Mém. Soc. géol. France, N.S., 1990, n° 156, pp. 15-27
Mém. Soc. géol. suisse, 1990, n° 1, pp. 15-27
Vol. spec. Soc. Geol. Italiana, 1990, n° 1, pp. 15-27

ECORS-CROP traverse and deep structure of the western Alps : a synthesis

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Key words. – Western Alps, Reflection seismology, Gravimetry, Magnetism, Structural geology, Collision models, Lithospheric wedging.

Abstract. – This is a synthesis of the main results of the ECORS-CROP geotraverse through western Alps. A vertical seismic reflection profile has been complemented by a wide angle seismic reflection experiment and by a specific gravity and magnetism mapping program. Putting together all data suggests that, in a system where the seismic reflectors are dominantly dipping to the SE, there is a mantle slab at 25-30 km depth below the internal zones. This is best explained by a model of lithospheric wedging whereby, after subduction of the Piemontese ocean and the related collision, the lithospheric thrust could have been initiated along the Valaisan trough, a weak zone of possibly oceanic nature. Further plate convergence would be accomplished by crustal wedging in external zones and possibly by back-thrusting in the internal zones.

Traverse ECORS-CROP et structure profonde des Alpes internes : synthèse

Mots clés. – Alpes occidentales, Sismique réflexion, Gravimétrie, Magnétisme, Géologie structurale, Modèles, Collision, Ecaillage lithosphérique.

Résumé. – Cette note est une synthèse des résultats les plus saillants de la traverse géophysique ECORS-CROP des Alpes occidentales. S'appuyant sur un profil de sismique réflexion verticale, cette traverse a aussi mis en œuvre un profil de sismique réflexion grand angle et des levés spécifiques de gravimétrie et de magnétisme. L'intégration de toutes ces informations suggère l'existence d'un coin de manteau à environ 25-30 km sous les zones internes, dans un système où les réflecteurs sismiques sont préférentiellement inclinés vers le SE. Ces résultats plaident en faveur d'un modèle d'accrétion lithosphérique. Après la subduction – collision de l'océan piémontais, une écaille lithosphérique se serait initiée à partir de la zone de faiblesse du Sillon valaisan, de nature peut-être océanique. La convergence des plaques se poursuivrait par des écaillages crustaux dans les zones externes et, peut-être, par des rétro-écaillages dans les zones internes.

I. – INTRODUCTION

The Alps are the mountains where geological observations are densest and where a number of modern geological concepts originated. They have long been interpreted as a continent-continent collision chain that involves the paleo-European continental margin (Helvetic + Penninic pile of nappes), and the eastern Apulian margin (Austroalpine and south-Alpine domains). Both margins are separated by an ophiolitic suture. Vialon presents a general description of the belt in this volume.

The Alpine collision began with the subduction of the Piemontese ocean, during early Cretaceous (130 Ma) and led to the closure of this ocean along the ophiolitic suture. For the western Alps, a SE-dipping oceanic subduction is generally accepted which is followed by the progressive subduction of the European lithosphere reaching at 100 Ma maximum depths at 90 km (3 GPa, Chopin [1984]), thus inducing the formation of Penninic thrusts (100-40 Ma). With continuing compression, a last rupture of the external crystalline massifs during late Tertiary (40-25 Ma) would have generated first the sub-Alpine nappes and, more recently, the Jura decollement. The later thrust system was active in the upper crust until the late Messinian (4 Ma). In the western part of the arcuate Alpine belt, this interpretation suggests a westward migration, through space and time of major deep crustal and perhaps lithospheric thrusts with an easterly dip [Dal Piaz *et al.*, 1972; Gillet *et al.*, 1986]. It is not clear whether the subduction-related collision was characterized by lithospheric flaking as proposed by Ménard and Thouvenot [1984], Butler [1986] and Polino [1986] or by crustal imbrication [Hsü, 1979; Mattauer *et al.*, 1987; Ziegler, 1987]. Also, the interpretations favoring a NW-thrust motion do not readily explain the back folding and thrusting affecting the internal parts of the belt. More accumulation of detailed geological information about the structure and history of the Alpine belt is not likely to advance our present knowledge much further. Important geophysical investigations in the 1960's revealed that the Moho deepens below the chain and sharply rises with the Ivrea

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The direction and the French-Italian coordination was taken by a staff whose members are : Guy Aubert, Marcello Bernabini, Christian Bois, Sergio Lorenzoni, Carlo Morelli and Claude Sallé.

body [Giese, 1968; Berckhemer, 1968]. More recently, local seismic sounding and gravity modelling have been combined with geological observations [Ménard and Thouvenot, 1984]. Further progress depends more on combined geological-geophysical studies; this is why a complete geophysical traverse, based on a vertical seismic reflection profile was undertaken.

The joint French-Italian ECORS-CROP program was launched in 1985 to conduct a vertical seismic reflection (VSR) traverse of the western Alps. The traverse presented here is the southeastern part of the 350 km long traverse, now completed, which extends from the Massif central (France) to the Monferrato (Italy) (figs. 1 and 2). Our 190 km long segment begins in the Bornes sub-Alpine massif, follows the upper Isère (France) and Orco (Italy) valleys, and end in the Po plain, NE of Torino. This profile was selected because it intersects at high angles the main Alpine structures in a domain where they are relatively cylindrical, allowing thus a two-dimensional geometrical analysis (fig. 1). Furthermore, NW-directed thrusts dominate [Choukroune *et al.*, 1986; Platt *et al.*, 1989], over presumably subordinate and later strike slip motion parallel to major tectonic contacts [Ricou, 1984; Gillcrist *et al.*, 1987]. The ECORS-CROP profile is thus parallel to the mean NW transport direction. The seismic profile extends from the relatively stable European foreland to the tilted outcrops or the overriding south-Alpine hinterland of the Apulian microplate. Together with the recent ECORS Pyrenees profile [Choukroune *et al.*, 1989] it is one of the most comprehensive cross-section through a collision belt.

The geophysical traverse consists of a vertical reflection profile, a gravity survey centered on the seismic line, an aeromagnetic profile flown at 4000 m and a wide angle reflection (WAR) experiment, conducted to obtain a cross-section of the crust-mantle boundary in the vicinity of the planned VSR line. The results of these experiments have been partially and separately published [Bayer *et al.*, 1987, 1989; ECORS-CROP deep seismic sounding group, 1989; Hirn *et al.*, 1989] and are gathered in this volume. Structural field work accompanying the traverse has permitted to take into account the constraints of balanced cross-sections in the external domains [Mugnier *et al.*, 1989, 1990; Guellec *et al.*, 1989, 1990], and to discuss in detail the interpretation of the internal [Tardy *et al.*, 1990; Polino *et al.*, 1990; Lacassin *et al.*, 1990] and south-Alpine [Roure *et al.*, 1989; 1990] domains.

The purpose of this paper is to present the vertical seismic reflection profile in some detail, and to discuss in an integrated manner the various results which have been obtained along the traverse and are developed within this volume.

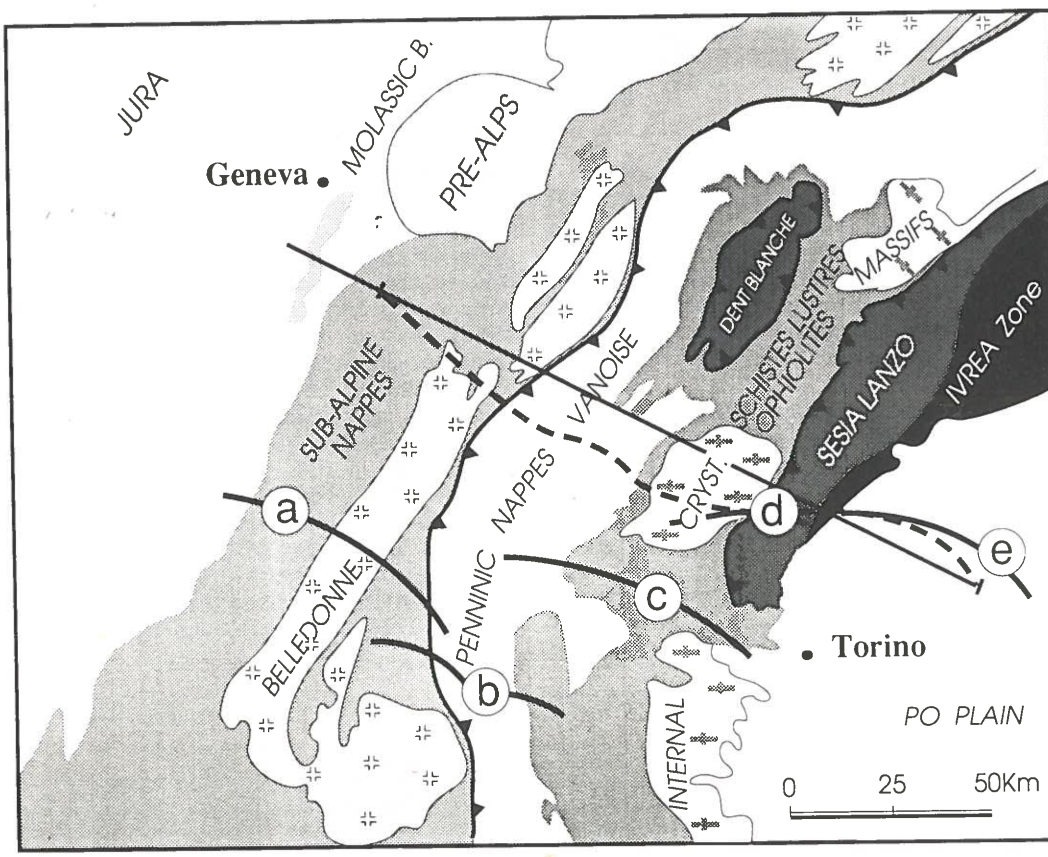

Fig. 1. – Location of the ECORS-CROP traverse (dashed line) through the western Alps. The curved segments represent the fans of mirror points of the WAR experiment and the straight continuous line, the projection of gravity data shown in cross section in figure 5 (note that the gravity profile extends further west than the ECORS-CROP traverse).

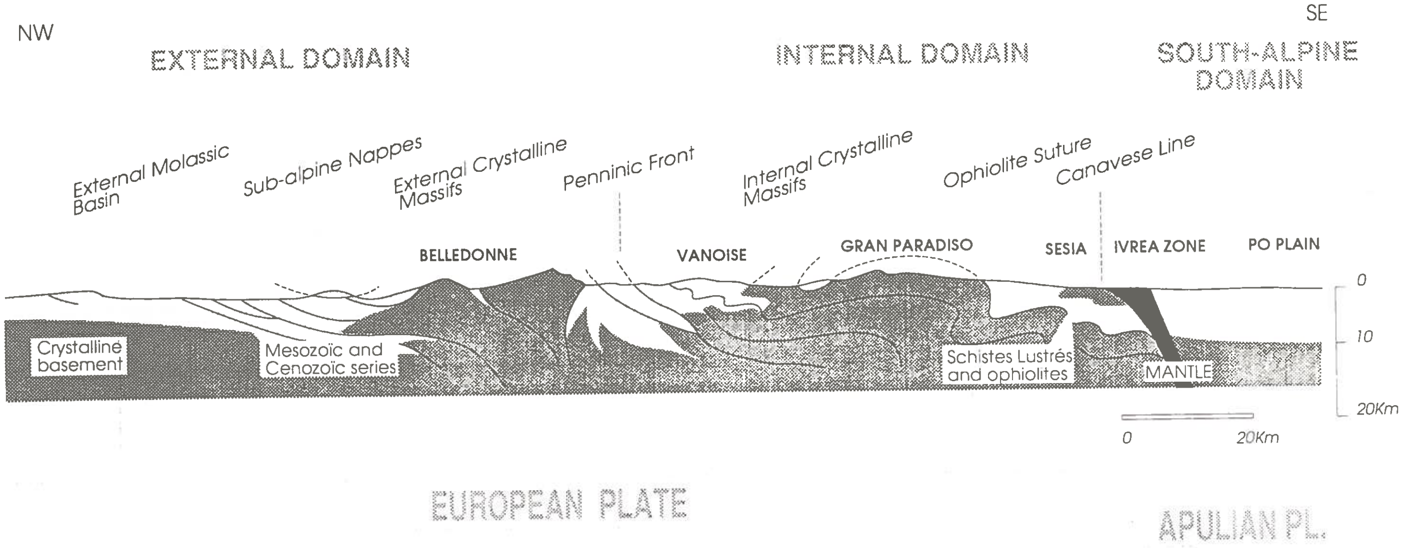

FIG. 2. – Simplified geological section along the ECORS-CROP geophysical traverse [after P. Vialon, 1986].

II. – Vertical seismic reflection (VSR) profile

The VSR profile was achieved by combined vibrators and dynamite shooting. The technical data and field parameters have already been presented [Bayer *et al.*, 1987] and are further discussed in this volume by Damotte *et al.* With respect to the seismic version presented in our 1987 publication, the new version of the profile has been improved in several ways. The 5 km vertical stripe which was missing along the French-Italian border is now filled. The stack data on the Italian side have been processed further and time-migrated with, as a result, a better definition of the reflectors. The stack data have been processed through an automatic treatment producing a coherency filtered stack (Marthelot and Bano, written comm.). The original stack will be published in ECORS-CROP final report (in preparation). The line drawing of the non-migrated section presented here, shows only the most prominent reflectors, (pl. Ib and fig. 3b). In addition, a line drawing of a depth-migrated profile was prepared by Guellec (for migration data see Damotte *et al.* [1990]) (fig. 4).

The description of the line drawing and the relation between reflectors and possible geological features are detailed within the structural papers of the volume referred to above. Only the following general observations need to be recalled here :

1) overall the reflectors have a moderate eastward dip. However, three main domains (1, 5 and 6 in fig. 3) display a westward dip. At the western end of the profile, the high energy reflectors (1) dipping to the NW beneath the sub-Alpine nappes mark the thrust on which the sedimentary cover of the Belledonne massif slipped westward. The westward dipping reflectors (5 and 6) seem to be cut by the series of east dipping (4) reflectors. They may signal an episode of back thrusting or alternatively, a late doming;

2) a clearly layered lower crust (2 in fig. 3) is nearly continuous from the western end of the profile (and beyond as shown by Bergerat *et al.*, 1989, 1990) to nearly below the Penninic front; it disappears eastward. The base of this layered section seems to coincide with a WAR reflector (I in fig. 5) interpreted as the Moho below the crust of the European foreland [ECORS-CROP DSSG, 1989]. A reflective zone below the Gran Parasido at 3 s TWT (7 in fig. 3b) suggests the presence of either a similar lower crust at a shallower depth or a piling of crustal nappes (fig. 4);

3) the ophiolitic nappes and the Sesia zone are transparent with the exception of a flat reflector (8) which coincides with a WAR reflector (III) (fig. 5), representing the top of the mantle below the Sesia zone. The virtual absence of reflectors above (8) may be explained by the steep dip of otherwise complex geological structures cropping out in the ophiolite suture and the Ivrea zone. The same reasoning applies to the seismically transparent Belledonne massif and its steep median high-angle thrust (fig. 2). In contrast, the Penninic front (4 in fig. 3) is underlined by two high energy reflectors suggesting either that this thrust, emerging locally at a high angle, flattens at depth or that these reflectors represent late and low temperature faulted features;

4) the easterly dipping reflectors (9) are ascribed to the subsidence of the Po plain [Roure *et al.*, 1989].

III. – Wide-angle reflection (WAR) seismics

The WAR fan shooting experiment, described by the ECORS-CROP DSSG [1989] and Hirn *et al.* [1989], was conducted to map the very deep interfaces below the profile. The location of the mirror points used to construct the profiles incorporated in figure 5 is shown in figure 1. When projecting the P-wave WAR reflectors on the VSR profile, it should be kept in mind that except for fans d and e of mirror points below the Internal zone and the Po plain, all the others depart from this profile by variable distances, reaching 50 km for fan b. Surface geology and the Bouguer gravity map [Bayer *et al.*, 1989; Rey *et al.*, 1990] suggest

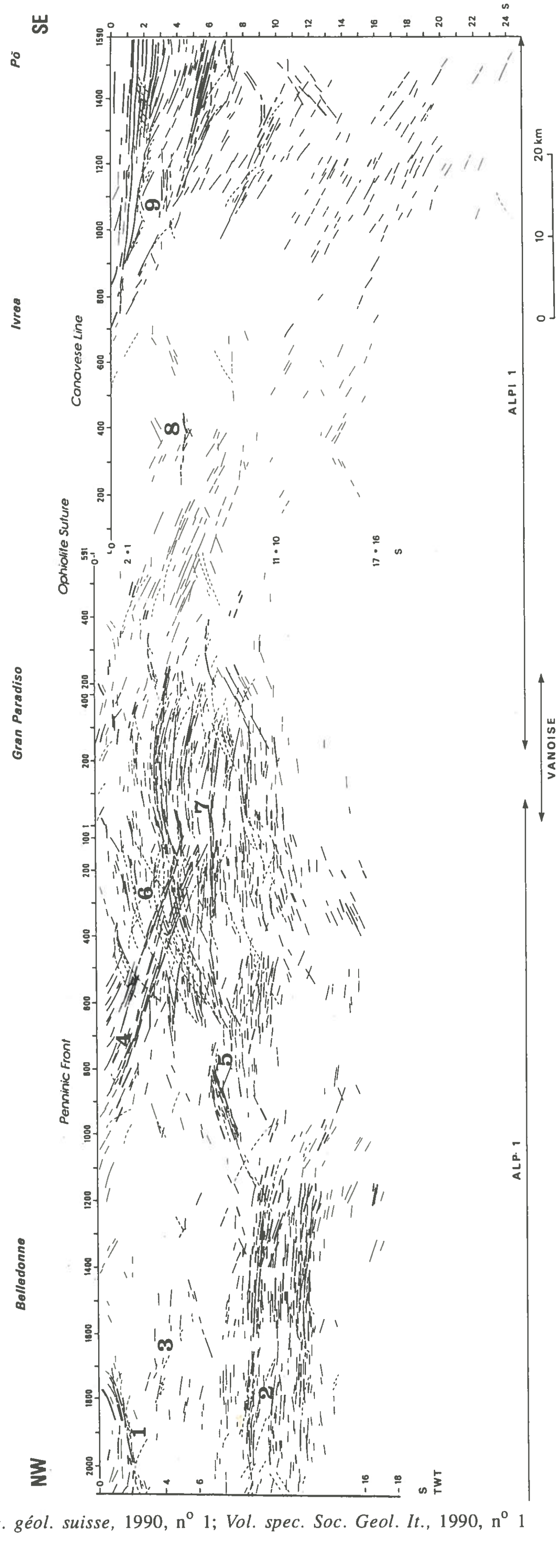

FIG. 3. – Reduced copy of pocket plate I showing the vertical seismic reflection profile of the ECORS-CROP traverse through the western Alps; line drawing of the most prominent reflectors.

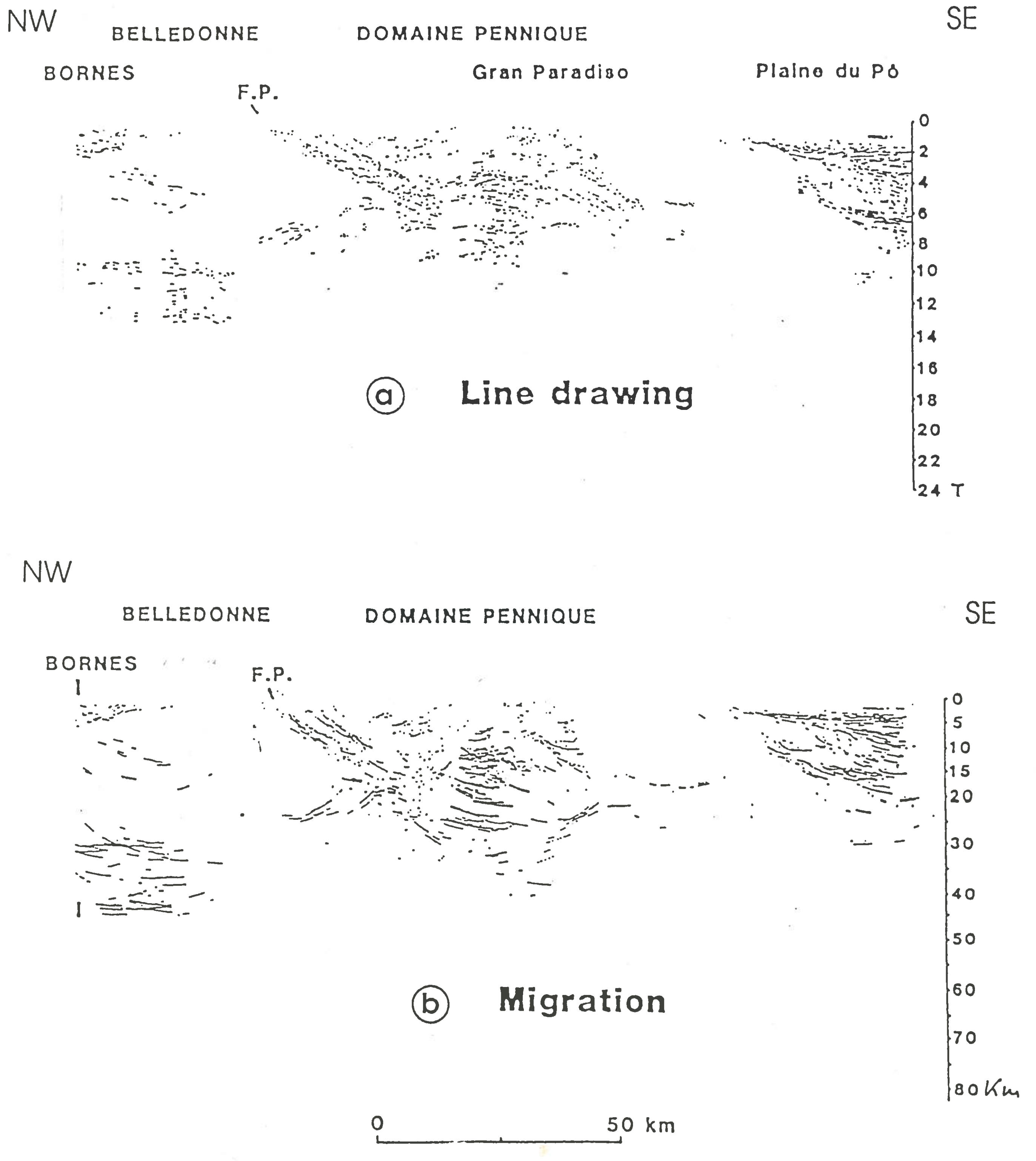

FIG. 4. – a : line drawing. b : depth-migration of the line drawing. For technical data about depth migration see Guellec *et al.* [1990].

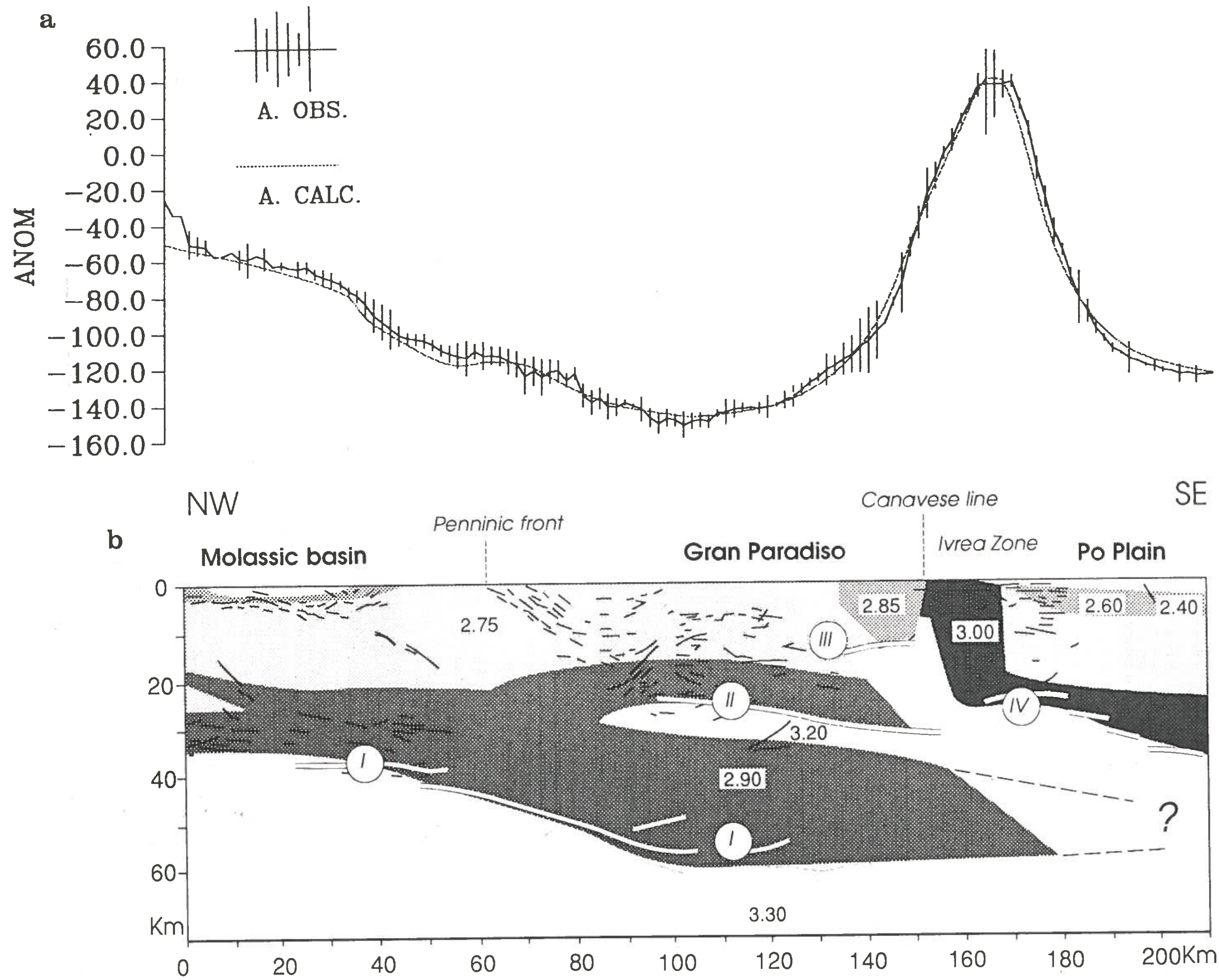

FIG. 5. – Density cross sections along the ECORS-CROP traverse (straight line in fig. 1). a : Bouguer anomaly profile. The calculated curve is issued from the density model (densities in kg/m³). b : gravity model with a constant density lower crust on which have been superimposed the depth-migrated line drawing of figure 4 (thin black line) and the WAR P-wave reflectors (blank lines). Location of WAR reflectors, mainly I and II, is uncertain because of their distance to the profile (see text). A possible eclogitic extension of lower crust below the Po plain is shown by dashes [modified from Bayer *et al.*, 1989].

that, in this part of the Alpine belt, the deep structures can be reasonably extended along strike, a necessary assumption to project the WAR data in the plane of figure 5. These questions are discussed further in this volume by Thouvenot *et al.* [1990].

The WAR results point to an overall structure similar to that deduced from the 1960's seismic refraction experiments, showing in particular a Moho deepening eastward below the belt and sharply rising in the Ivrea area [Giese, 1968; Berckhemer, 1986]. This encourages to interpret the WAR reflectors as also imaging the Moho. The critical results of the WAR experiments are the following :

1) the deep reflecting horizon (I in fig. 5) equated with the Moho beneath the European foreland extends continuously, or nearly so, as far as below the Gran Paradiso;

2) this Moho marker, which is almost horizontal under the sub-Alpine nappes and the Belledonne massif is flexured eastward with dips reaching 20°. This brings the Moho from 37 km below the sub-Alpine nappes to approximately 55 km below the Gran Paradiso massif. Beyond to the east, there is no deep Moho image, before reaching the Apulian domain. This may be caused by the screening effect of marker II. However, frequency decrease in the Moho reflection spectrum when going eastwards may suggest that

the lower part of the crust was metamorphosed into eclogites, making the seismic imaging of the crust-mantle boundary impossible;

3) there is a highly reflective horizon (II) at 35-30 km below the Penninic zone which corresponds to a velocity contrast of more than 1 km s^{-1}. Such a large contrast points to a crust-mantle interface or possibly to a granulite-eclogite interface, as discussed below;

4) there is a sharp upheaval of the Moho reflector (III) below the Ivrea zone and seemingly a stepwise descent of markers (IV) to more than 35 km depth below the Po plain. The Moho is found however deeper than in the previous seismic models [Berckhemer, 1968; Giese, 1968; Ménard and Thouvenot, 1984]. This requires a larger volume of Apulian lower crust in the Ivrea body than thought before.

IV. – Gravity

New measurements have been added to previous gravity data with a station density over 0.1 stations/km^2. This results in a new Bouguer anomaly map [Bayer *et al.*, 1989; Rey *et al.*, 1990]. A Bouguer profile calculated along the line of the figure 1 by projecting the available gravity data, is presented in figure 5. The consistency between the VSR and WAR profiles and the gravity data was tested and two main density models were proposed, mainly differing by the adopted densities for the subducted European crust under the internal zones [Bayer *et al.*, 1989; Rey *et al.*, 1990]. The model of figure 5 assumes that the metamorphism occurring during and after subduction has fully re-equilibrated the crust of the deepened European foreland to an uniform density of 2900 kg m^{-3}, whereas the other model assumes that densities have not been homogeneized and that a layered crust is preserved, with densities of 2900 kg m^{-3} for the lower part of the crust and 2750 kg m^{-3} for the upper part. With either of these crustal models, the presence of a heavy slab is found to be necessary above the subducted European foreland. The models are sensitive to the length of the European crustal slab extending below the internal Alps, which is estimated at 80 km ± 15 km. This estimate may be a minimum if one considers the possibility that the deepest crust in these zones has been transformed to eclogites (see below).

The assumption of a two-dimensional structure in this part of the Alps is supported by the remarkable cylindricity of the Bouguer anomalies in map; it is also illustrated by the similarity of the model of figure 5 with the density cross section along Grenoble-Torino profile [Fig. 8 in Rey *et al.*, 1990] for which the Moho depth is better constrained thanks to its proximity with the WAR reflecting fans and with the EGT-S 1983 seismic profile [Thouvenot *et al.*, 1985].

V. – Magnetism

The use of geomagnetic data in the Alps was so far limited to the Ivrea-Body interpretation [Lanza, 1975]. An aeromagnetic profile was carried out in the frame of the ECORS-CROP program, but was not sufficient to interpret correctly the observed magnetic field which is partly due to the lateral effect of magnetized structures, such as the Lanzo massif. Rey *et al.* [1990] have used an homogeneous magnetic anomaly map built at the altitude of 3000 m [Mouge and Galdeano, 1989]. Like the gravimetric map, the magnetic map exhibits regional lows, over the external and Penninic domains. These lows are relayed to the east by positive anomalies, running over the Ivrea-Verbano zone. Strong positive magnetic anomalies occur also in the ophiolite massifs of the Penninic zone. Interpreting the magnetic anomaly along the ECORS profile has required the evaluation of the lateral effect of the magnetized Lanzo massif. Magnetization measurements in granulitic specimens from the lower crust of the Ivrea zone [Belluso *et al.*, 1989] explain well the magnetic positive high associated with this zone. Accordingly, Rey *et al.* [1990] consider the magnetic regional pattern corrected for the Lanzo effect, as mainly due to the lower crust. They use the density cross-section (fig. 5) to constrain the shape of the magnetized lower crust, assuming an horizontal bottom at 26 km depth, associated to the Curie isotherm. The satisfactory matching thus found between the calculated and stripped magnetic anomaly indirectly supports the density model of figure 5.

VI. – Cross section balancing

In spite of the favorable situation of the profile allowing for a two-dimensional cross section balancing, the balancing seems reasonably constrained only in the external domain. In the internal domain, the stratigraphic pile is too deeply eroded, the deformations too penetrative, and the kinematic patterns too complex to permit an application of balancing procedures. Nonetheless, it is clear that the Prealps klippen, or the thrust sheet imbrications at the footwall of the Penninic front imply transverse displacements of 50 km or more across this front. Balancing has been achieved in the sedimentary cover of the external domain and the Jura by Guellec *et al.* [1989, 1990] and at the scale of the crust by Mugnier *et al.* [1989, 1990]. Guellec *et al.* [1990] postulate to about 20 km shortening for the Jura and about as much for the Subalpine chain cover. The Jura shortening may be traced within the crust, where about 25 km of displacement is estimated along the Belledonne basal thrust (reflectors 3 in fig. 3), using the distance separating the hanging and footwall cutoffs of the thrust. A more general figure of 40-50 km shortening from the unaffected European crust to Belledonne eastward, is obtained from a comparison between the pre-collisional and the present day crustal thicknesses. The pre-collisional thickness of this segment of the extended European passive margin is itself deduced from an isostatic compensation model, based on the thickness of sediments deposited on the crust.

VII. – Discussion

Evolutionary models for the development of the Alps must be compatible with the geometrical constraints introduced by VSR and WAR reflectors and by the gravity and magnetic data. Such models must also account for the 40-50 km shortening deduced from balancing the external domains. In this respect, a good starting point is figure 5 showing the favoured gravity model and the main seismic reflectors used in its elaboration. Rey's *et al.* [1990] contribution in this volume shows that other possible gravity models do not depart much from the one retained here.

1) The problem of eclogitized deep crust

The possibility that Alpine crust may be still eclogitized at depth has major bearing on structural models, because eclogitized mafic rocks become indistinguishable from mantle rocks by seismic and gravity means. Surface occurrence of eclogites, including the deepest ever recorded with equilibration around 3 GPa (90 km) [Chopin, 1984], points to the relevance of this question in the case of the internal Alps, as already noted by Butler [1986].

In felsic granulites, the transformation to eclogite facies occurs with a density increase from 2.85 g cm^{-3} to 3.12 g cm^{-3} and in mafic granulites with a density increase from 2.90 g cm^{-3} to 3.2-3.4 g cm^{-3}, whereas in the later the seismic P-velocity increases from 7.5 to 8.10 km s^{-1} [Ringwood, 1975]. Thus deep crustal formations with a mixed acid-mafic composition, such as those in the Ivrea zone, if they are completely eclogitized, would be impossible to distinguish from mantle rocks, by gravity or seismic means. At 500-600°C, a granulite is transformed into eclogite for pressures in excess of 1 GPa, if its composition is mafic, and for pressures in excess of 1.8-2.0 GPa if its composition is felsic [Ringwood, 1975]. It is important to notice that the pressure is strongly composition-dependent. If the eclogitic formations are still hydrous, the temperature cannot exceed about 650 °C in mafic ones, because melting reactions occur above these temperatures. However if the rocks are dry, the melting does not appear below 1100 °C.

Obtaining pressures in excess of 1 GPa, necessary to form eclogites is not a problem in the Alps. There may be more difficulty with temperature requirements. As noted by Chopin [1984], formation of eclogite requires a small thermal gradient, produced by fast burial in a subduction zone (700 °C at 3 GPa). After subduction, these comparatively low temperatures increase by thermal relaxation and the eclogites may partially melt. If the melts remain trapped, the average density and seismic velocity may drop and the Moho signature may be restored; if the melts can escape, the residue would keep their mantle-like properties, but magmatism may be recorded above the melting slab. However these predictions depend on the amount of water present or introduced at the time of melting and on the final temperature of equilibration. These two unknown parameters control the amount of melt generated, and thus the response of the system.

This analysis applies to the deep crustal slab below Gran Paradiso (fig. 5). Pressures of around 1.5 GPa obtained in this deep slab would make eclogitization possible. The absence of any reflector below and east of this massif is also compatible with this hypothesis (see § III). If the metamorphic transformations were completed as proposed by Butler [1986], the actual extension of the deep crustal slab to the east would be impossible to determine, making the amount of crustal shortening mentioned above, a minimum figure. However, this 20 km thick slab, subducted more than 40 Ma ago, should have thermally reequilibrated to temperatures above 650 °C where wet anatexis occurs. Although, such melting is not recorded in superficial magmatism above the presumed slab, that is in the Ivrea zone and Po plain, this does not rule out an interpretation of an eclogite tail below the Po plain as the amount of melt is unknown.

Another critical site where the eclogitization problem arises is the presumed mantle slab capped in figure 5 by the WAR reflector II, above which the crust is unusually bright (7 in fig. 3). Can this reflector separate granulites from eclogites ? These eclogites would have to be formed during an early Alpine crustal subduction (probably Cretaceous, considering their internal and comparatively shallow location [Dal Piaz *et al.*, 1972; Gillet *et al.*, 1986]), being progressively uplifted by understacking subsequently to their formation. The lower contact of these presumed eclogites with underlying granulites is necessarily tectonic (greater pressure over lesser pressure) and the upper contact, most probably a phase transition contact. If the granulitic crust has a contrasting lithology like the present day Ivrea zone, owing to the large pressure interval for eclogitization in mafic and felsic rocks mentioned above, the transition should take place over more than 10 km, an interval too large for the expected thickness of a seismic reflector. Incidentally, this would explain the absence of such a reflector in European deep slab if, below the Po plain, it were eclogitized. Finally the possible occurrence

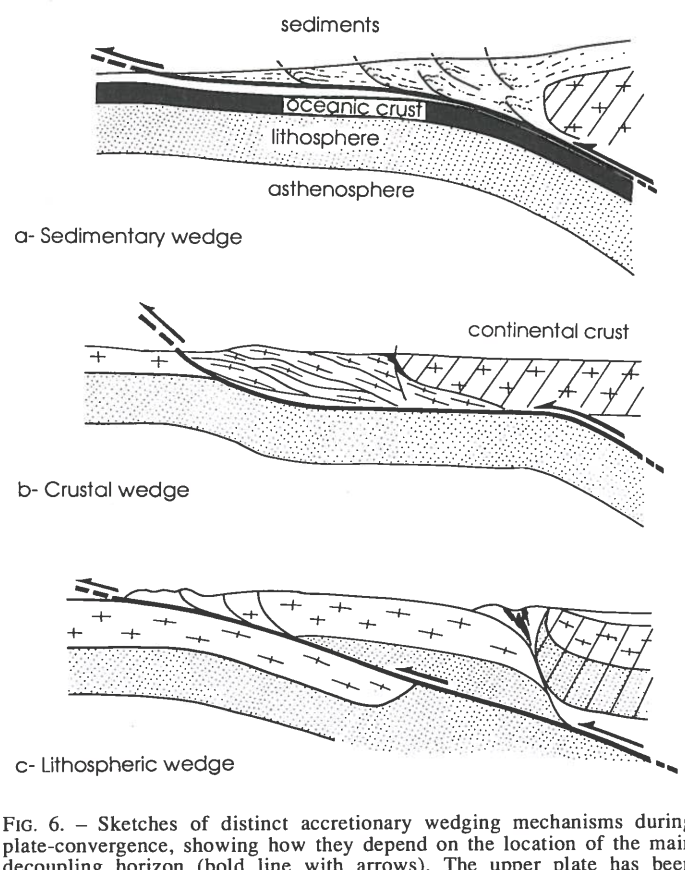

FIG. 6. – Sketches of distinct accretionary wedging mechanisms during plate-convergence, showing how they depend on the location of the main decoupling horizon (bold line with arrows). The upper plate has been hatched in the three sketches. a : sedimentary accretion in an oceanic subduction zone. b : continental crust accretion in the Himalaya collision belt [inspired from Mattauer, 1986]. c : lithospheric accretion in a collision belt (this study).

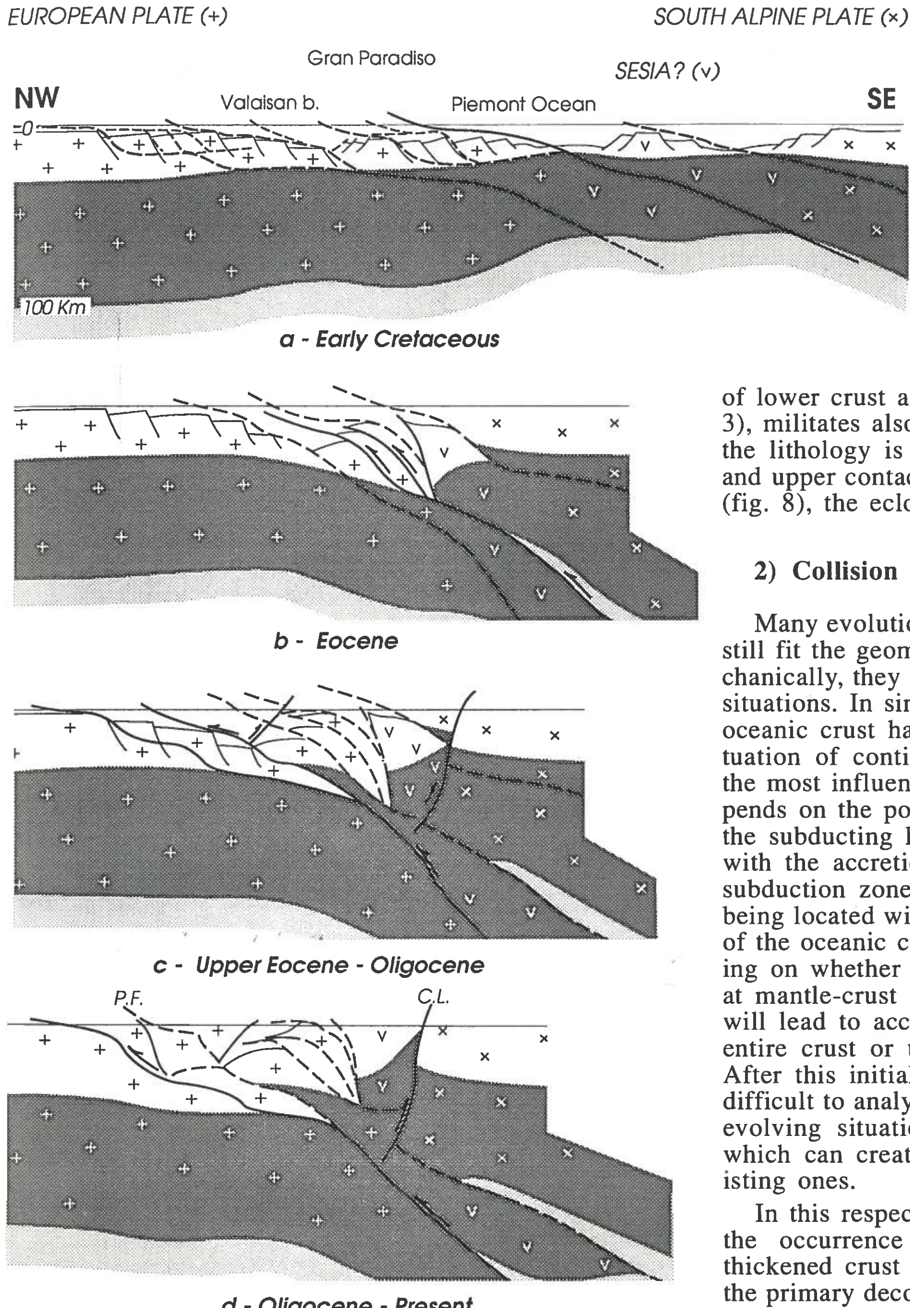

FIG. 7. – Classical evolutionary schemes for the western Alps along the ECORS-CROP traverse, implying lithospheric accretionary wedging and crustal imbrication. Lithospheric rupture is initiated along weakness zones (Piemontese ocean, Valaisan basin and possibly a basin east of Sesia if this piece of crust is not attached to the South Alpine plate [Mattauer *et al.*, 1987]). Active and potential movement zones : full and dashed lines, respectively. PF : Penninic front; C.L. : Canavese line [Lacassin *et al.*, 1990].

of lower crust above reflector II (brigh reflectors 7 in fig. 3), militates also in favor of a Moho reflector. However if the lithology is monotonously mafic or if both the lower and upper contacts with the high density sliver are tectonic (fig. 8), the eclogitic hypothesis remains possible.

2) Collision models

Many evolutionary models can be imagined which would still fit the geometrical constraints shown on figure 5. Mechanically, they all derive from a limited number of starting situations. In simple words, it can be stated that, once the oceanic crust has been consumed by subduction and a situation of continent-continent collision has been created, the most influential parameter for the further evolution depends on the position of the main decoupling level within the subducting lithosphere. An analogy can be made here with the accretion of a sedimentary wedge in an oceanic subduction zone, which results from the decoupling level being located within or at the base of the sedimentary cover of the oceanic crust (fig. 6a). In a collisional belt, depending on whether the decoupling level is within the mantle, at mantle-crust interface or within the crust, the collision will lead to accretionary wedging of slabs of lithosphere, entire crust or upper crust, respectively (figs. 6b and c). After this initial wedging, further developments are more difficult to analyse because they are controlled by local and evolving situations of mechanical weakness or stiffness, which can create new decoupling levels or inhibit preexisting ones.

In this respect, the most striking feature of figure 5b is the occurrence of a mantle slab inserted within the thickened crust of the internal domain. This suggests that the primary decoupling level was located within the mantle, pointing to a situation of lithospheric accretion. This leads to the model of figure 7 which is favoured within the ECORS-CROP Group and was presented in a preliminary shape by this group [Bayer *et al.*, 1987]. It cannot be excluded, however, that the main decoupling level ramping from the mantle is at the mantle-crust interface or above, leading to an alternative model of crustal accretion (fig. 8) which is also recalled below.

3) Lithospheric accretionary wedging

The lithospheric accretionary wedging occurs after complete subduction of the Piemontese ocean, at 110 Ma

[Lemoine and Trümpy, 1987], and the collision between the Apulian (south-Alpine) and the European plates, which is responsible for the uptilting of the deep crust and upper mantle of the Apulian plate promontory as the Ivrea body. This also explains the presence of mantle at shallow depth below the ophiolite suture (reflector IV). 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. It can be speculated that a lithospheric rupture within the European plate was guided by the existence of the Valaisan trough which may have been a narrow oceanic rift parallel to the Piemontese basin [Lemoine and Trümpy, 1987], in which case the main thrust should emerge on the site of this former trough, that is in the vicinity of the Penninic front.

The gravity modelling suggests that the apparent extension of the European slab below the internal domain is 80 ± 15 km, to be compared to the 40-50 km deduced from crust balancing (§ V). This represents however a lower constraint on the amount of shortening by thrust, west of the ophiolite suture. Problems consisting to locate the emerging surfaces of the lithospheric thrust and to balance the entire external crust have been considered by Mugnier *et al.* [1990]. These authors propose that 25 km of shortening correspond to the Jura decollement. The remaining 15-25 km to 40-70 km of shortening required respectively by crust balancing and gravity modelling are possibly accommodated along the main deep thrust emerging as the Penninic front and along splays of this thrust emerging at high angle in the median thrust zone of the Belledonne massif. Finally, geological evidence for a late transport direction toward the SW, outside the plane of the ECORS-CROP section [Ricou, 1984; Mugnier and Gidon, 1988], may introduce the possibility of a discrepancy between deep and shallow motion directions, making impossible a two-dimensional balancing.

This discussion shows that balancing constraints are too loose to weigh much on the interpretation. Laubscher [1988] envisages a total shortening of 130 km on the basis of a sinistral displacement of Monferrato with respect to the Ligurian Alps and Butler [1986] several hundred kilometers, essentially accommodated by subduction below the Po plain. Laubscher's estimate exceeds by 50 km the shortening indicated by gravity modelling. The difference may be explained in several ways : penetrative deformation in the Internal zones, back-thrusting of these zones or further extension below the Po plain of an eclogitized European crust, not seen by gravity (see above).

The stepwise descent of WAR reflectors below the Po plain and the possibility of having shallow dipping back thrusts within the sedimentary content of this subsiding basin [Roure *et al.*, 1989], suggest that the overall shortening was not entirely accomodated by the NW-directed thrusts and deformation zones described above. There may have been a contribution of SE-directed back thrusts [Butler, 1986; Heitzmann, 1987] or back folds [Escher *et al.*, 1988], as in the Pyrenées [Choukroune *et al.*, 1989]. The role of these back-thrusts is emphasized by the alternative evolutionary model described in the following section.

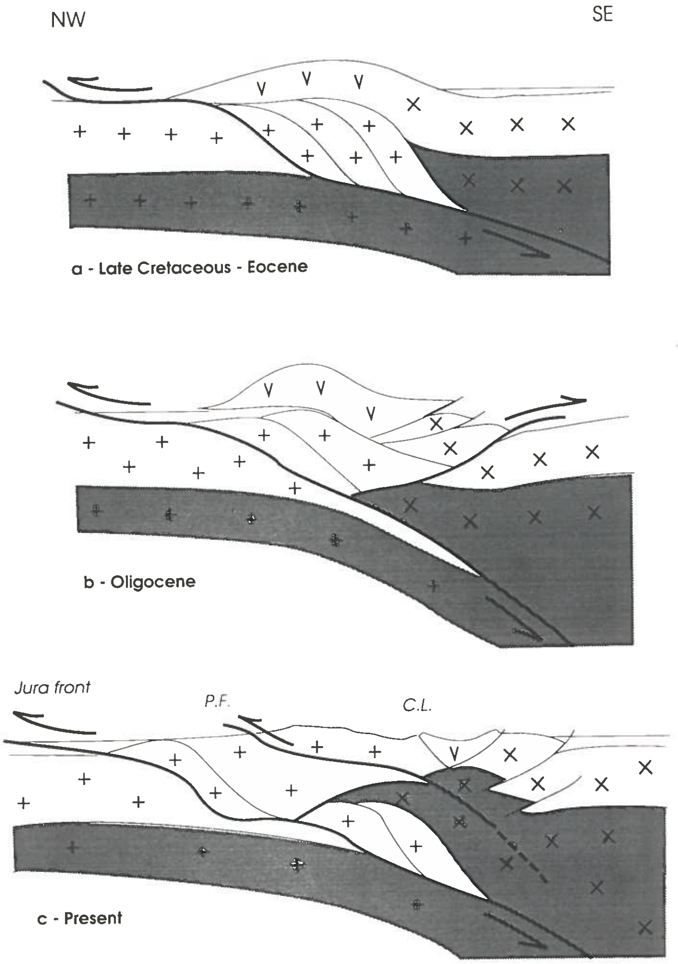

FIG. 8. – Alternative schema for the ECORS-CROP traverse implying in (a) a crustal accretionary wedging by thick-skinned imbrication of upper and lower crust, followed in (b) by mantle indentation and back thrusting, and in (c) by west-oriented thrust. Same decoration as in figure 7 [Roure *et al.*, this volume].

4) Crustal accretionary wedging with mantle indentation

Roure *et al.*'s [1990] evolutionary scheme of western Alps is close to that of Laubscher and Bernoulli [1982]. It assumes a major decollement at mantle-crust interface within the subducting European plate (fig. 8). Accretion of European crust imbricates is induced by the indenter effect of the Insubrian mantle, during the SE-dipping subduction. As early as Oligocene, the pile of accreted crust can escape toward the SE by back-thrusting, inducing a new V-shape of the Alps with two diverging thrust fronts. Along this profile, the stepwise structure of WAR reflectors below the Po plain (IV in fig. 5) can result either from steep normal or reverse faulting. Along this profile, the back-thrusting interpretation is mainly supported by the existence of a barely visible flat reflector (9 in fig. 3), oblique on the east dipping sediments filling the subsiding Po basin. This possible reflector could derive from an initially NW dipping back-thrust, now rotated to the horizontal by the subsidence. Closer inspection of the VSR profile [Roure *et al.*, 1989] suggests that the back-thrusting would predate Burdigalian deposits.

More recent shortening would be accomodated by out-of-sequence westward thrusts such as those responsible for the strong reflectors 4 in figure 3. These thrusts would also be responsible for the introduction of an Apulian mantle sliver within the internal Alps crust, accounting for the occurrence of the mantle slab identified in these areas at 30 km depth.

VIII. – Comparison with the NFP–20 seismic profiles

The ECORS-CROP profile images the deep structure of the western Alps, from the undeformed European foreland to the north, to the Po plain to the south. Three Swiss profiles have been conducted in the central, allochthonous part of the belt, reaching neither the autochthonous foreland to the north, nor the south-Alpine thrust front to the south [Pfiffner *et al.*, 1988; Frei *et al.*, 1989; Bernoulli *et al.*, 1990]. A rapid comparison has to be made between all these profiles.

In both the ECORS-CROP and Swiss sections, the European Moho dips progressively southward and the crustal geometry of the external units (Aar and Belledonne crystalline massifs, detached Mesozoic cover,...) are much alike.

Only the South Swiss traverse image the shallow north dipping Apulian Moho. The East NFP profile clearly shows recent backthrusts in the southern part of the transect [Roeder, 1987; Laubscher, 1988], becoming a deep indentation of south-Alpine crust in the NFP 20 South profile [Bernoulli *et al.*, 1990]. This is unlike the ECORS-CROP profile where backthrusts are not obvious and would predate the Burdigalian [Roure *et al.*, 1989].

As in the Pyrenées [Choukroune *et al.*, 1989; Roure *et al.*, 1990], wedging is envisioned to explain the V shape of the Swiss profiles in the eastern-southern Alps, but it is still not obvious whether the main indenter is made by the rigid Apulian upper mantle [Roure *et al.*, 1990], or by the lower crust [Frei *et al.*, 1989].

The West NFP traverse, as the ECORS-CROP profile, is located west of the Rhone Simplon fault and images the same linear reflectors which outline the base of the upper Penninic nappes. Nonetheless, a southward extension of the profile in Italy is still needed to complement the transect, and unlike the ECORS-CROP profile, the NFP West traverse has not identified the high velocity marker feature related to the Ivrea body or Marker II, that we interpret here as a crust-mantle boundary.

Similarly, no evidence of imbricated mantle slices are detected east of the known extension of the Ivrea body [Laubscher, 1988]. Thus, the ECORS-CROP traverse reveals a more complex crust-mantle structure than the NFP traverses : most of these profiles show the authochthonous Apulian and European Moho, but ECORS-CROP also records two intermediate Moho reflectors (Ivrea and Marker II).

IX. – Conclusions

The integration of wide angle seismic reflection, gravity and magnetic data in the vertical seismic reflection profile has resulted in a somewhat constrained geometrical figure of the deep structure of the western Alps (fig. 5). Incidentally, this demonstrates the interest of traverses combining all possible geophysical techniques.

Prominant features of the geometrical model are (1) the predominant western vergence of major thrusts with, possibly, a subordinate component of back-thrusting affecting the most internal zones and the Apulian plate, and (2) the occurrence of a mantle slab within the thickened crust of the internal Alps.

Although the presence of a similar slab is not documented in central Alps by the NFP profiles [Bernoulli *et al.*, 1990], the overall geometry of the ECORS-CROP and NFP profiles are much similar. This suggests that the thrusting mechanics may be much alike along the different profiles, in spite of their distinct orientations with respect to the general SE-NW displacement direction of the Alps. This displacement direction is parallel to the ECORS-CROP profile. Partitioning of the SE-NW displacement into a dextral E-W strike-slip component recorded by the Insubric fault and a S-N thrust component may explain the S-N displacement recorded along the NFP profile [Lacassin, 1988].

The overall NW vergence of the deep structures confirms the SE-directed subduction of the European plate beneath the Apulian plate. After the Cretaceous consumption of the ocean separating these two plates and once a continent-continent collision situation is created, several evolutionary models can explain the geometrical figure obtained (fig. 5), depending on the location of the main initial decollement level within the subducting plate. The discovery of a mantle slab below the Internal zones suggests that the decollement was located inside the mantle, pointing to a model of lithospheric wedging and accretion (fig. 7). More classical models of crustal wedging and accretion with possibly an important component of back thrusting (fig. 8) remain however compatible with the data.

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