

Bayer, R., and 22 others, 1987, Premiers résultats de la traversée des Alpes occidentales par sismique réflexion verticale (Programme ECORS-CROP): Paris, Académie des Sciences Comptes Rendus, v. 305, p. 1461–1470.

Bayer, R., Carozzo, M.T., Lanza, R., Miletto, M., and Rey, D., 1989, Gravity modelling along the ECORS-CROP vertical seismic reflection profile through the western Alps: Tectonophysics, v. 162, p. 203–218.

Berckhemer, H., 1968, Topographie des "Ivrea-Korpers" abgeleitet aus seismichen und gravimetrischen Daten: Schweizerische Mineralogische und Petrographische Mitteilungen, v. 48, p. 235–246.

Bergerat, F., Mugnier, J.L., Guellec, S., Truffert, C., Cazes, M., Damotte, B., and Roure, F., 1990, Extensional tectonics and subsidence of the Bresse Basin. A view from ECORS data: Société Géologique de France, Bulletin (in press).

Butler, R.W.H., 1986, Thrust tectonics, deep structure and crustal subduction in the Alps and Himalayas: Geological Society of London Journal, v. 143, p. 857–873.

Chopin, C., 1984, Coesite and pure pyrope in high-grade blueschists of the Western Alps: A first record and some consequences: Contributions to Mineralogy and Petrology, v. 86, p. 107–118.

Choukroune, P., Ballèvre, M., Cobbold, P., Gautier, Y., Merle, O., and Vuichard, J.-P., 1986, Deformation and motion in the Western Alpine arc: Tectonics, v. 5, p. 215–226.

Damotte, B., Nicolich, R., Cazes, M., and Guellec, S., 1990, Mise en oeuvre, traitement et présentation du profil Plaine du Pô–Massif Central: Société Géologique de France, Bulletin (in press).

ECORS-CROP, 1986, Rapport d'implantation du profil "Structure profonde des Alpes": Paris, Institute Français du Pétrole, p. 73.

ECORS-CROP Deep Seismic Sounding Group, 1989, A new picture of the Moho under the western Alps: Nature, v. 337, p. 249–251.

Gillet, Ph., Choukroune, P., Ballèvre, M., and Davy, Ph., 1986, Thickening history of the Western Alps: Earth and Planetary Science Letters, v. 78, p. 4–52.

Guellec, S., Tardy, M., Roure, F., and Mugnier, J.L., 1990, Une interprétation tectonique nouvelle du massif subalpin des Bornes (Alpes occidentales): Apports des données de la géologie et de la géophysique profondes: Paris, Académie des Sciences Comptes Rendus (in press).

Hirn, A., and 8 others, 1989, Mapping the Moho of the Western Alps by wide-angle reflection seismics: Tectonophysics, v. 162, p. 193–202.

Laubscher, H., 1988, Material balance in Alpine orogeny: Geological Society of America Bulletin, v. 100, p. 1313–1328.

Lemoine, M., and Trumpy, R., 1987, Pre-oceanic rifting in the Alps: Tectonophysics, v. 133, p. 305–320.

Marthelot, J.M., 1990, Computer-generated images of the Alpine crust: Société Géologique de France, Bulletin (in press).

Mattauer, M., 1986, Intracontinental subduction, crust-mantle decollement and crustal-stacking wedge in the Himalayas and other collision belts: Geological Society of London Special Publication 19, p. 37–50.

Mugnier, J.L., Guellec, S., Ménard, G., Roure, F., Tardy, M., and Vialon, P., 1990, Crustal balanced cross-sections through the external Alps deduced from the ECORS profile: Société Géologique de France, Bulletin (in press).

Nicolas, A., Polino, R., Hirn, A., Nicolich, R., and ECORS-CROP Working Group, 1990, ECORS-CROP traverse and deep structure of the western Alps: Société Géologique de France, Bulletin (in press).

Rey, and 8 others, 1990, Gravity and aeromagnetic maps on the Western Alps: Contribution to the knowledge on the deep structures along the ECORS-CROP seismic profile: Société Géologique de France, Bulletin (in press).

Ringwood, A.E., 1975, Composition and petrology of the Earth's mantle: New York, McGraw-Hill, 618 p.

Roure, F., Polino, R., and Nicolich, R., 1990, Poinçonnement, rétrocharriages et chevauchements post-basculement dans les Alpes occidentales: Evolution intracontinentale d'une chaîne de collision: Paris, Académie des Sciences, Comptes Rendus (in press).

Thouvenot, F., Paul, A., Senechal, G., Hirn, A., and Nicolich, R., 1990, ECORS-CROP wide-angle reflection seismics: Constraints on deep surfaces beneath the Alps: Société Géologique de France, Bulletin (in press).

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