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Tectonic and Metamorphic Events in the Alps

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With 11 figures in the text

Abstract

This paper represents an attempt at summarizing available structural and textural data relative to the interplay between phases of deformation and/or recrystallisation, mainly in the Swiss Alps. A picture of increasing complexity emerges as one considers tectonic units from the external to the internal zones. Some correlations are suggested, although a synthesis is premature. This type of investigation must be pursued, as it may well afford information where other methods are insufficient. Attention is drawn to some important questions which have not yet been answered.

Résumé

Cet article constitue un essai de synthèse des données structurales et texturales sur les relations entre phases de déformation et/ou de recristallisation, surtout dans les Alpes suisses. L'image qui en découle augmente de complexité lorsque l'on envisage les unités tectoniques depuis les zones externes vers les zones internes. Certaines corrélations sont suggérées, bien qu'il ne soit pas encore temps, par manque d'informations dans certains secteurs, d'en faire un ensemble cohérent et bien fondé. Ce type d'investigation doit être poursuivi, car il peut fournir des informations, là où d'autres méthodes se révèlent insuffisantes. On attire l'attention sur certaines questions importantes qui sont sans réponse convaincante à l'heure actuelle.

INTRODUCTION

Hypotheses attempting to account for the existence of the spectacular Alpine mountain ranges of Europe probably began in prehistoric times. But for the development of our scientific understanding we are indebted to the

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work of a number of men working around the turn of the last century (ARGAND, HEIM, BERTRAND, LUGEON, etc.). In terms of their extraordinary natural abilities and mental powers several could well be termed geniuses. They clearly had great physical energy in order to collect the vast amount of factual data from field studies in such difficult terrain. More important, they were able to compile and collate this data and eventually to build up a convincing model to account for all they saw. It would be fair to say that, not only were the seeds of present day plate tectonics theory sown by these master geologists, but that the seeds had already developed into robust saplings in their own lifetimes. The effects of ramming together two originally separate continental plates they understood as "Africa over-riding Europe". What present day concept improves on this description?

Not surprisingly some modifications have had to be made to the explanatory model they put forward to account for the Alps, but what is perhaps a surprise to geologists working today is that, after more than half a century of work, how little we need to modify their basic interpretation.

What we describe below are some of the new data; it might be termed "icing on ARGAND's cake". We will describe the ways that the sequence of deformational events can be elaborated and subdivided, and the ways that the effects of the rise and fall in thermal activity can be assessed and related to the deformational phases. Both of these facets of Alpine study necessitate a setting in time; the events have to be related to each other first in relative terms and eventually in absolute terms. Because it is possible to date a geological event in various ways it is useful to start by setting out the methods which have been used in establishing time sequences in the Alps.

1. STRATIGRAPHIC RELATIONS OF ROCK STRATA

This method is based on an interpretation of unconformities. The deposition of sediments on the truncated edges of previously tilted or folded strata establishes a time interval in which the deformation occurred. Although this is a powerful method, it clearly depends on precise stratigraphic determinations of the ages of the strata involved.

2. PRESENCE OF CLASTIC FRAGMENTS

The incorporation of pebbles into sedimentary strata establishes the time at which the source rocks were unroofed by erosion. Interpretation of pebbles in this way has been used to determine the time at which a nappe came within close proximity to a basin where sedimentation was actively proceeding (TRÜMPY and BERSIER, 1954). However, as TRÜMPY has pointed out, this date may be only that of a particular increment in the emplacement history of the nappe, and it may not necessarily give the age of the main movement. The arrival time of pebbles in the molasse may only indicate the last phase of displacement. The age of the movement must lie between that of the youngest pebbles and that of the oldest conglomeratic strata. The effectiveness of this method clearly rests on the accuracy of recognition of the source rocks of the pebbles and on the precise determination of the age of the matrix of the detrital facies. Therein lies a common difficulty; incorporated fossil fragments used for dating the conglomeratic strata are easily reworked in this type of depositional environment and the beds may in fact be younger than they at first appear to be.

3. ABSOLUTE AGE DETERMINATIONS

These well established methods, based on radioactive decay of certain unstable elemental isotopes have undergone great refinement in recent years. There are, however, difficulties in interpreting the results. Depending on the particular isotopic method used, different apparent age data are obtained. These ages relate to the differing temperature thresholds at which the isotope "clocks" are set and they are generally interpreted as cooling stages in the thermal history rather than successive separate peaks of metamorphic activity (JÄGER, NIGGLI and WENK, 1967). Although the potassium-argon method has been very successfully applied to investigate the later stages in the cooling history of the mineral products of Alpine metamorphism, some anomalous ages appear to be the result of argon leakage, whereas others seem best explained by argon gain from pre-Alpine age source material (HUNZIKER, 1974).

4. TECTONIC STRUCTURES AND THE TEXTURES OF METAMORPHIC ROCKS

This method is based on detailed field study of the small scale structural features seen in deformed rocks linked with microscopic examination of rock samples showing these features. The structural mapping enables a sequence of deformation events to be established, and the geometric features on this scale are then coupled to the textural features seen in individual metamorphic crystals (SPRY, 1969). The nucleation, and subsequent growth of specific mineral species are matched with microfolds and other features indicating deformation. In this way phases of deformation can be related to the evolution and fluctuations of orogenic metamorphism. As the same deformations are often reflected in the development of stratigraphic unconformities (some of which set narrow limits on a particular phase of movement), the age of synkinematic metamorphism may sometimes be evaluated more precisely using this approach than by employing radio-isotope methods.

This method is a very powerful tool, and has been applied to determine the relationships of metamorphism and tectonic history in many orogenic belts (ZWART, 1960, JOHNSON and STEWART, 1963). In Alpine studies much detailed data of this type is available in theses of limited distribution, and one of the aims of this paper is to draw this information together in a more generally accessible form.

The application of the method is not always simple and there are several points that will need further discussion. The main issue here is correlation, not only correlation between structures in different tectonic units or zones, but also correlation between observations made on very different scales. It is often difficult to know to what degree one may extrapolate or interpolate from one scale to another. What may appear to be concordant on one scale may be discordant on another. However, structural correlations do seem to be generally possible in the Alpine area and indeed many seem to us completely convincing. Those points which concern difficulties of correlation between different structural units will be considered later.

This then is the manner in which many investigations into the thermal and tectonic history have been made over the past decade in the Swiss Alps (and also to a certain degree in the French and Italian Alps). The purpose of this paper is to present the critical observations in each of the areas in which they have been recorded and to suggest possible correlations and interpretations of the data. These are mostly derived from personal investigations, together with a wealth of unpublished material due to the efforts, past and present, of students at the Imperial College of Science and Technology, London and at the University of Lausanne, Switzerland and from other published sources.

Tectonic deformation of rock generally leads to the alignment of certain mineral species by mechanical rotation of the already existing mineral species or by stress-controlled growth under metamorphic conditions. As a result the rock acquires a new fabric superposed across any already existing fabric of sedimentary, igneous or metamorphic origin. Such tectonically induced fabrics may be either planar or linear, and it is also common for planar and linear fabrics to be combined together. The terms used to describe these types of tectonic fabric are often a source of confusion and so we have thought it advisable to define those which we use in this paper.

Planar fabrics are generally grouped under the general term *cleavage*. Cleavage can be of several types depending upon the rock composition, its crystalline state before deformation and the metamorphic state during the period of rock deformation.

Slaty cleavage is a planar fabric seen in low grade metamorphic rocks produced by a preferred alignment of platy minerals (micas, chlorites, illites etc.) usually accompanied by a dimensional preferred orientation of non-platy mineral species such as quartz. The fabric is generally developed fairly uniformly throughout the rock (a feature sometimes described as "penetrative"), but it may be accompanied by more or less regularly spaced discontinuities (seen as darker stripes or seams enriched in micaceous components), which appear to be the result of local removal of more soluble silicates and carbonates by the process of pressure solution. With increasing metamorphic grade the grain size of the minerals increases, the mineral assemblage changes and the rocks pass by way of phyllites into true schists. In high grade rocks a penetrative *schistosity* appears as the structural equivalent of the slaty cleavage in low grade rocks. Virtually all the phyllosilicates show a strong preferred alignment in the schistosity, and it is fairly common for quartz, carbonates and other mineral species to show a similar shape fabric. The significance of slaty cleavage and schistosity appears to be the same: they both form perpendicular to the shortest axis of the finite strain ellipsoid (axes $X > Y > Z$) of the deformation in which they formed, and they both form when deformation and metamorphism are synchronous or broadly so. No localities are known to us where two or more schistosities or slaty cleavages can be found.

Another common variety of planar fabric is known as *crenulation cleavage* or strain-slip cleavage. Unlike the previously described types of cleavage this is not penetrative, the cleavage surfaces are discrete surfaces or narrow zones which separate narrow strips of uncleaved rock generally a few millimetres in thickness (termed microlithons by DE SITTER (1958)). As the name implies, the cleavage surfaces are usually related to microfolds and they form parallel to the limbs of the folds. The spaced cleavage surfaces are produced by mechanical realignment of the platy minerals in the limbs of folds developed on some pre-existing rock fabric generally accompanied by removal of the more soluble components (quartz and calcite). Crenulation cleavage generally forms in rocks which had a strong planar anisotropy before the deformation which produced it. Sometimes this anisotropy is a pre-existing sedimentary fabric, but it is more usual for it to be an earlier tectonically induced fabric such as slaty cleavage or schistosity. The fundamental significance of crenulation cleavage is quite different from the previously described penetrative fabrics. It does not have any firmly fixed relationship to the finite strain ellipsoid of the deformation which led to its formation. However, it generally lies close to the XY plane of this ellipsoid, because folds formed by such a strain generally have their axial surfaces sub-perpendicular to the direction of maximum shortening. As the microfolds and associated crenulation cleavage increase in intensity the cleavage comes to lie progressively closer to the XY strain plane. Crenulation cleavage is generally produced in rocks undergoing deformation in low metamorphic states, low enough for there to have been little or no extensive recrystallisation and change of shape of the phyllosilicates. It is usual for crenulation cleavage to occur with other types of cleavage, and it is not uncommon for two or more crenulation cleavages to occur together in the same rock.

The *linear fabrics* that are found in the deformed rocks of the Alps are also of several distinct types. The commonest types of linear fabric found in all zones of the Alps are aligned parallel to the hinge lines of contemporaneously formed folds. These structures take several forms; *fold ridges and ripples, fold mullions, and rods* generally associated with *intersection lineations* where the folded lithological surfaces are cut across by cleavage. Where crenulation cleavage and slaty cleavage (or schistosity) occur at the same locality it is usual to find two or more crossing linear fabrics of this type, each one parallel to the axial directions of folds formed during the deformation which gave rise to the respective cleavage. No simple relationships exist between these axial directions and the directions of principal strain which produced them, and regional strain or displacement directions cannot be deduced from these types of linear structure.

Another type of linear fabric that is commonly developed in certain (but not all) zones is a *stretching lineation* parallel to the X-direction of the strain ellipsoid to which it is related. Within the Helvetic nappe region the intensity of lineation of this type generally increases with depth in the nappe pile. From strain measurements made using the oolitic limestones, conglomerates and rocks containing fossil strain markers, the lineation intensity is seen to be related to the amount of strain and the degree of prolateness of the strain ellipsoid. In many of the highly metamorphic zones stretching lineation is absent, probably because the metamorphic peak occurred after the main deformation phases, but structures of this type can be proved in some regions of the Upper and Lower Pennine Nappes from studies of the relationships of lineation and strain using deformed conglomerates, xenolithic enclaves in deformed basement granites and pillow lavas.

A third type of linear fabric is confined to crystal-filled tensile fissures and opened shear fractures in rocks deformed below the lower amphibolite facies. The crystals which grow in these fissures (generally quartz, calcite, chlorite, actinolite, stilpnomelane) have a marked elongate habit with the long axes of adjacent crystals being sub-parallel. This *fibre lineation* appears to be oriented parallel to the direction of maximum elongation of the incremental strain ellipsoid at the time of formation of the crystals. Geometric analysis of these lineations has been used to evaluate the sequential deformation history in parts of the Helvetic and Ultrahelvetic nappes (Durney and Ramsay, 1973).

The data presented below is set out according to the regional geological pattern, proceeding from the less metamorphic external zones to the highly metamorphic core of the orogen. The structural entities[1]) that are envisaged are classic Alpine domains, namely a) external zones, i.e. the Helvetics (and Ultrahelvetics), the external crystalline massifs; b) the External Pennine zone (the Sion-Courmayeur zone); c) the Lower Pennine nappes; d) the Upper Pennine nappes: – the Grand St. Bernard nappe; – the Dent Blanche nappe; e) the Prealpine nappes; f) south of the Insubric Line – the Ivrea zone. The structural and textural relationships seen in each of these zones will now be described.

THE HELVETIC ZONE

In the Helvetic zone sensu stricto the sequence of events has been clearly defined in a number of localities along the Alpine arc.

The earliest recognisable phase of deformation produced isoclinal folds, an axial surface schistosity and a prominent stretching lineation. The angle between the axial direction of the isoclinal folds and the stretching lineation is very variable and locally it is very small.

The rocks have evidently undergone recrystallisation during this first phase of deformation, which must post-date the youngest sediments belonging to the Helvetic sequence. The metamorphism in fact outlasted the deformation, producing in particular albite porphyroblasts. Radiochronometric data from the Glaris nappe (Frey et al., 1973) indicate a metamorphic peak in Lower Oligocene times with continued recrystallisation into the Lower Miocene, characterised by the late growth of stilpnomelane and biotite.

A second phase of deformation gave rise to a crenulation cleavage, isoclinal folds and a superposed intersection lineation. The latter is generally subhorizontal, while the cleavage surfaces plunge steeply to the south or southeast. Hardly any mineral growth accompanied this event. In the Morcles-Diablerets-Wildhorn ensemble, it definitely post-dates all mineral growth except perhaps some slight recrystallisation in the cleavage planes and in late quartz-calcite veins (associated with brittle features mentioned below). Hence this structure may correspond to movements in the late Miocene or perhaps even as late as Pliocene times.

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[1]) This structural subdivision ignores a major paleogeographic problem, i.e. that of the lateral extent of paleogeographic features, and especially of basins. The Bündnerschiefer south of the Gotthard massif may, for instance, be partly included in the External Pennine zone, while the Piedmont schistes lustrés may die out eastwards (cf. Trümpy, 1971), or the contrary (cf. Tollmann, 1965). Obviously, we cannot enter into this controversy here, and trust that the chosen scheme will be satisfactory for the present purpose.

Various sets of very late formed structures such as kinks and conjugate folds have been described. Their formation is generally accompanied by slip along bedding or cleavage surfaces.

This sequence of events applies equally to both cover and basement (cf. Ramsay, 1963, von Raumer, 1971, Steck, 1968, Labhart, 1965). The detailed evolution of deformation and recrystallisation and their interrelationship is very complex and varies from nappe to nappe and even within individual nappes (Durney and Ramsay, 1973). A wealth of mainly unpublished data on the subject has been accumulated by Durney (1972a). He has demonstrated the variability of direction and values of the incremental strains in a segment of the Helvetic nappes, the important rôle played by pressure solution processes in the formation of slaty cleavage and, through fluid inclusion geothermometry, he succeeded in following the changes of temperature during deformation. He was able to show that maximum temperatures were generally attained during the early stages of ductile deformation. The post-kinematic porphyroblastesis of albite occurred therefore at moderate temperatures and does not represent a metamorphic peak.

In practically all Mesozoic and Tertiary rocks in this zone it is evident that migration of silicate and carbonate material by diffusion and solution processes is extremely important. Structures of tectonic origin resembling the stylolites seen in diagenetically modified sediments are very abundant, and evidence of the removal of material from clastic particles of known original shape by pressure solution processes is very clear (figure 1). The sinks for this material seem to be several, pore spaces are reduced (and rock density increased) and much of the material is taken up by the syntectonic filling of tensile fissures and pressure shadows around resistant objects (Durney, 1972b).

A typical graph for the Helvetic zone is shown in figure 11.

All these events were preceded by gravitational emplacement of material, in particular of Ultrahelvetic units and the parautochthonous Flysch.

A prominent stretching lineation is present in most Helvetic rocks; it is clearly related to the first episode of deformation. It lies in a northwesterly direction near Martigny and gradually changes to a north-south direction towards the Aar massif, thereby retaining a perpendicular relationship with the longitudinal direction of the mountain chain, to which the main Helvetic folds are sub-parallel. In some parts of the Helvetic zone, however, the axes of early folds lie almost parallel to the stretching lineation. This is the situation with small scale folds located in the inverted limb of the Morcles nappe, and of the major folds of the Croix de Fer above Martigny, in the Chamonix-Martigny synclinal zone. Such a relationship has been interpreted as the consequence of reorientation of the fold axis during progressive deformation, in areas of high strain (Ayrton, 1972). This same reorientating mechanism must play an important rôle in the more internal and increasingly deformed parts

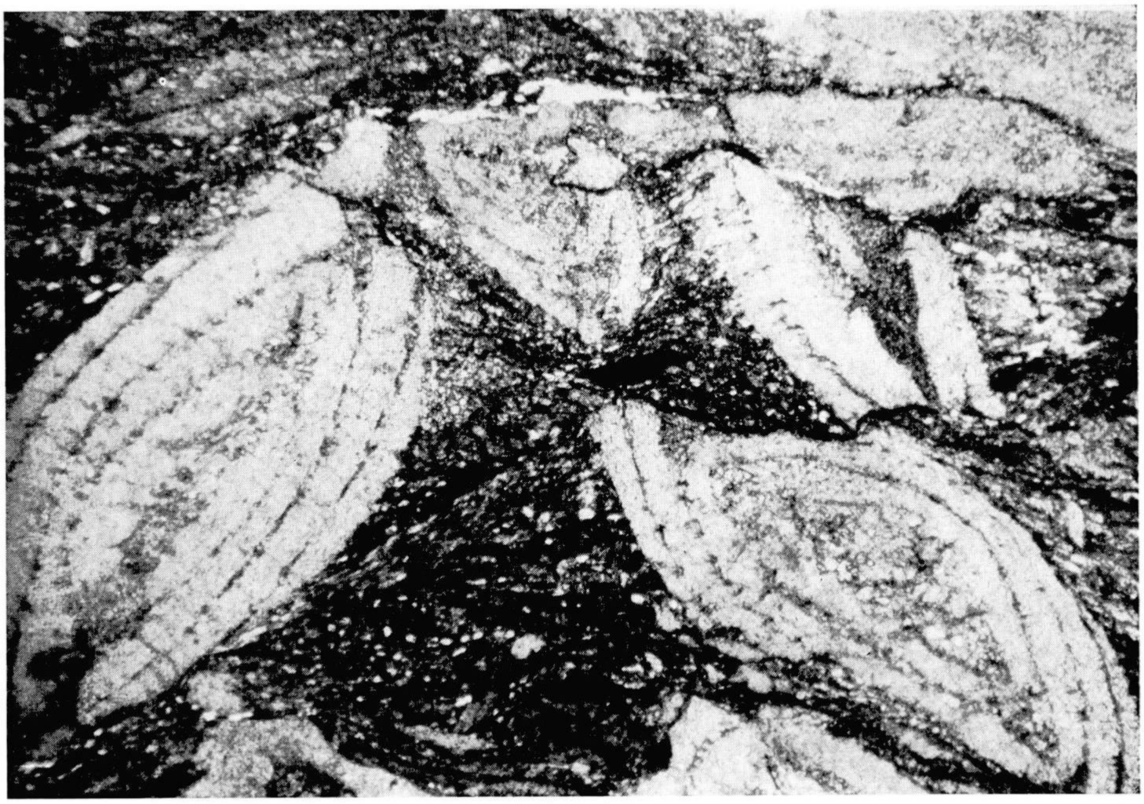

Fig. 1. Nummulitic limestone with the nummulites cut by pressure solution surfaces, North of Val Frisal, Graubünden.

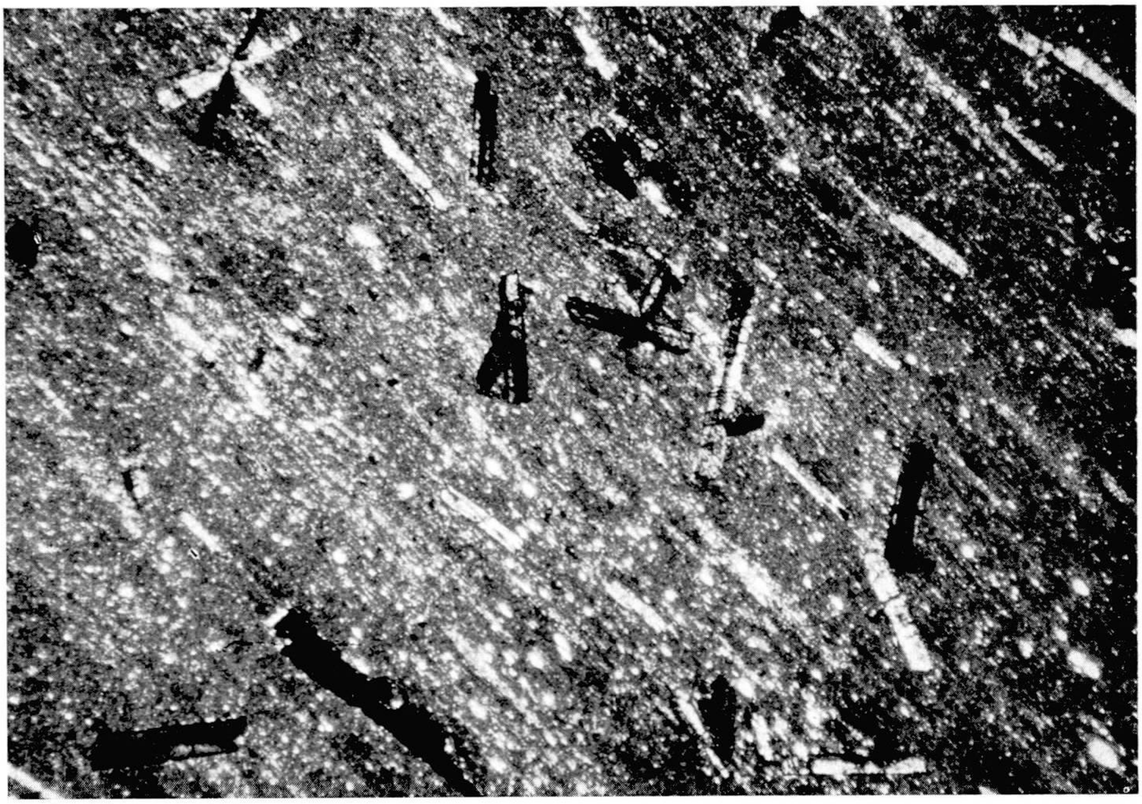

Fig. 2. Crystals of chloritoid growing across a previously formed schistosity. Quartenschiefer. Curaglia, Val Medel, Graubünden.

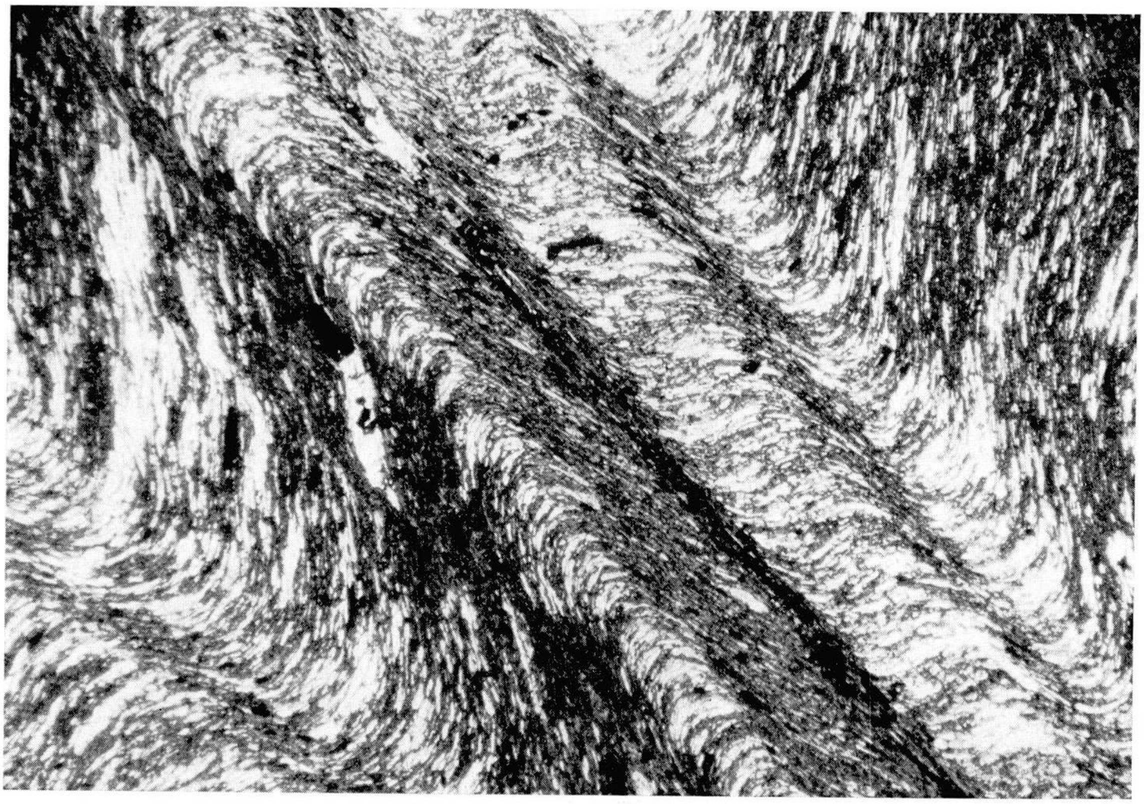

Fig. 3. Crenulation cleavage in Jurassic schists of the Inferno Series, Val Camadra, Ticino.

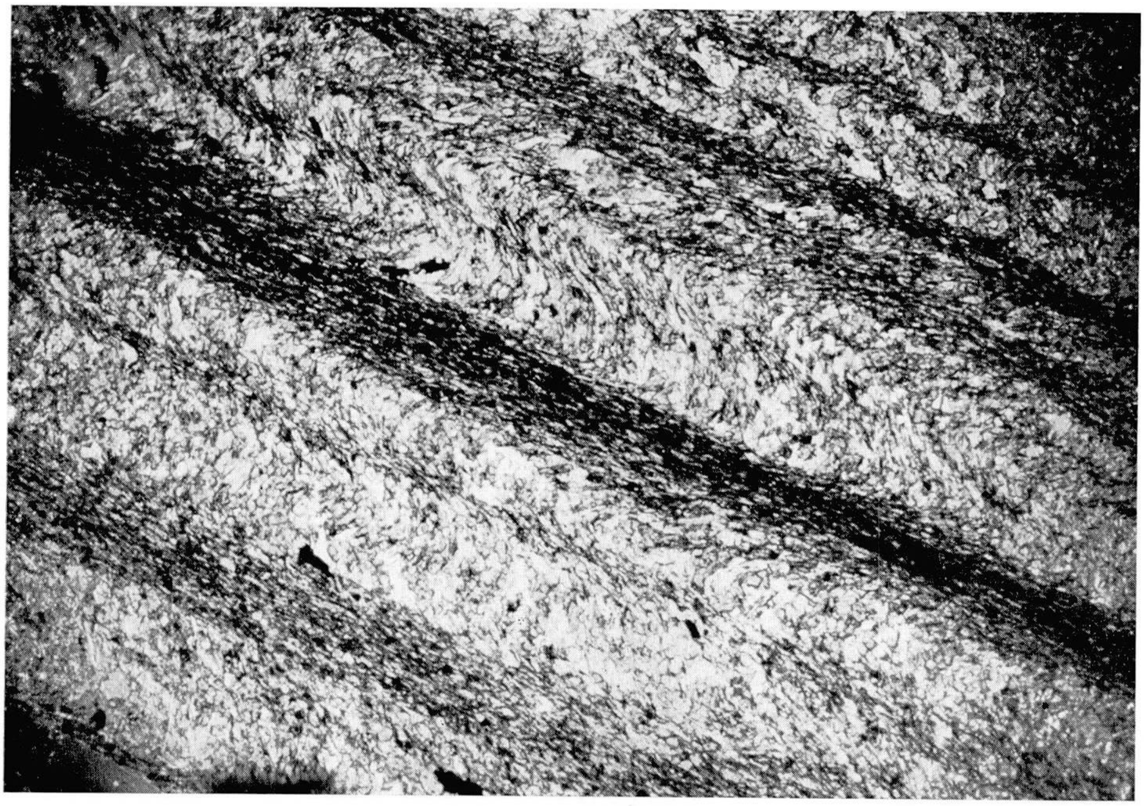

Fig. 4. Pressure solution stripes developed from crenulation cleavage in Jurassic schists of the Inferno Series, Val Camadra, Ticino.

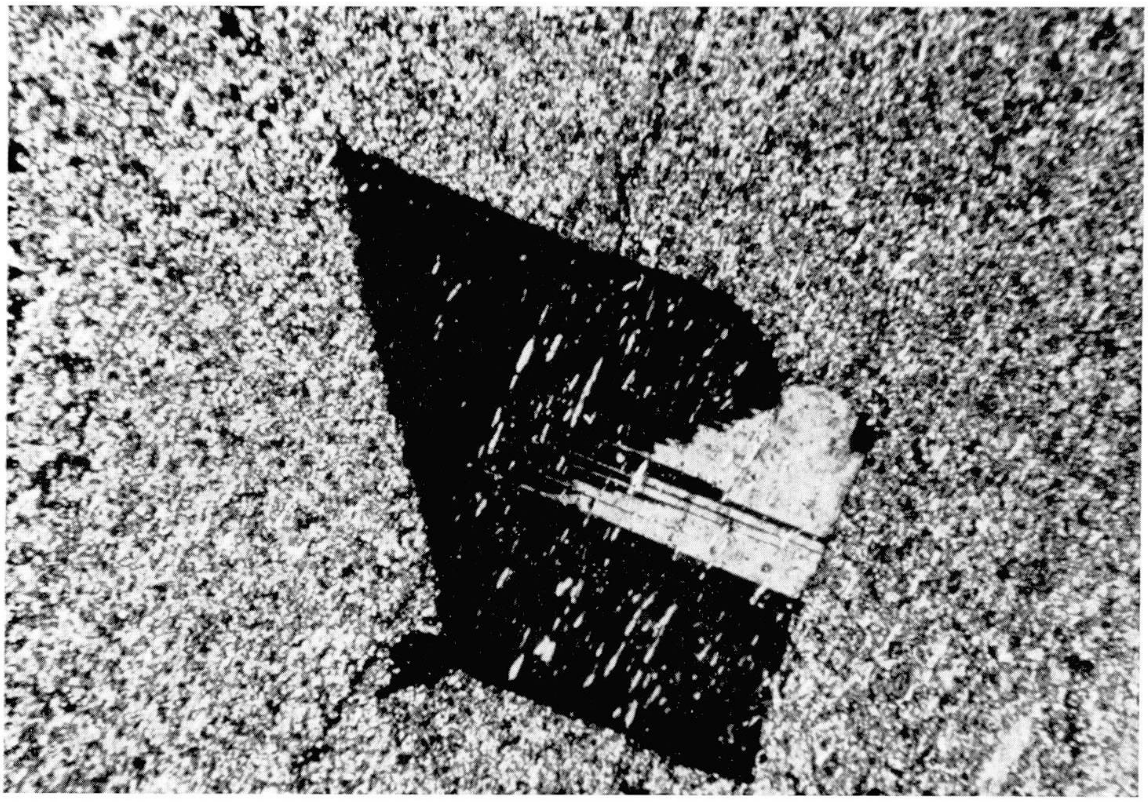

Fig. 5. Post-kinematic albite porphyroblast in limestone from the Sion-Courmayeur zone. Val Ferret, Valais.

Fig. 6. Syntectonically formed garnets with "S"-shaped inclusion trails. Val Piora, Ticino.

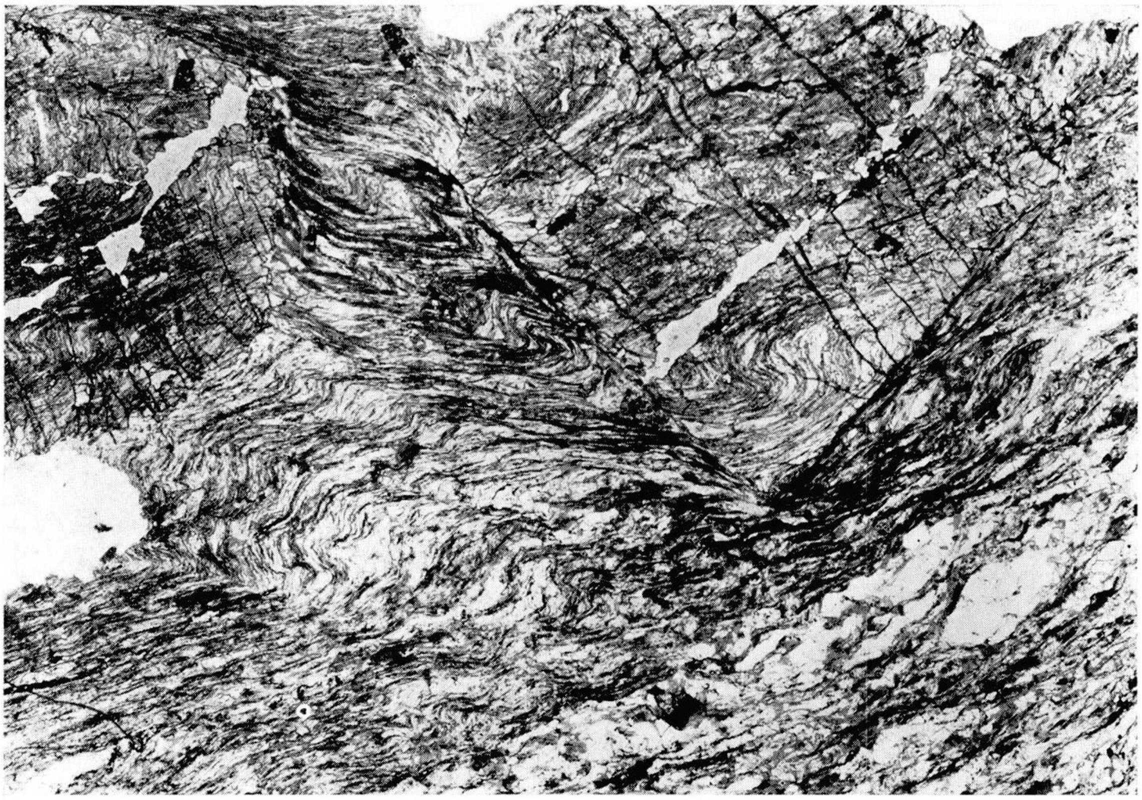

Fig. 7. Garnet porphyroblasts helicitically overgrowing D_2 microfolds in schist of Liassic age, Passo di Naret, Ticino.

Fig. 8. Idiomorphic garnet and staurolite porphyroblasts showing static overgrowth of previously folded compositional layering. P. Molare, Ticino.

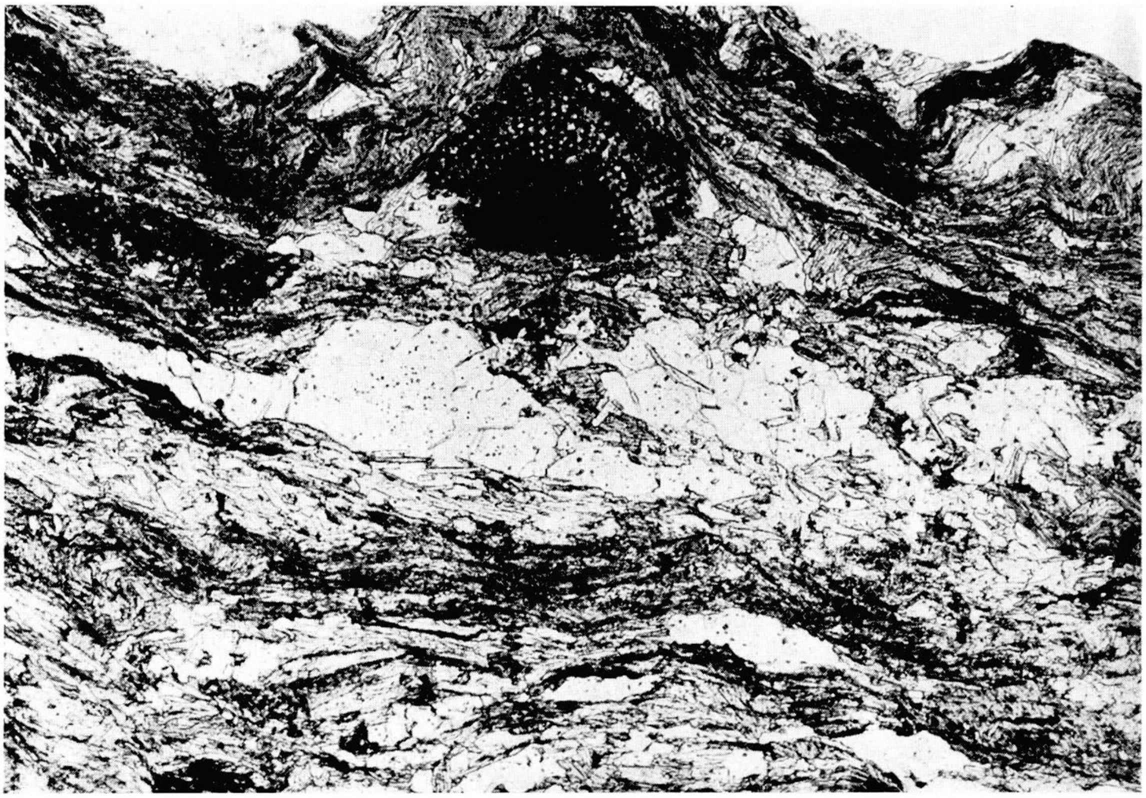

Fig. 9. Well preserved fossil fragments in garnet-kyanite-staurolite schist.

Fig. 10. D_3 crenulation cleavage developed in mica schists around large post D_2 garnet. Val Cavagnoli, Ticino.

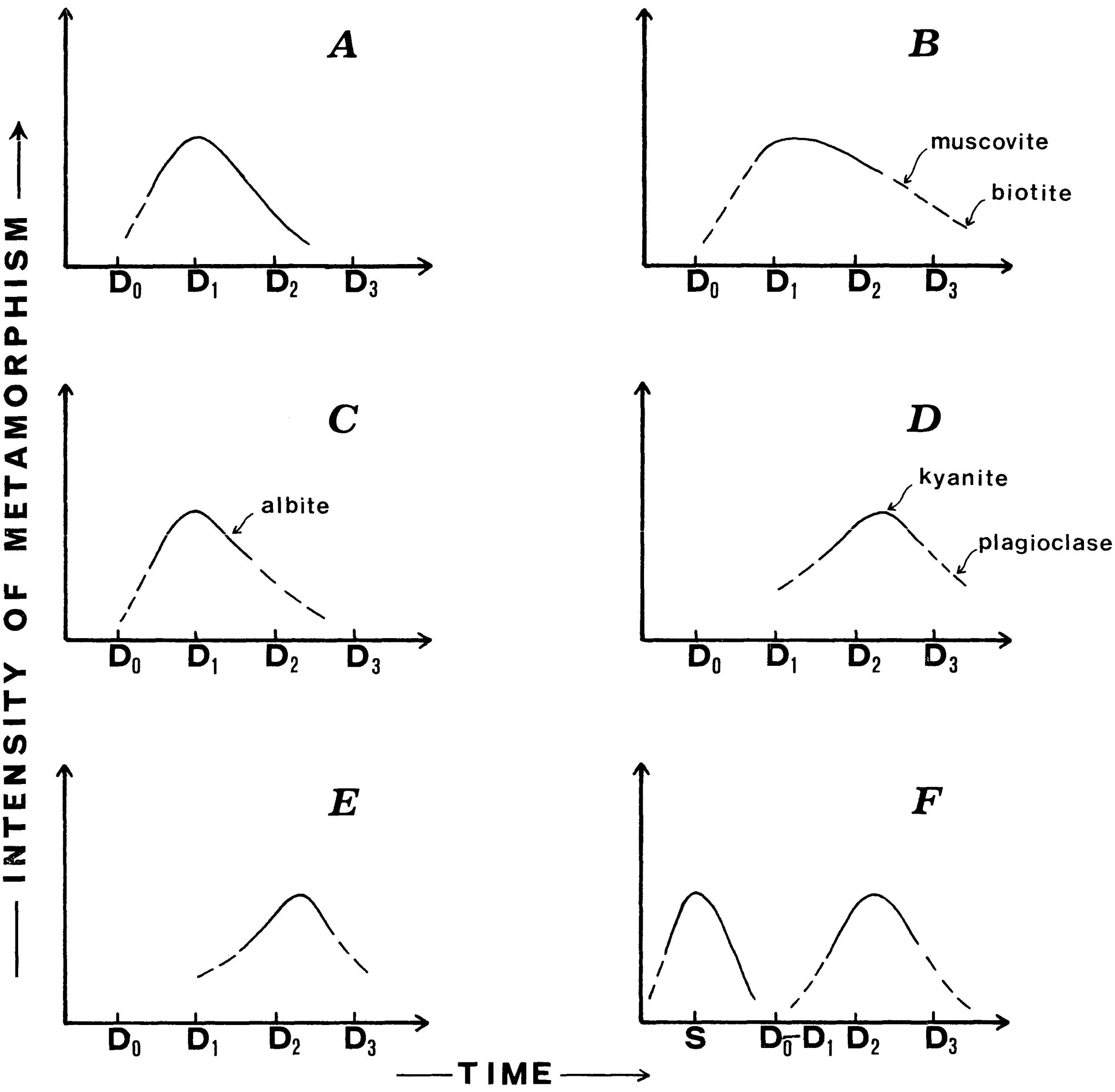

Fig. 11. Schematic representation of the relationships of deformation and crystallisation in various Alpine tectonic zones. The following points must be made concerning these graphs, in which time is represented horizontally:

1. Phase nomenclature (D_0, D_1, D_2 etc.) is only valid for the particular zone to which the graph refers. Tentative correlations are suggested in the text. 2. The intensity of metamorphism, which should be represented by a number of variables, is essentially assessed according to the degree of chemical reconstitution of the rocks and the presence of index minerals. There is no vertical scale – a peak only represents, for a particular zone, a moment during which the effect of metamorphism was at its height.

A: The Helvetics in Valais, Switzerland.
B: The cover of the Gotthard massif (cf. Cobbald, 1969).
C: The Sion-Courmayeur zone (cf. Burri, 1969).
D: The Lower Pennine nappes (cf. Hall, 1972).
E: The Dent Blanche nappe (Pillonet klippe, cf. Dal Piaz and Sacchi, 1969).
F: The Sesia Lanzo zone (cf. Dal Piaz et al., 1972).

D_0 represents a phase of gravitational movement.
S in graph F represents the Cretaceous phase of subduction.

of a mountain chain. Recent investigations in the covers of the Belledonne and Pelvoux massifs indicate considerable variation in the plunge of the main fold axis within an undeformed axial surface, as well as a variable relationship between the fold axis and the direction of maximum elongation (GRATIER et al., 1973, especially p. 28, 29, 43). These variations have been attributed to interference of the main Alpine deformation structures with the east-west Cretaceous structures which are known to exist in this area and which become the dominant structural features further south. No doubt this is a likely explanation especially as an unconformity is known in rocks of Upper Cretaceous age but some variation in the attitude of the fold axis, and particularly in the angle between X and the axial directions may be due to increasing strain. The so-called "tectonique transversale", characteristic of paracrystalline structures in the Franco-Italian Alps (i.e. the main structures of the internal crystalline massifs and schistes lustrés) is exactly what one should expect in areas of high strain. We shall return to this important point, as there still seems to be a tendency to derive regional strains and displacements from axial directions: east-west structures do not necessarily imply north-south displacement or compression.

THE ULTRAHELVETIC ZONE

Events in the Ultrahelvetic zone vary in complexity along the mountain chain. In the Valais, after the initial period of gravity emplacement (and "diverticulation"), the sequence was submitted to the same deformational and metamorphic history as the Helvetic rocks. Further west, in France, early east-west folds were formed in pre-Nummulitic times (BARBIER, 1948; BARBIER and BARFÉTY, 1972). To the east, in the Val Camadra-Greina area, the structural sequence is similar to that of the Ultrahelvetic units of the Valais; sliding and thrusting preceded the development of slaty cleavage and internal deformation, and these events were followed by two sets of crenulation cleavage. COBBOLD (1969) described these structures and showed that the metamorphism, which reached a peak during and after the formation of the slaty cleavage (see figure 2), continued to influence the rocks throughout the deformational sequence. Muscovite crystallised after the first of the crenulation cleavages, biotite after the second, observations which suggest a decrease in temperature (see figure 11).

The well-known "fan" structure seen in the Gotthard massif and its folded schistose envelope of Mesozoic rocks is the result of a late stage back-folding associated with the formation of a northward-dipping crenulation cleavage. This cleavage is often associated with extensive pressure solution phenomena even though pressure solution features seem to be rather uncommon during the earlier deformations at higher metamorphic grade. At some localities on the southern side of the Gotthard massif the marked redistribution of silica and carbonates by this process leads to the formation of a tectonic stripe lithology crossing the primary lithological layering (figures 3 and 4).

There is some conflict as to the extent of thrusting and nappe formation before the onset of penetrative deformation. NABHOLZ and VOLL (1963) consider them to have been contemporaneous. This is opposed to views put forward by JUNG (1963), WUNDERLICH (1957, 1958, 1963) and CHADWICK (1968). CHADWICK attributed the initiation of movement of the Helvetic nappes to uplift produced during and by the first phase of internal deformation (his phase B), while the emplacement of the Pennine nappes preceded it. He also demonstrated that the steep mineral lineation represents the X axis of the strain ellipsoid of the first phase of deformation. He pointed out that first-phase fold hinges are markedly curved within the plane of schistosity and suggested that this was probably due to differential strain effects. Radiochronometric ages of north-south oriented hornblendes from the Gotthard massif and its Mesozoic cover suggest a likely correlation between the main lineation and the Upper Eocene-Lower Oligocene event (STEIGER, 1962, 1964).

Structural maps made of the Pennine front, particularly by CHADWICK (op. cit.) and HIGGINS (1964), suggest an evolution of the metamorphic/deformation relationship with recrystallisation lasting longer (or deformation occurring earlier) in the southern regions (cf. figures 6 and 7). In the area discussed by NABHOLZ and VOLL (op. cit.), there is considerable similarity between the structures in the cover of the Gotthard massif and those in the Pennine front, which may reflect their paleogeographic convergence or proximity. Further complications exist to the south in the Molare and Val Piora synforms (cf. THAKUR, 1973; SIBBALD, 1971), towards the Nufenenpass (HIGGINS, op. cit.) and in regions further to the west (LISZKAY-NAGY, 1965). Somewhere in this zone there is a dividing line between those northern areas showing Helvetic-type relationship, with a metamorphic acme during and after a first phase of deformation and those southern areas of Pennine-type, where recrystallisation attains a peak after a second phase of structural evolution.

EXTERNAL PENNINE ZONE (SION-COURMAYEUR ZONE)

BURRI has recently given an excellent account of the geology of this somewhat enigmatic zone in the region between the valleys of Bagnes and Entremont. He also described and illustrated (BURRI, 1969, figure 8) the relationships between phases of folding and the weak metamorphism which affects these rocks. Three sets of folds have been distinguished. The first folds are isoclinal and often intrafolial and are possibly contemporaneous with the emplacement of the main allochthonous units. The micaceous components are oriented parallel to the axial surface of these folds, forming a true schistosity. Metamorphic recrystallisation accompanied the development of these structures, some of which are of hectometric proportions. They generally plunge gently to the south in those regions which are outside the reorientation influences of the superposed deformation. A second phase of folding produced more readily visible structures than did the first phase. They are more open than the early folds and generally plunge eastward at angles of 50 to 55 degrees, with axial surfaces which are sub-parallel to the associated cleavage. A post-metamorphic cleavage is developed here; micas are deformed and reoriented mechanically. Although few large structures are associated with this second phase it may be responsible for some tectonic repetition. The third fold phase produced more open structures, some of which exceed 10 m in amplitude. Their orientations are variable but many plunge from 10 to 50 degrees to the northeast, with an axial surface dipping about 50 degrees or less to the southeast. In general, they are overturned to the northwest and accompanied by a coarse post-metamorphic "axial-plane" cleavage.

Burri mentions the development of albite in the Pierre Avoi digitation. These albite crystals were considered to be "authigenic" by Oulianoff who related their development to the nearby occurrence of Triassic rocks (Oulianoff, 1953). They sometimes exceed 1 mm in length. They have been reinvestigated and are remarkable in several ways: a) many are clearly zoned, b) idiomorphism is the rule, but some show signs of corrosion or dissolution, c) many contain inclusions of calcite and white mica, aligned in continuity with the orientation of the matrix (external schistosity or S_e) (figure 5).

The nature of zonal structure of the albites is somewhat variable. It is commonly due to the concentration of inclusions, often carbonaceous, in the central part of the crystal or along certain crystallographic directions, such as has been described and illustrated by Spencer (1925), in his study of authigenic minerals in limestone from Bengal. Chemical variation in successive zones was revealed by a slight difference in the extinction angle within a single crystal. Microprobe analysis[2]) showed that there is a very small increase in calcium content towards the crystal margin (reverse zoning) and that the average composition of the feldspar is nearly pure albite, never exceeding 1% An.

Of particular importance is the fact that the schistosity fabric of the matrix continues, undeflected, into the albites, in the form of rectilinear inclusion trails. This must mean that these crystals cannot be of authigenic origin (i.e. diagenetic or post-diagenetic), but that they must have formed during a post-kinematic metamorphic event relative to the first phase of deformation. This

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[2]) By G. Burri, Institut de Physique Expérimentale, Université de Lausanne, to whom we are much obliged. A more detailed account of these albites is in preparation.

conclusion concerning the dating of this mineral is identical to that deduced in the Helvetic region (figure 11).

The slight increase in Ca at the margins of crystals, which are often inclusion-free, may point to a rise in temperature during their formation.

This suggests a sequence in which, initially, calcite recrystallised but not feldspar (at least not the bulk of the feldspar porphyroblasts), followed by a stage of feldspar growth which left the carbonate matrix unaltered. This seems surprising as calcite is generally recognised to recrystallise quite easily. It may be that the interlocking of calcite crystals to form the schistose fabric increases their resistance to recrystallisation and reorientation.

Some of the albite porphyroblasts show signs of late deformation, which can be correlated to the subsequent events recognised by the structural study.

To date the deformational and metamorphic events in this zone, it is important to know the upper extent of the stratigraphic column in the Valaisan zone. If, as BARBIER (1948) and BARBIER and TRÜMPY (1955) have shown for the French part of this zone, the succession extends into the Nummulitic, the rocks comprising the zone possibly escaped metamorphism and deformation in Cretaceous times. A second possibility might be that deformation and recrystallisation affected certain deep levels of the sediments in the Valaisan trough, leaving the upper ones relatively intact and with sedimentation continuing, at the same time as the deformation. This would be like the situation in the Western Pacific, for instance, where troughs are the site of simultaneous sedimentation, deformation and metamorphism (cf. MIYASHIRO, 1967). However, it is not very likely that severe deformation and recrystallisation could have occurred in the Valaisan trough while sedimentation was quietly continuing to the north (Ultrahelvetic domain) and to the south (Briançonnais zone).

An alternative explanation may be that sedimentation did indeed stop in Upper Cretaceous times in the eastern part of the zone. The explanation is in harmony with the recognition of the general trend of "younging" of Flysch formations and deformation from east to west. The Maestrichtian age of the Niesen Flysch[3]) a sediment which was presumably derived from the northern part of the Valaisan trough, supports this idea. Some tectonic activity did occur in Upper Cretaceous times, but it is doubtful whether it produced either large crustal shortening or severe recrystallisation in this zone. It seems likely that gravity slides were probably its most important consequence. Basic igneous rocks exposed in the zone near Visp indicate that some fracturing of the crust must have occurred but the time of emplacement of these is not

[3]) It is noteworthy that the Niesen Flysch itself shows signs of metamorphism and internal deformation, although these features are not uniformly developed throughout the nappe (cf. MARTINI, 1972); they may represent the effect of overriding units. The previously reported occurrences of glaucophane in the Niesen nappe are all situated in Quaternary deposits. No glaucophane has been found in numerous sections of Niesen rocks.

precisely known. There is no evidence at present for a high pressure metamorphism of Eo-Alpine age as can be recognised further south.

This discussion suggests that metamorphism, the development of schistosity and strong internal deformation are not older than Paleocene (they are possibly the products of the Upper Eocene-Lower Oligocene event) a deduction which has important implications for the Simplonic nappes.

A possible graph for the Sion-Courmayeur zone might be as shown in figure 11.

This scheme is more or less identical with those put forward for the evolution of the Helvetic and Ultrahelvetic zones. A D_0 phase is postulated to account for the gravitational sliding of the nappes which pre-dates the onset of the main penetrative deformation. This sliding accounts for early movements of the Niesen nappe, and it is possible that all the main piling up of nappe units is due to early tectonic activity under the influence of gravity.

D_2 and D_3 probably correspond to the crenulation cleavages associated with back-folding structures seen in the southern Gotthard and at many localities in the Pennine zone.

THE LOWER PENNINE NAPPES

Over much of the region occupied by the Lower Pennine nappes the major structures appear to have been produced during three major phases of deformation each of which gave rise to folds. Practically everywhere there is a metamorphic peak of amphibolite facies between the second and third phases of deformation, but waning recrystallisation effects tend to outlast deformation and in some places significant recrystallisation has gone on into the period of the third deformation (see figure 11). No localities are known to us of any indication of an Eo-Alpine high-pressure metamorphism; if such a metamorphism did take place, all characteristic minerals and textures have been completely overprinted by later recrystallisation.

The first recognisable phase of structural development led to the formation of large nappes with cores of crystalline basement gneiss and granite. In some places these are large recumbent isoclinal folds with the basement surrounded by a more or less unbroken (although often highly stretched) envelope of dolomitic and ankeritic marbles and quartzites generally attributed to the Trias. At other localities the sheets of basement appear to rest discordantly on mica schists, probably of Jurassic age, and are probably best explained as thrust sheets.

Some workers have noted the lack of internal deformation during D_1. HALL'S work (1972) in the Bosco area, showed that Hercynian structures were still recognisable. At these localities there seem to be no D_1 minor structures and no indication of the grade of metamorphism that accompanied the first phase. MILNES (1973), working in the Simplon region also came to the conclusion that much of the strain now apparent in the rocks developed later than the nappe-forming movements. Most recumbent closures and in particular the frontal folds of nappes can be demonstrably related to later phases of deformation. It may be that gravitationally controlled mechanisms operated in many, possibly most cases of nappe formation. Gravity may have been responsible for the individualisation of the nappes; the nappes were then subsequently subjected to penetrative deformation. This concept may go a long way to explaining certain features of the Pennine nappes as a whole. An early metamorphic lineation and associated isoclinal fold hinges can be seen to be deformed by second-phase structures.

The second phase of deformation produced the main metamorphic foliation schistosity and mineral lineation throughout these nappes. Amphibolite facies recrystallisation culminated in the production of post-kinematic idiomorphic porphyroblasts of alumosilicates, staurolite, garnet and mica. These structures helecitically overgrow microfolds produced during the D_1 and D_2 events (figures 7 and 8). One remarkable feature of these highly recrystallised Mesozoic metasediments is the occasional presence of very well preserved fossil debris described by HIGGINS (1964b) as illustrated in figure 9.

As a result of the prolonged high thermal state of the rocks in this part of the Alps, it is not easy to determine the absolute age of the period of formation of the main schistosity. It may well be correlated with the important thermal event recognised elsewhere to occur during the late Eocene or early Oligocene. This event could be younger than this however; it is unlikely to be older. The schistosity is developed throughout most of the pre-Triassic basement rocks and in Mesozoic argillaceous and calçareous rocks. In the basement areas the intensity of development of the schistosity is very variable, and zones of high deformation (shear zones) are frequently accompanied by sigmoidally shaped schistosity surfaces (RAMSAY and GRAHAM, 1971).

The growth of the large porphyroblasts of kyanite, staurolite and garnet took place after the formation of the main schistosity but as a continuation of the metamorphic regime which gave rise to this schistosity. There was a considerable period of time between the main period of D_2 deformation and the end of metamorphism in the Lepontine area. At some localities recrystallisation continued throughout the third deformation phase and it occasionally persisted after this phase of deformation.

This third phase of deformation produced chevron folds and a crenulation cleavage. The crenulation cleavage is superposed on the micas of the previously crystallised rocks but it does not penetrate into the previously formed porphyroblasts of kyanite, staurolite and garnet (figure 10). Randomly oriented prisms of tourmaline allow an estimate of strain produced by the third phase of deformation (Thakur, op. cit.; a similar late development of tourmaline has been observed by Nicolas in the Stura di Lanzo – cf. Nicolas, 1969).

The third deformation is responsible for a considerable amount of crustal shortening, the formation of large back-folds and the thickening of the nappe pile. As Hall (op. cit.) points out, index mineral isograds have been displaced during the development of these folds (Wenk, 1973, p. 284, also draws attention to this point). Isograds based on plagioclase composition seem to more or less coincide with those based on porphyroblast compositions of the post-D_2 metamorphic acme. Feldspar growth continued throughout the D_3 event. This event is probably of Miocene age. The main D_3 crenulation cleavage passes upwards into the Upper Pennine nappes, where it is an axial plane cleavage to the large back-folds. Thus, the Gotthard fan, the Mischabel back-fold, the Bagnes fan and other structures including the overturning of the root-zone probably all have a common origin and a common age.

THE UPPER PENNINE NAPPES

The Grand St. Bernard nappe and its cover (schistes lustrés)

Three sets of structures appear to be generally developed throughout this nappe. Locally there are additional phases of deformation, generally formed later than the development of the main schistosity.

Several authors equate the first phase of deformation with the formation of the dominant metamorphic planar structure – Zwart (1974), and Muller (1968) in Switzerland, for instance, Caron (1974) and Fiora (1974) in the Western Alps. This deformation phase is generally followed by two sets of crenulation cleavage. Recrystallisation appears to have continued throughout all these phases, a deduction that is somewhat at variance with the generally held view that crenulation cleavage is a post-metamorphic structure. The formation of crenulation cleavage may not always be indicative of a decrease in the intensity of metamorphic conditions; it forms because the rock fabric cannot be reorganised into a new planar schistosity fabric. Although crenulation cleavage is generally indicative of a decrease in thermal state it sometimes forms without decrease in metamorphic grade and in general its presence probably only implies deformation later than some previously formed schistosity or slaty cleavage.

In the schistes lustrés of the Northern Cottian Alps, Caron (1974) has shown that there are several generations of lawsonite, at least one of which is later than a set of crenulation cleavage. This is a situation in which one would expect the development of polygonal mica arcs. As such arcs appear to be lacking, the usually accepted concept which takes them to be indicative of static post-kinematic recrystallisation needs to be amended. The persistance of the dominant schistosity is reminiscent of the situation in rocks of the Sion-Courmayeur zone, where conditions leading to the crystallisation of late albite do not seem to have reoriented the carbonate matrix.

FIORA (1974) has also noted more than one period of lawsonite growth, as well as the very late blastesis of oligoclase, which is akin to the situation in the Lower Pennine nappes (cf. HALL, op. cit.). WARRAK (1974), in an area west of the Ambin massif, straddling the Briançonnais and the schistes lustrés zones, describes a very long and complicated structural-metamorphic history with the development of several cleavages, and prolonged recrystallisation. Again lawsonite appears at different times in the sequence[4]) and some assemblages indicative of high metamorphism post-date crenulation cleavage(s).

Crenulation cleavage systems which have a low dip, are often associated with back-folding. In some areas, the back-folding appears to be contemporaneous with the first of the crenulations (ZWART, op. cit.), in others the second (MULLER, op. cit.), and occasionally both sets are involved in the formation of these structures (BURRI, oral communication on the Val de Bagnes area).

As with the Lower Pennine units, a major question concerns the exact nature of the first phase of deformation, and of its relationship with the formation of the nappes. There are many indications that the penetrative deformations were superposed on a nappe pile, units were tectonically emplaced, possibly gravitationally, before the development of schistosity and internal deformation. The schistes lustrés do not everywhere represent the autochthonous cover of the Grand St. Bernard basement. They were emplaced on the basement by some early tectonic event, a phenomenon known as "substitution de couvertures". The first deformation phase recognised by ZWART (1974) may have to be subdivided into two sub-phases and indeed he does suggest that it was only towards the end of this episode of tectonism that schistosity and isoclinal folding set in.

Two distinct episodes of metamorphism have been recognised in the Upper Pennine zone, the first the high-pressure Eo-Alpine Upper Cretaceous event and the second, a lower-pressure (and higher temperature) Upper Eocene-Lower Oligocene event. There are two basically different views on the development of the high-pressure assemblages; the oldest concept considers them to be the result of piling up of nappes during the first phase of movement. ELLENBERGER, working in the Pays de Vanoise, pioneered the idea of a "géosynclinal de nappes", producing high-pressure parageneses, followed by the development of first an east-west metamorphic lineation and coeval schistosity, then a north-northwest lineation associated with a cleavage (ELLENBERGER, 1958).

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[4]) There are also several generations of glaucophane in the Pennines, but the two minerals do not always coexist.

He recognised the development of late porphyroblasts of glaucophane and albite. Glaucophane appears in both early and late assemblages. ZWART (1974) also concludes that the early high-pressure metamorphism occurred during or even before the first phase of deformation, while the second probably corresponds with the 38 m.y. event. BEARTH (1966) has tentatively suggested a sequence with nappe emplacement first, then compression, folding, internal deformation and recrystallisation, and with transitions between the two stages. In the internal part of the Cottian Alps, MICHARD (1967) has come to much the same conclusions as ELLENBERGER in the Vanoise, with metamorphism (glaucophanitic) setting in after nappe emplacement, with gradual rise in temperature (and possibly falling pressure). This was concluded by growth of albite, white mica and chlorite after a period of back-folding. NICOLAS (op. cit.), however, suggests that the high-pressure metamorphism accompanied nappe emplacement.

Quite a different interpretation of the metamorphic assemblages has been put forward by DAL PIAZ et al. (1972). They postulate the development of the high-pressure parageneses during a phase of subduction which preceded nappe emplacement (see also the later section on the Dent Blanche nappe).

We have already referred to the so-called "tectonique transversale" of the Franco-Italian Alps, where east-west structures are widespread. In fact these structures give the major tectonic features of the southern part of the Val d'Aoste, the Dora Maira, Grand Paradis, Ambin massifs and schistes lustrés etc. There is disagreement as to the age and significance of these structures (see summary in BERTRAND, 1968). They are often attributed to north-south displacement of material. The folds are, however, overturned both to the north and to the south (and MICHARD, op. cit., has also noted a certain degree of curvature of the fold axes, either towards the southeast or towards the southwest). Another interpretation will be put forward here: the east-west structures may have rotated into this position from say, a north-south direction, due to high strain. This is the interpretation proposed for the Croix de Fer structure in the Chamonix-Martigny synclinal zone (AYRTON, op. cit.), based on theoretical ideas developed by RAMBERG (1959), FLINN (1962) and RAMSAY (1967). More recently SANDERSON (1973) has offered a similar explanation for the so-called "tergiversate" folds of Northern Cornwall and Devon, overturned both to the east and to the west. Early "transversal" (i.e. north-south in the Central Alps) structures have been observed in the Molare region (THAKUR, op. cit.), and in Val Piora (SIBBALD, op. cit.). Synmetamorphic west-north-west to north-west folds have been observed by DAL PIAZ and SACCHI (1969) in the Pillonet klippe (see below). Also, there appears to be a general change in the directions of main axial trends in the Ticino, as one goes towards the root-zone, which may also be explained in a similar way and correspond to a strain gradient.

The attraction of this concept is that it involves no drastic reorientation of the principal strain axes, only of the values of the finite strains. NABHOLZ and VOLL (op. cit.) have commented on the constancy[5]) of the stretching direction in the Gotthard area.

The Dent Blanche nappe

Not much data is yet published on the structure and metamorphic features of the highest of the Pennine nappes. On the Italian side, it appears that the basement gneiss of the nappe and the underlying schistes lustrés have undergone a similar structural evolution. In the Pillonet klippe, for instance, DAL PIAZ and SACCHI (1969) have defined three phases of deformation: D_1 is represented by a north-west to west-northwest lineation, possibly a stretching lineation; ubiquitous tight to isoclinal folds trending west-northwest to north-west and with horizontal axial surfaces formed during D_2 – they are synmetamorphic and correspond, according to the authors, with the east-west ("transversal") folding described in the Cottian and Graian Alps; deformation during D_3 produced north-east-trending flexures and kinks.

Again, no early folds with a longitudinal trend have been observed.

Metamorphic activity reached a peak during and after the second phase of deformation, while D_3, predominantly post-metamorphic, may be correlated with crenulation cleavages associated with the back-folding.

A metamorphism/time graph for this unit appears in figure 11.

Work in progress on the Swiss side of the Dent Blanche suggests a similar sequence of events. In the Val de Moiry, for instance, various structures including a north-west-trending lineation are deformed by a prominent gently-dipping crenulation cleavage associated with back-folds, some of hectometric dimensions. These cleavages are found above and below the thrust-surface, which itself is much less folded than the rocks on either side. This intriguing feature is especially clearly seen in the magnificent cross-section at Zermatt: the major back-fold hardly seems to affect the thrust-surface at the base of the Dent Blanche nappe. Perhaps the last movements of the nappe post-date the back-folding phase[6]). Another explanation may be that, for mechanical reasons, the thrust took up the deformation in the form of horizontal translation rather than through the formation of folds. The thrust-surface is however not perfectly planar, and gentle undulations do affect it.

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[5]) DURNEY, in the Morcles-Diablerets-Wildhorn ensemble has, on the other hand, demonstrated a considerable amount of variation in the direction of stretching, but this appears to be related to local, differential movement and strain at different levels of the nappe pile (DURNEY, op. cit). It may also be dependent, in part, on the Alpine arc.

[6]) The superposition, near Zermatt, of the Dent Blanche nappe on a Flysch formation of presumably Eocene age (Barrhorn Series) is an indication in this respect.

A synthesis by Dal Piaz et al. (1972) correlating radiochronometric data with petrographic and structural evidence suggests that a complicated series of events took place in the Sesia-Lanzo zone and in other units of the internal parts of the Northwestern Alps. During the Eo-Alpine metamorphic event (of Cretaceous age) high-pressure assemblages were formed, in which glaucophane was at first randomly oriented. Mineral orientation developed as the material was subducted along a Benioff zone and then moved back up towards the surface. This was followed by gravitational movement of nappes (during which, presumably, recrystallisation was at a minimum), and a second metamorphic episode produced the greenschist assemblages, with a peak at 38 m.y. The piling up of nappes would be responsible for a rise of temperature, not of pressure. Late phases of deformation affect the whole edifice.

A metamorphism/time graph for the evolution of a large portion of the Upper Pennine units might be shown as in figure 11. This shows a phase, preceding development of the nappes, during which the blue-schist assemblages formed. There may be a causal relationship between the early metamorphism and the initiation of nappe development, due to an increase of the pore-fluid pressure in certain zones.

PREALPINE NAPPES

Information on the deformational history of the Prealpine nappes is not yet available, but it is quite evident that parts of this nappe pile have undergone penetrative deformation and developed schistosity and cleavage. Many parts of the Prealpine nappes seem to have been submitted to bulk translation with little internal strain.

From the metamorphic point of view, more is known (Martini, 1972). Weak recrystallisation is seen in some of the Prealpine units. The degree of metamorphism seems to increase upwards in the nappe pile, with stilpnomelane appearing in the Gets nappe, the highest tectonic unit in this segment of the Alpine chain. The Gets and Simme nappes are of very internal origin, and are far travelled. It is therefore remarkable that they managed to escape internal deformation (large volumes of Simme Flysch show hardly any sign of schistosity or cleavage). This is probably because transport occurred at a high tectonic level. Penetrative deformation was probably taking place at deep tectonic levels allowing nappes in the upper levels to slide on surfaces of décollement. It seems likely that these nappes (with Flysch deposits of Upper Cretaceous age) slid away northwards from their roots and only later became involved in crustal shortening with concomitant penetrative deformation. These nappe packets may have been the "surf boards" riding the front of the main orogenic wave. Gravity seems to have been the principal force responsible for the emplacement of these units and it appears that the more internal the origin of the nappe, the greater the rôle of gravity in its development and emplacement: in LUGEON's words of 1901: "plus la racine est lointaine (interne), plus est grand le chemin parcouru par la nappe".

SOUTH OF THE INSUBRIC LINE – THE IVREA ZONE

Investigations are under way in the region of Finero with the purpose of unravelling the detailed metamorphic/deformational history of the mafic-ultramafic rocks of the Ivrea Zone (for the fundamental geology of the region, cf. SCHMID, 1967).

Although at this stage conclusions are somewhat premature, it is apparent that a number of structures and metamorphic features are superposed on the main (Hercynian) rock fabric and metamorphic assemblages.

It is likely that the large antiforms which constitute the major structures here are due to Alpine tectonics. It is tempting to correlate formation of the locally prominent flaser structure with the few 170 m.y. dates that have been obtained on micas in this region (McDOWELL and SCHMID, 1968). A gently-dipping cleavage is possibly akin to the crenulation cleavages related to back-folding so evident north of the Insubric Line.

CONCLUDING REMARKS

Although data are still lacking from many key areas, kinematic pictures are slowly emerging from detailed structural investigations throughout the Swiss (and Franco-Italian) Alps.

Firm correlations are often difficult to make from zone to zone and may be impossible in certain cases. For example, an event classified as D_1 in one zone may have occurred at the same time as one classified as D_3 in another. In some zones (e.g. Briançonnais zone) thick masses of almost undeformable dolomite of sluggish metamorphic reactability may separate zones where deformational and metamorphic sequences are more easily established. Domains which were far apart are now juxtaposed. In spite of these reservations, it is likely that the first phase of penetrative deformation in the Helvetics is coeval with the second in the Lower Pennines, and the arching of the Gotthard massif and of the Helvetic nappes is probably correlated with the third Pennine phase. The longest, most complicated and least known history is possibly that of the Upper Pennine units. The latter part of this history seems to some extent intermediate between that seen in the Helvetic and Lower Pennine elements.

An important contribution of this type of analysis is the fact that recrystallisation often outlasts the formation of crenulation cleavage. A corollary, in the absence of polygonal arcs, may be that these do not represent static, mimetic, post-kinematic recrystallisation, but possibly synkinematic (MISCH, 1969) or even pre-kinematic (to some extent – cf. HIGGINS, op. cit.) metamorphism.

The late appearance of lawsonite (cf. CARON, 1974, in particular) may lead to a reconsideration of the conditions of its formation. Is subduction really necessary, or, as suggested by CARON, could local structural and chemical factors control its stability? NICOLAS (op. cit., p. 371) has also suggested a mechanism of segregation of synkinematic lawsonite and glaucophane in different parts of folds by differential movement. These observations should trigger off renewed interest in stress-induced recrystallisation, "tectonic overpressures" and the importance of chemical factors in catalysing recrystallisation.

The interpretation of the axial direction of folds is a somewhat complex matter; it is now realised that there is no simple correlation of axial direction with translation direction or strain axes. It is well established that a fold hinge may begin its life in one direction, and that it may become subsequently reoriented through progressive deformation and increasing strain. Finally, at high strains the fold-axis is likely to become aligned sub-parallel to the direction of maximum elongation. The geometry of many structures should be reconsidered in this light, and there is no doubt that this will lead to a rethinking of the likely displacement history.

Does the recent work show any improvements on ARGAND'S views of the structural evolution of the Alps? Certainly our appreciation of the succession of events has been sharpened. The mechanism of back-folding has been reinterpreted; back-folds result from a late stage shortening of the crust, with the development of a cleavage, as a rule affecting an already constituted nappe pile. Back-folding is thus not due to "encapuchonnement" (ARGAND, 1922; 1934), nor is it really a back-*sliding* phenomenon, if this implies primarily the action of gravity – LEFÈVRE (1968) has rightly criticised the use of the term "rétrocharriage", from this point of view.

Another important advance is the recognition of periods of considerable mineralogical reconstruction during periods of deformation when the rocks were not undergoing active straining. The main static phase could well mark the stage of crustal "lock-up", when the two colliding plates had been firmly jammed together.

Recrystallisation often outlasted the back-folding phase. This may be dependent on local factors and particularly on proximity to the Ticino "hot spot". It might also be explained by energy released by internal deformation and strain; an increase in the amount of friction might lead to a local increase in temperature, which could exceed specific mineral reconstruction thresholds (cf. Reitan, 1968a and b). The marked tendency of feldspar to crystallise considerably later than many other metamorphic minerals is an important feature in many metamorphic areas that is worthy of further study: it may well be due to relatively high metamorphic pressures (Banno, 1964).

Another point of interest is that the index mineral isograds, in contrast to metamorphic zoneography based on the anorthite content of plagioclase have been displaced by the late back-folding movement. This feature is of vital importance when estimates of thermal gradients are made.

Penetrative deformation seems to have been nearly everywhere preceded by gravity emplacement of allochthonous units, the extent of the gravitational movement increasing from external to internal parts of the Alps (compare, for instance, the Helvetics and the Simme nappes). In the upper nappes there seems to be a consistent time lag between the period of gravity sliding and the onset of internal deformation.

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