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The Alpine metamorphisms and their environments in the Western Alps: unsolved problems

by *Jacqueline Desmons*[1]

Abstract

A few problems related to the Alpine metamorphisms in the Western Alps are reviewed and briefly discussed. They concern the Eo-Alpine phase, the Briançon belt, the correlations of tectonic and metamorphic events, the external units, the P–T estimates and the correlations of tectonic and metamorphic events. It is emphasized that opinions remain open as concerns the age, site and vergence of the Mesozoic subduction zone, as well as the south- or north-Tethyan origin of the Pennine nappes and, thus, the site of the oceanic suture.

Keywords: Metamorphic evolution, subduction, P/T-estimates, Western Alps.

A consensus currently exists on a general scheme of the Alpine metamorphisms in the Western Alps as elaborated in the seventies (e.g., Frey et al., 1974; Hunziker, 1974; Bocquet, 1974; Desmons, 1977; Bocquet et al., 1978). The scheme includes three main metamorphic facies: i) eclogite and jadeite-glaucophane in the internal units; ii) greenschist in all units (grading into amphibolite towards the Central Alps); and iii) very low grade facies in the external units; and three main metamorphic phases: a) Eo-Alpine (Cretaceous), mainly of high P/T; b) Meso-Alpine (latest Eocene), mainly of greenschist facies; and c) Neo-Alpine (Oligo-Miocene), of very low to low grade.

Among the problems which are now clearly defined but not yet solved, the following can be mentioned.

1. Evolution of the Eo-Alpine parageneses

A spread of radiometric ages from Early to latest Cretaceous is found for the high-pressure parageneses in the internal Sesia zone. Oberhänsli et al. (1985)

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proposed to consider the youngest ages, mainly measured on phengites, as cooling ages during the Late Cretaceous uplift (or up-thrusting?) in a glaucophane-epidote, locally greenschist facies. A Mid Cretaceous age has also been obtained in the Monte Rosa (HUNZIKER, 1970; MONIÉ, 1985). The question arises as to whether in the various Western Alpine units that experienced the high-pressure overprint, the chronology was similar to that proposed for Sesia. Was an Early Cretaceous isotopic opening followed by a protracted (65 Ma...) evolution still under high-pressure conditions? In other words, how many of the Late Cretaceous radiometric ages are crystallization ages, or cooling ages, or recrystallization ages, or only apparent ages?

2. Subdivisions and ages in the Briançon belt

The Briançon belt actually consists of various thrust sheets. The total shortening in the Briançon belt is likely to have been enormous, from both thrusting and folding. This is shown by the different sedimentary sequences in the Mesozoic cover (BOURBON et al., 1973), not entirely accounted for by synsedimentary tectonics, by the numerous narrow subunits (especially narrow in the Bernhard pass region: BURRI, 1983), by structural analysis (PLATT and LISTER, 1985a and b) and by the reduced size of entire thrust sheets (e.g. the narrow Sapey zone with its tiny remnants of Palaeozoic basement: DÉTRAZ, 1984) where the shortening may not be due only to Hercynian tectonics. The correlation between the Bernhard-Ruitor-Vanoise crystalline rocks with the Italian "internal zone" (the polymetamorphic crystalline rocks of Valsavaranche and Val di Rhêmes) is not understood. The mineral associations show metamorphic jumps between the various Briançon subunits (examples are mentioned in Chap. 4).

Two models have been considered for the age of the jadeite-glaucophane assemblages in the Briançon-Ambin crystalline rocks (BOCQUET, 1974; DESMONS et al., 1982): an Eo-Alpine or a Late Eocene age. Radiometric support of an Eo-Alpine age remains tenuous (DESMONS and HUNZIKER, in prep.). The first alternative implies that the contact between both the Triassic to Mid Eocene sedimentary cover (not metamorphosed before Meso-Alpine times) and the crystalline basement post-dates the jadeite-glaucophane parageneses in the latter. There is now a general agreement on the thrust position of the cover on the basement, though not on the distance of the transport. The second alternative would assume in Late Eocene times a very deep intraplate subduction not associated with any shear heating and a Mesozoic to Paleogene history drastically different from the other Pennine basement units. Moreover, in this last alternative, the difference in pressure of an estimated 4 kb indicated by the mineral associations in both cover and basement could only be accounted for by a complicated T and P distribution in this rather thin rock sequence.

3. Low to very low grade facies in the external units

In the external units the precise metamorphic history and facies relationships in the low to very low-grade metamorphics are not yet clear. On one hand, there is a zoneographic gradation towards the more internal greenschists, which are Meso-Alpine in age, in part younger. On the other hand, anchizone illite crystallinity values are related to the heating due to post-Early Oligocene thrusts (APRAHAMIAN and PAIRIS, 1981). Scanty information indicates both Meso-Alpine (BONHOMME et al., 1980, etc.), and Neo-Alpine radiometric ages (e.g., LEUTWEIN et al., 1970), depending on the locality and the mineral considered.

4. Estimates of the P and T conditions

Estimates of the P and T conditions often differ from one author to another for the same assemblages in the same unit. Here are a few examples from the French Western Alps.

Ambin and S Vanoise basement, jadeite-bearing assemblages:		
GAY (1972)	7–8.5 kb	300–400 °C
DESMONS (1977)	~ 10 kb	≦ 350 °C
GOFFÉ (1982)	6–7 kb	300–350 °C
Vanoise, Mesozoic cover, lawsonite–chloritoid assemblages:		
DESMONS (1977; Fe–Mg-carpholite not considered)	≧3.5 kb	325–370 °C
GOFFÉ and VELDE (1984; Fe–Mg-carpholite considered)	8 kb	350 °C
Piemont ophiolites in SE France (Queyras), jadeite-lawsonite assemblages:		
STEEN (1975)	> 7–9.5 kb	200–300 °C
DESMONS (1977)	10–11 kb	< 340–370 °C
SALIOT et al. (1980)	7–10 kb	350–400 °C
CHOPIN (1981)	≧ 7 kb	250–350 °C
LECASSIÉ and MAURIN, in CARPÉNA and CABY (1984)	6–8 kb	300–350 °C

Many reasons may account for these varying P,T estimates, such as the lack of experimental upper pressure limits of some mineral stability fields, the lack of precise pressure data for increasing Fe-contents in minerals, etc., all leaving a clear field to personal biases. The drawbacks of these discordant estimates appear crucial when palinspastic interpretations and reconstructions are given.

High to extremely high pressures have recently been proposed for early Eo-Alpine stages in the internal Pennine thrust sheets: 16 kb for white schists in the Monte Rosa (CHOPIN and MONIÉ, 1984) and more than 28 kb for pyrope-coesite in Dora-Maira (CHOPIN, 1984), where values of the order of $\geq$ 10–12 kb, 450 ± 50 °C were set forth so far (from stable Na-pyroxene and kyanite: POGNANTE, 1984). If the extreme conditions estimated for Dora-Maira actually refer to an Alpine paragenesis, in order to explain the discrepancy in estimates of pressure with the adjacent Alpine units, two possibilities seem to exist: either these adjacent units also experienced prior very high pressures, but traces thereof have not yet been identified; or tectonic shortening has brought together units that experienced utterly different metamorphic evolutions and were once lying very far apart.

5. N–S variations in the metamorphic conditions

In addition to the P and T decreasing from E to W across the Western Alps during each metamorphic phase, variations also appear from N to S in a single unit, parallel to the axis of the Alpine belt. For instance, in Eo-Alpine times, the pressure in the ophiolite-bearing Piemont unit reached higher values in eclogites in the Zermatt area than in the jadeite-glaucophane-lawsonite assemblages of the Queyras (DESMONS, 1977; SANDRONE et al., in press) or in the Ligurian region (CORTESOGNO and VENTURELLI, 1978). Also, the minimal geothermal gradient (T/P gradient) inferred from the various assemblages in the ophiolitic rocks was lower in the south (10 to 12 °C/km) than in the north (15 °C/km). Other N–S variations appear in the Briançon-Bernhard subunits, from the glaucophane-epidote assemblage in the Metailler subunit and the Ruitor massif, through the glaucophane-jadeite assemblage in the Southern Vanoise to the glaucophane-lawsonite assemblage in the Acceglio zone. These longitudinal variations may be due to subduction-collision mechanisms gradually varying from N to S (e.g., DEBELMAS, in press). While investigating these variations, one has meanwhile to allow that some of them may be mistaking and in fact result from differences in the age or in the tectonic-structural relationships of the assemblages compared.

6. Relationships of the metamorphic phases with thrusting and other deformation phases

Further investigations remain to be made concerning the relationships between the main thrusting and metamorphic phases. It has been shown (GOSSO et al., 1979) that in the Sesia zone thrusting already occurred under HP conditions, thus as early as Late Cretaceous at least. The general distribution of HP-assemblages (Metamorphic map of the Alps: ZWART and NIGGLI, 1973) clearly shows that the overall thrust boundaries separating the structural units postdated the HP metamorphic imprint. On the other hand, the structural boundaries are intersected by the Meso-Alpine isograds. However, according to SALIOT and VELDE (1982) the Si contents in white micas would indicate that in the Pennine area thrusting preceded crystallization of Si-rich (HP-indicating) phengites. This statement relies on an assumed validity of phengite composition as precise indicator of pressure; its value is weakened also by the fact that chronological correlations of deformation planes between far-lying rock samples is a delicate problem. The highest phengite contents and the most frequent 3T polymorphs in K-white micas are found in Eo-Alpine metamorphics and especially where the Meso-Alpine overprint has been weak or of a low grade. This is shown on the maps presented by FREY et al. (1983), extending from the Central Alps to the northernmost Western Alps.

The tectonic imbrication of yet unmetamorphosed, fluid-rich, sedimentary rocks with comparatively dry crystalline rocks played a prominent part in the Alpine metamorphic phases, in bringing the necessary fluids to the hydrating reactions of the basement. The CO_2 and volatile carbon contents of these fluids have been studied only locally in the Western Alps and a synthetic investigation is needed.

Recent structural data show the succession of events in various Pennine units to be close to the following found in the Southern Vanoise (PLATT and LISTER, 1985a and b): i) large, recumbent folds with a vergence transverse to the axis of the Alps, post-dating the crystallization of the HP minerals and probably associated with nappe displacement; ii) a folding phase in greenschist facies, transverse to the Alpine axis, preceding the thermal peak of metamorphism indicated by albite porphyroblasts and green biotite; and iii) internal-vergent thrusting and folding (the so-called backthrusting and backfolding), in low greenschist facies, which were followed by up-doming and shearing. Examples of similar successions of events are given by BROUDOUX (1985), CARON (1977), DÉTRAZ (1984), MARION (1984), PERUCCIO-PARISON (1984), SAVARY and SCHNEIDER (1983), VEARNCOMBE (1983), VISSERS and COMPAGNONI (1984) and others. In addition, two phases of "backthrusting" have been identified in the Zermatt area by MILNES et al. (1981) and MÜLLER (1983). The low grade of the post-Eocene phases in the Western Alps does not facilitate the radiometric dating of these deformation phases (DESMONS and HUNZIKER, in prep.). Further investigations will have to confirm whether this scheme has to be refined or altered and how it correlates with the Dauphiné-Helvetic belt. In the Briançon and Piemont units of SE France a second deformation phase is reported to be parallel, not transverse, to the Alpine axis. This shows both external and internal vergences (TRICART, 1984).

The relationships of the Pennine units with the structural history as deciphered in the Sesia zone is not known, especially with that eastern part of the Sesia zone that escaped most Meso-Alpine recrystallizations. Here, four deformation phases have been recognized, which post-dated the HP peak and predated the

Meso-Alpine metamorphic and deformation phase (WILLIAMS and COMPAGNONI, 1983).

7. Tectonic environments

The last problem that will be mentioned here has already been the subject of much thinking and modelling. It concerns the tectonic environments that gave rise to the estimated pressures and temperatures.

We must keep in mind that a high P/T-generating environment is a dynamic environment, with transient geotherms. Here, a rock mass will change places and experience other conditions, or else its temperature will re-equilibrate as depressed isogeotherms tend to return to a normal attitude after a few million years. In the subduction model, if a subducted rock body has to be rescued from drowning into the mantle, it has to be exhumed. The P–T paths followed by rocks after the pressure peak must have resulted from tectonic exhumation, not from erosional unroofing which calculations show to be too slow a process (ENGLAND and THOMPSON, 1984).

a) The model devised by DAL PIAZ et al. (1972) explains with one subduction zone the glaucophane-jadeite and eclogite assemblages. This model had to be extended by the following alternative (see Chap. 2 above): a Late Eocene intracontinental subduction (BOCQUET (1974); DESMONS, 1977) which took into account a possible Eocene age of the HP parageneses in the Briançon basement. A deep Late Eocene subduction, though unnecessary if the Briançon glaucophane-jadeite assemblages prove Eo-Alpine in age, has been assumed in a few parts of the Alps in connection with the Cainozoic volcanism and with a vergence towards the external units: during Paleogene times in southern France (GIRAUD, 1983) and during the Pliocene in the Southern Alps (CASTELLARIN and VAI, 1981).

Apart from the subduction model, most frequently considered in the Alps, two others worked out to account for the development of high pressures will be mentioned. A fluid overpressure model was adopted by CARON (1977) for the Piemont calcschists of the Cottic Alps. However, as observed by this author, rock cohesion is not strong enough to sustain large stresses and overpressed fluids are rapidly drained off. This model is thus not likely to account for the Eo-Alpine blueschists and eclogites, especially in such a heterogeneous rock pile as constituted by the Alpine rock sequences. Perhaps it applies to the Cainozoic lawsonite-bearing assemblages, and particularly to vein filling.

The model in which pressure was generated by a tectonic piling up of units is found in ELLENBERGER's (1958) nappe geosyncline. This model was developed in the Vanoise and was based on the assumption of Paleogene high pressures. It has also been adopted by VEARNCOMBE (1983) in the Gran Paradiso. In addition to some chronological impossibilities in the case of the Vanoise, the tectonic piling-up model, like the subduction zone encounters the difficulty of preserving, thus exhuming the HP assemblages.

OBERHÄNSLI et al. (1985) advocated two different HP-generating phenomena in Eo-Alpine times: a subduction zone concerning the Piemont-Ligurian oceanic crust and a significant crustal thickening giving way to the eclogite facies in the Sesia zone.

I would mention a few alternative approaches to the problem, thus widening the field of investigation and calling for stronger support of the current models.

b) A few radiometric measurements and radiolarian determinations in ophiolitic sequences of the Alps, the Apennines and Corsica (FONTIGNIE et al., 1982; BIGAZZI et al., 1972; OHNENSTETTER et al., 1981; DE WEVER and CABY, 1981) show that the oceanic basin was open and accreting since the Jurassic (since Late Triassic according to CARPÉNA and CABY, 1984). During that period the stratigraphic record in the Pennine sedimentary sequences expresses a strong instability. Although it has left no so far-recognized trace, we should not brush aside without further inquiry a Jurassic subduction in the Alpine area (already proposed, e.g. by BIJU-DUVAL et al., 1977). Perhaps there were also Jurassic thrust movements. Both phenomena are known in the East Mediterranean area. If such was the case, the P,T conditions needed for eclogite and glaucophane-jadeite assemblages would have been met as early as the Jurassic. However, the rocks concerned do not seem to have been exhumed as Jurassic metamorphic ages have not yet been obtained. Jurassic HP-metamorphics may have all sunk into the mantle, perhaps as a consequence of a subduction process continuously lasting until (?Early-)Mid Cretaceous. One could think, however, of some scraping-off process of oceanic crust as advocated in the Franciscan trench melange and this would make the search for Jurassic radiometric ages in HP-parageneses no hopeless effort.

c) The main subduction zone may have been intra-oceanic, not marginal to a continental plate, a hypothesis already considered in the Tethys area by a few authors. The concomitant volcanism, if any, may thus have been an island arc volcanism, built on oceanic crust, not an Andean-type volcanism built on continental crust. Its products would be buried under the Alpine thrust sheets, or, at best, eroded, deposited and so far not recognized. A long time may have elapsed between the onset of the subduction during the Jurassic and a first, early, collision associated with ophiolite emplacement onto one of the margins (the southern or the northern one?). During this long period a wide expanse of oceanic crust may have been consumed. The final closing of the oceanic basin may have followed after some further time span.

d) In most subduction models of the Alps Africa is considered as forming the upper plate. The vergence of the early Cainozoic thrusts and of the Cretaceous thrusts in the Eastern Alps was towards Europe. This stands in contrast with the relationships in the other Tethyan belts and has been discussed by AUBOUIN and DEBELMAS (1980).

The subduction zone might actually have dipped under the European plate, or under an oceanic part of the European plate. Concerning the piling sequence in the very early stages of the convergence, in particular the vergence of the ophiolite emplacement, we do not have unequivocal data. The puzzling reconstruction of MILNES et al. (1981) for the Zermatt–Simplon area applies to later times, following the main nappe movement. According to these authors, the relative position of units then was, from top to bottom: Bernhard, ophiolites and Monte Rosa. We do not know which tectonic evolution led to this intermediate intra-Penninic position of the ophiolite nappe.

The Middle to Late Cretaceous thrusting which emplaced the Austro-Alpine nappes and exhumed the Eo-Alpine HP-metamorphics was Europe-vergent. When confronted with the problem of the vergence and with the thinness of the thrust sheets, most tectonicians propose models of subhorizontal intracontinental shearing, once developed as flake tectonics by OXBURGH (1973).

After the Late Eocene thrusts and folds, which were also Europe-vergent and were accompanied by the Meso-Alpine metamorphics, the Oligo-Miocene thrusts and folds, now quite thin-skin, were in the internal Pennine area of an Apenninic type: Apulia-vergent.

e) The Pennine nappes might represent the imbricated fragments not of the European margin but of the southern margin. Sedimentological and palaeontological evidence (PANTIĆ and FELBER, 1983; see also TRÜMPY, 1984) does show that some Mesozoic sedimentary sequences from the Pennine realm have south-Tethyan affinities. This has so far been explained because the structures were oblique to the palaeogeographical trends. As concerns the basement, parts of the Pennine crystalline rocks bear strong resemblance to South-Alpine crystalline sequences (pers. data). Such lithological similarities, in the case of pre-Hercynian metamorphic rocks, would be difficult to explain in the current reconstructions: Laurasia evolution was distinct from Gondwana up to the Late Palaeozoic Pangea assembly. The Pennine domain, as did the Austro-Alpine domain, might have constituted a frontal part of Gondwana, more peripheral and detached earlier than Apulia, thus somehow recalling the Carnic microplate of DEWEY (1973). This microplate is likely to have also experienced strike-slip movement. Its squeezing between both Europe and Africa would have originated the significant thickening shown by the gravity profiles under the frontal Pennine units. The hypothesis of a Gondwanan origin of the Pennine nappes, however, stands against widely accepted data supporting a European origin: for instance, the consistent sedimentary pattern of the Alpine sequences from the Dauphiné-Helvetic to the Pennine domain, and the common gap in metamorphism and tectonic style between both Pennine and South-Alpine domains and, in the Eastern Alps, the Austro-Alpine domain also.

In the hypothesis of a Gondwanan origin, the "North-Penninic transform zone" (Trümpy, 1985; Debelmas, in press) would represent the suture marking the oceanic gap. The Valais belt now lies here, with its hemipelagic deposits and, in the Western Alps, no typical oceanic ophiolites. Thus, the problem remains of the relative geodynamic significance of both Valais and Piemont-Ligurian belts.

Finally, I will emphasize that the developments of these last paragraphs are no creed but only discussions of a few options which, I think, so far remain open.

While discussing the geochronology of the Western Alps, Hunziker and Martinotti (Mem. Soc. Geol. Ital., in press) also suggest that the major Eo-Alpine suture was located north of the Penninic domain. The same opinion thus concomitantly springs from various lines of reasoning. Hunziker and Martinotti argue that all units affected by the Eo-Alpine HP-metamorphism were more likely adjoining each other than separated by the oceanic basin. In a forthcoming paper (Radelli and Desmons, in prep.) an overall reconstruction of the Alpine oceanic domains will be proposed, together with a few answers to the above mentioned palaeotectonic problems.

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