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Caledonian-Variscan structures in the Alps - an introduction

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Within the general framework of the Third Conference on "Geodynamics in the European Variscides" the Caledonian-Variscan structures of the Alps were the main topic of discussion during a meeting held at Fribourg, Switzerland, on the 23rd and the 24th of October 1987. Reports of three preceding meetings (Weber, 1985, Walter, 1987, von Raumer, 1988), along with important recently published reviews, show that the classical views of Kossmat (1927) and Stille (1951) on the Variscides of Central Europe have to be considered in the wider framework of a tectonic setting between the Precambrian shields of Africa, North America and the Baltic region. Since Stille's heroic attempts, there has been considerable hesitation in trying to fit the Caledonian and Variscan structures of the Alps into a larger European framework. The delay in arriving at a new synthesis is understandable when it is appreciated that such a coordination not only involves the application of tectonic and stratigraphic criteria, but also the recognition of older structures which have survived Alpine overprinting, and a search for their parallels outside the Alpine orogen.

The Alpine perspective

The Alps of today represent a zone which may have been as wide as 1100 km, before folding, now reduced to a width of 300 km. Within this telescoped structure, it is a major task to distinguish the remnants of pre-Permian structural elements of the Variscan megasuture, along which the European and African cratons were welded together to form part of the Permian Pangea supercontinent.

Recent Alpine cross-sections (e.g. Escher et al., 1987) and the map of Alpine metamorphism (Frey et al., 1974, Niggli, 1973) illustrate the complex pattern of the pre-Permian basement and its Mesozoic sedimentary cover in a spectacular way. As zones of increasing intensity of Alpine metamorphism are traced Permian basement is controlled by its increasing plasticity. Along the northern external sing plasticity. Along the northern external margin the basement appears as upthrust and updomed (ramping) structures surrounded by Mesozoic cover and overridden by nappes of plastic Mesozoic sediments. Farther south, where the grade of Alpine metamorphism is higher, the pre-Permian basement itself has behaved in a highly plastic manner, and has evolved along with its Mesozoic cover into large nappe units of Penninic style. In the South Alps the pre-Permian basement is not affected by Alpine transformations.

Although the Alpine overprint does not facilitate the recognition of older structures, research on Alpine structures helps us to understand the pre-Permian evolution of Europe better in general. Thus we learn that orogenic evolution involving several orogenic phases, over about 110 Ma, is accompanied by characteristic sequences of metamorphic reactions, deformation episodes and recrystallisation processes in a changing environment of pressures, temperatures and chemical activities. This very detailed insight into mountain building processes helps us to understand the pre-Permian evolution which can be deciphered from the Variscan structures of Central Europe. This transfer by analogy of Alpine processes to older orogenic structures can be regarded as a kind of "actualistic law" or extension to the principle of uni-

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formitarianism. It implies that geological history is a sequence of processes which occur on a very small scale, but become visible because of their total effect on a very large scale. Many of the details of the geological processes, which have been observed during Alpine evolution, have been overlooked in Variscan areas because of the telescoping of events which are difficult to separate during the long time-span involved when areas of Variscan and Caledonian metamorphic rocks are under consideration. Nonetheless, a knowledge of pre-Permian evolution of areas outside the Alps also helps in the interpretation of the corresponding structures within the Alps, which are often only preserved as relics.

The contrasting experience of mountain-building processes, by geologists working within and outside the Alpine area, has led to different views about the pre-Permian structure of Europe. Following SUESS (1888), KOSSMAT (1927) proposed a pattern of paleotectonic zones for the Variscan of Europe, which STILLE (1951) interpreted in terms of a sequence of orogenic phases. They spanned the Variscan and Caledonian eras, each era having several orogenic phases and even subphases. This detailed view of the tectonic evolution of Europe was only carried as far as the border of the folded Jura, i.e. it was not extended into the area of Alpine deformation. However, STILLE (1951) was sure, that there had also been major Variscan deformation events within the Alpine tectonic domain, writing (p. 41) "In den Alpen gibt es wohl keinen Raum, von dem man auch nur mit einiger Bestimmtheit behaupten dürfte, dass er vor der grossen alpidischen Gebirgsbildung nicht schon eine gleichfalls recht bedeutende Faltung von variszischem Alter erfahren... hatte." At that time there was already a wealth of literature, going back to 1750, describing older structures within the Alps. Particularly STUDER (1851), FAVRE (1867), ARGAND (1916) and HEIM (1919) gave general reviews of older structures occurring in the Alps.

After a period of hesitation, it is generally admitted nowadays that there are essential parts of Caledonian-Variscan structures partly concealed within the Alps, representing the connection between the Massif Central in the West and the Bohemian massif in the East and including also the elements of the South European Variscan fold belt. Today, the numerous detailed observations gathered throughout the Alps are being pieced together, like puzzle stones, in an attempt to unravel the structural framework of these segments of the Variscan fold belt.

Terminology

When we are considering pre-Permian structures, we have to unravel all events back to the Permian, and rebuild the megastructure of Pangea. Such reconstructions (MATTE, 1986, NEUGEBAUER, 1987, SKEHAN and RAST, 1983, ZIEGLER, 1984, 1987, ZWART and DORNSIEPEN, 1980) show that in Permian times a large mountain belt existed, of which one part is preserved today in the Appalachian and Moroccan mountain chains. Parts of their northeastern prolongation appear today in the scattered pieces of Variscan basement of Central Europe. In the reconstruction of this huge structure, we have to reconcile different nomenclatures used on either side of the Atlantic ocean.

Terms like "Variscan" and "Hercynian" are often used synonymously, although "Hercynian" also appears as a term describing geological events of late Variscan age only. For the sake of general clarity it would be best to stick to STILLE's original definitions of the terms. The original term "herzynisch" meant a given tectonic direction (NW-SE, Harz-mountain) in areas of Variscan deformation in Europe, while "Variscan" embraced all deformation events occurring in Devonian to Permian times, inclusive. Modern isotopic ages lead to the conclusion that there may be pre-Devonian events belonging to the Variscan orogenic cycle, so terms like "early Variscan" or "eo-Variscan" may be useful, and "late-Variscan" could serve for events of Permian age, in preference to geochronologic terms or absolute age dates. The terms used in Appalachian geology complement STILLE's nomenclature. The "Acadian" phase of intra-Devonian age (with at least four subphases) predates the "Bretonic" phase of STILLE (which also has several subphases). A late phase of evolution in late Carboniferous to Permian times, is described as "Alleghenian".

The Caledonian era after STILLE comprises the orogenic phases from Ordovician to Silurian times. The term "Caledonian" itself is used with different meanings, including the geotectonic evolution of the Caledonian fold belt as well as the evolution of "Caledonian age", which is found in Variscan areas. The central parts of the European Variscan mountain chain, including also parts of the Variscan basement of the Alps, took part in a geologic evolution with both Caledonian and Variscan events.

Independent of the classification of eras major orogenic phases are bound to the limits of colliding continental blocks, giving rise at different zones and times to the Caledonian, Acadian-Ligerian, Variscan and Alleghanian fold belts.

The periods of deformations are frequently described as "orogenies", which raises the question of what is meant by a "phase", and what by an "orogeny"? Their distinction depends upon the scale of observation. As a good example of the importance of scale, we may recall the classical observation of RODGERS (1971) comparing the Taconic large sedimentary unconformities found throughout the northern Appalachians with a small scale Taconic chemical unconformity discovered in a rimmed garnet crystal from Cambrian metasediments.

What appears to be a break in sedimentological or structural evolution on the scale of crustal segments, may appear to be continous on a microscopic scale, giving rise to opposite interpretations. From a regional geological standpoint phases of deformation in higher crustal levels are defined by the ages of unconformities, which necessarily lead to the episodic interpretation of orogeny, as tectonic events need the time for storage of energy to overpass mechanical thresholds. Today these classical structural uncomformities "should be taken to indicate the moment when a given area is overtaken by the orogenic front, rather than a separate event", as the sedimentary records from the northern border of the Variscan area indicate, that orogeny is not a process of separate phases, but more or less a continuous one (FRANKE and ENGEL, 1986). The episodic tectonic phases of upper crustal levels represent in consequence stages in the building up of a larger orogenic belt. Orogenic evolution in lover crustal levels is related to metamorphic overprint and deformation. Phases may be the episodic, local expression of overpassing a mechanical threshold, as for example the onset of a new mechanism of gliding in crystal lattices, a different mechanism of recrystallization or a phase change with their consequent effect on the plasticity of a particular rock during regional metamorphism. Depending on crustal level, an orogenic phase can be represented also by the influx of magmatic rocks, or of metamorphic fluids, with the consequent geochemical changes (e.g. BREWER and LIPPOLT, 1974, DUTHOU, 1979). Orogenic phases such as the Acadian are the large scale expression of a sum of transformations leading to a major, distinct state in the evolution of an orogenic cycle. Orogeny itself can only be appreciated as an evolution through time, comprising the totality of all geological processes such as sedimentation, tectonics, metamorphism and the formation of melts. As orogeny is the geological history between crustal plates, one orogenic phase may lead already to the final consolidation of a fold belt. In general, depending upon velocities of plate motion an orogeny may last for 80–150 Ma, and in consequence may comprise several major orogenic phases and the stepwise building up of the orogenic system through the different accretions (Konsolidierungsphasen, STILLE, 1924).

The Models

In contrast to the surface with its sedimentary records orogenic phases in lower crustal levels can be represented in the space of pressure-temperature-time (P–T–t) as tectonic and metamorphic processes are dynamic and continuous in time. On such a diagram the Barrovian facies series with kyanite-sillimanite-andalusite succeeding one another in time, often observed in metamorphic terraines of Variscan age, may be interpreted as part of a cycle of orogenic evolution, beginning with an initial geotectonic event such as continental collision and following a P–T–t path determined by mountain building and subsequent erosion.

Thermal modelling has contributed to a better understanding of such processes (OXBURGH and TURCOTTE, 1974, ENGLAND and THOMPSON, 1984, ENGLAND, 1987), and different possibilities for P–T–t evolution have been discussed by THOMPSON (1981) and THOMPSON and ENGLAND (1984). From this point of view, an orogeny may be represented by a loop on the P-T-diagram in the simplest case, with stages of high pressure/low temperature, moderate pressure/high temperature and finally a decrease in both pressure and temperature to low values. More complex paths will be followed, if one process of evolution along this simple path is overprinted by a new process thus producing a "break" in the normal P–T-t-path (THOMPSON and RIDLEY, 1987). But in all cases orogenic evolution is combined with migration of a given terrane through different geothermal gradients, and this migration only follows a continuous path, thus pleading again for a continuity of orogenic processes. As global tectonics is the history of thicker piles of the crust, points of different levels in the earth's crust do follow different paths in the P–T-diagram (THOMPSON and ENGLAND, 1984). It follows that such diagrams are the graphical expression of what is meant by "Stockwerktektonik" (WEGMANN, 1956), with each crustal layer responding in its own fashion to changes in physico-chemical conditions.

Bearing in mind that an orogenic evolution may be represented as a kind of loop in P–T space, any stage may be represented as a point on this loop, the corresponding rock series having their proper mineralogical compositions depending upon the pressure and temperature at this point. Thus we should not distinguish a "Hercynian-type evolution" (ZWART et al., 1978) of Central Europe, characterised by low pressure/high temperature metamorphism from an "Alpine-type evolution" in the Alps, characterised by high pressure/low temperature evolution. Both should rather be seen as "points" on one type of orogenic loop, representing the general type of orogenic and metamorphic evolution which occurred during both Paleozoic and Mesozoic-Tertiary times.

Taking into consideration the P–T-t loop model for orogenic evolution of deeper crustal levels, we can also imagine that such a process of evolution may stop at a given moment and given crustal level, leaving zones of different "maturity" in terms of their orogenic evolution, the "time-space realms" after ROBINSON (1983). The zones of Variscan Europe established by KOSSMAT (1927) have to be interpreted as an image of the evolution through time and at different crustal levels. At present, they are interpreted as different nappe units of Variscan age, in which different grades of metamorphism are exposed due to differences in the depth of erosion (WEBER and BEHR, 1983, BEHR et al., 1984). Although the recognition of these zones has previously ceased at the "Alpine front", we now have enough data to include the Alps also in these Variscan structures.

The Variscan units in the Alps

Already KOBER (1927, 1928) interpreted parts of the Eastern Alps to represent the "Antivariszikum", and in analogy to the northern "Rhenoherzynikum" they were interpreted by STILLE (1951, p. 58) to represent the "Antirheniden", and he even spoke of "Antirhenoherzynikum" and for the more internal parts he created the term "Antisaxothuringikum". But such interpretations were limited to the less metamorphic Paleozoic units, as the real difficulties arise only, when high metamorphic series have to be compared. Besides this comparative "stratigraphy" the major problem was to reverse the Alpine tectonics. Speaking with TRÜMPY (1960): "The history and structure of the Hercynian Chain is extremely complex, and there is no reason to believe, that any part of the future Alps was not affected by these movements." From recent paleogeographic reconstructions (CLAR, 1970, SCHÖNLAUB, 1979, TRÜMPY, 1980, DEBELMAS et al., 1983, WILDI, 1985), it is possible to deduce the original positions of the different Alpine tectonic and sedimentary zones, by reversing the effects of Alpine tectonics. Such reconstructions support the idea, that the many basement relics of the Alps must have had their origin in parts, which today belong either to the Central European or to the Adriatic blocks. In a very general way the main tectonic units, the Helvetic, Penninic and Austroalpine realms, represent in the same sequence more internal to more external parts of the former southern wing of the Variscan chain, thus giving way to a two-sided structure of the Variscan orogene perhaps comparable to the extra-Alpine N-S section from France to Spain (MATTE, 1986).

In the western part of the *Southern Alps* basement is represented by segments of deep and intermediate crust (HUNZIKER and ZINGG, 1980, ZINGG, 1983), where sediments of Precambrian to lower Paleozoic age and mafic-ultramafic rocks suffered amphibolite to granulite facies metamorphism of Ordovician age.

After SCHÖNLAUB (1979) and FRISCH et al. (1974) the *Austroalpine basement* is underlain by late-Precambrian and early Paleozoic magmatic-sedimentary rock sequences, where basic-ultrabasic rocks represent island arc or active continental margin environments (NEUBAUER et al., 1987). Formation of eclogites (subduction) is followed by collision, high grade metamorphism and anatexis. When drawing a paleotectonic map of lower Carboniferous times, this basement of Caledonian age represents (NEUBAUER, 1988) a more intern (northern) situation. Farther to the south separated by an ophiolite zone of Cambro-Ordovician age followed a marine basin with detrital and shelf sediments, where a pre-Upper Ordovician trangressive conglomerate (Taconic phase?) reveals the existence of an older basement still farther to the south. A new tectonic phase is indicated through the formation of syntectonic flysch deposits of Carboniferous age. Also the Silvretta area represents a zone of high grade metamorphism (GRAUERT, 1969, FLISCH, 1987), as older, pre-Cambrian units were welded together with metabasic units (Cambro-Ordovician) and were intruded by Ordovician granites, before the main, early Variscan deformations took place. From the widely distributed eclogites and their metamorphic overprint (MAGGETTI et al., 1987) it must be concluded, that early Paleozoic subduction was followed by collision tectonics.

For the *Penninic realm* of the Eastern Alps (Tauern window) the greenstone sequences of early Paleozoic age were interpreted as back-arc and island arc settings (FRISCH and RAAB, 1987). In the large Penninic realm of the Central and Western Alps it is still difficult to obtain a reasonable view about the paleogeographic and paleotectonic situation of the different highly transformed basement relicts. After DAL PIAZ et al. (1972) "continental basement comprising Hercynian high temperature parageneses displaying a zoned distribution, and granitoid rocks extended from the Penninic zone of the Meridional Alps". The wide occurrence of Carboniferous and Permian sediments indicate, that the late Variscan basement was broken down into different Horst-Graben systems, where the formation of detrital sediments was accompanied by volcanism. Late Variscan granitoids transformed to augengneisses occupy wide parts of the different basement nappes (THELIN, 1983). Notwithstanding these late Variscan complications P. STILLE (1980) interpreted the metabasic series of the Berisal complex to represent the metamorphic products of a lower Paleozoic island arc with a descending slab of oceanic crust, and THELIN and AYRTON (1983) demonstrated, that lower Paleozoic crust is also involved in the Penninic realm.

In the *Helvetic realm* the External Massifs of the Western Alps represent relics of continental crust formed during Caledonian-Variscan times. Their rock series may be subdivided into an older basement and a cover of probably Paleozoic age. From the regional framework it must be concluded that the older basement could represent Cadomian-Panafrican or even older structures. The lithostratigraphic evolution of the cover comprising the formation of mainly detrital sediments, with interlayers of acid and basis volcanics, could represent a flat marine basin of taphrogenic origin during Cambrian and Ordovician times. It is not excluded that locally even pre-Cambrian sediments have been preserved. The geotectonic evolution supposed from Ordovician to Devonian times comprises subduction, collision and obduction with the early formation of eclogites (protoliths of Ordovician age, PAQUETTE, 1987), followed by high pressure kyanite-bearing mineral assemblages, formation of mylonites and folds of pennine style. Layers of eclogites accompanied by ultrabasic rocks can be mapped over several kilometers. They now have to be interpreted to be formed in situ, and in consequence large parts of the External Massifs must have been transformed under conditions of the lower crust before they underwent shearing during formation of nappes. The crustal thickening was compensated by updoming and erosion during Devonian to Dinantian times. This late history led to the formation of the sequence of mineral assemblages from Bi-Sill-GarII to Cord-Sill, Cord-Sill-Kf, formation of anatectic first melts and cordierite bearing incongruent melts. At the thermal peak shear zones developped (JOYE, 1987), which facilitated the income of granites of lower Carboniferous age (Vallorcine-granite).

At the surface contemporaneous formation of detrial sediments (Visean flysch) is accompanied by acid and basic volcanism. Locally Devonian basic rocks of back-arc character or ensialic rifting occur (MENOT, 1986). The late stage evolution comprises the formation of intramontaneous horst-graben systems filled by coarse grained detrital sediments, and the intrusion of late-Variscan granites and Permian rhyolites.

A comparison of lithologies from the Appalachians (ST. JULIEN et al., 1975; STANLEY and RATCLIFFE, 1987) and their metamorphism (ROBINSON and HALL, 1980) with the corresponding rocks in the External Massifs leads VON RAUMER (1987) to propose an "Acadian type" of crustal evolution for the External Massifs. This pattern of evolution can be followed from southern Brittany and the Massif Central, through the External Massifs and the southern Black Forest to the Bohemian Massif. This zone, corresponding to the "internal" Variscan structures described by MATTE (1986), was interpreted by VON RAUMER (1984) as an analog of "Saxothuringikum", but situated south of the Moldanubian core and is also consistent with the general paleotectonic pattern during early Carboniferous times proposed by ENGEL and FRANKE (1983). MENOT (1987) and VIVIER et al. (1987) even distinguish between external and internal regions in the Paleozoic rock sequences, and it is the merit of MENOT (1987) to have described the ultrabasic-basic sequences of Cambro-Ordovician age in the Helvetic realm.

As the basement relics of all Alpine tectonic realms show a long geologic evolution since pre-Cambrian or early Paleozoic times, the question after the pre-Cambrian crust arises,which necessarily was involved in the whole Paleozoic evolution. HATCHER (1983) gave an excellent example how pre-Cambrian basement in the Appalachian chain is involved in the later evolution. We find a structural behaviour familiar to us, as the pre-Cambrian basement in its Paleozoic framework behaves like the Variscan basement relics from the Alps in their mesozoic framework. In consequence it will be difficult to discover these oldest relics in the Alpine region. As an example of first pre-Cambrian data from the Alpine domain the results of GRÜNENFELDER et al. (1964) and NUNES and STEIGER (1974) may be cited. JÄGER (1983) discussed the meaning of such data, and precise recent results give evidence of Proterozoic and even Archean elements (GEBAUER and GRÜNENFELDER, 1983; GEBAUER, 1986; GEBAUER and QUADT, 1987) as well as from the metamorphic event of Panafrican age (SÖLLNER and HANSEN, 1987), the latter indicating the existence of Precambrian crust.

This short review demonstrates the detailed histories of evolution through time, with early Paleozoic sedimentation and magmatism, including oceanisation, followed by subduction, nappe tectonics, collision, updoming and crustal thinning. Late Variscan tectonic units are characterized by distinctive patterns of sedimentation, tectonics, metamorphism and associated magmatism. As a result, the whole spectrum of Caledonian-Variscan phenomena, known from the type areas of Variscan structures, has also been identified within all zones of the Alps. In a very general way the relics of basement in the Helvetic realm seem to represent pieces of continental crust, whereas in the Pennine and Austroalpine realms large pieces of oceanic crust are observed. The first steps have also been taken towards discovering parallels between the large pre-Permian megastructures outside the Alps with those in the Alpine basement.

In a general view two main periods of evolution seem to be relevant for these areas (VON RAUMER, 1988b). During Ordovician times a major break seems to determine the geotectonic evolution of large areas. Crustal thickening through formation of early Variscan nappes are the dominating process after an earlier rifting period. The continuation of such structures across the "alpine line" towards West could explain the occurrences of lower metamorphic units as "Klippen" above the higher metamorphic basement. As a consequence of crustal thickening the second phase started with the evolution of early thermal domes which, until lower Carboniferous times, still at the thermal peak, were overprinted by mylonitic shear zones in NE-SW, favouring the income of granites of lower Carboniferous age. The regions occupied today by the Alps took in consequence an active part in the long geologic evolution of a zone which has to be seen as part of a megasuture, along which the European and African cratons were welded together.

A considerable step forward in the reconstruction of the Alpine basement was taken at the meeting in Fribourg. Contributions from all five Alpine countries, published in this volume on the Caledonian-Variscan structures in the Alps, show how knowledge of the basement has advanced since the former meeting (VON RAUMER and OBERHOLZER, 1983). These first steps in the coordination of pre-Permian evolution and structures within the Alpine domain are still hazardous, and further work must be done to collect more data. Sedimentological records are needed, covering the detrital sediments of Triassic, Permian, Carboniferous and older ages, to have an insight into the dynamics of the sedimentary basins and to know more about the regions being eroded. Petrological and structural data are necessary to reveal the P-T-t paths of lower crustal levels, indicating thus indirectly earlier nappe tectonics. Such data also should contribute to the discussion, whether the Caledonian-Variscan overprint of older basement units can be seen as one sequence of events belonging to one cycle of evolution, or if a separation of Caledonian and Variscan events leads to a two stage model of evolution. Geochemical and geochronological data are still insufficient for many basement series. In spite of the Alpine overprint, it should prove possible to gather much more data from the different units and crustal levels.

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