Zeitschrift: Schweizerische mineralogische und petrographische Mitteilungen = Bulletin suisse de minéralogie et pétrographie

Band: 54 (1974)

Heft: 2-3: Alpidische Metamorphosen in den Alpen

Artikel: Very low grade metamorphism in the Western Alps

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DOI: https://doi.org/10.5169/seals-42205

Very Low Grade Metamorphism in the Western Alps

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Résumé

Au cours des dix dernières années diverses recherches ont démontré que le métamorphisme régional alpin dans les Alpes occidentales déborde vers le nord et l'ouest la limite externe du domaine pennique.

La preuve de l'existence d'un métamorphisme de très faible intensité dans les zones helvétiques et préalpines repose d'une part sur la découverte d'associations minérales de néoformation dans les grauwackes volcaniques du Flysch nordhelvétique (grès de Taveyanne), d'autre part sur la nature et la cristallinité des minéraux phylliteux, contenus dans diverses roches de série stratigraphique mésozoïque et cénozoïque.

Il est possible de reconnaître dans la formation des grès de Taveyanne diverses zones définies par des associations de silicates de chaux: zone à heulandite et laumontite, zone à laumontite, zone à pumpellyite-prehnite, zone à pumpellyite-actinote. En règle générale le degré de métamorphisme (ou de diagenèse profonde) augmente vers la limite interne du domaine helvétique et aussi d'ouest en est.

En première approximation l'image que l'on retire de l'étude des minéraux phylliteux concorde avec celle tirée des paragenèses de silicates calciques. Notons l'association étroite entre laumontite et corrensite. Il existe cependant certaines discordances; ainsi les données tirées de la cristallinité de l'illite indiquent que les grauwackes à laumontite seraient encore au-dessus de l'anchizone bien qu'elles aient subi de profondes transformations chimiques et minéralogiques.

La cause du métamorphisme de très faible intensité qui a affecté les roches du domaine nordhelvétique est à rechercher dans un enfouissement résultant de l'empilement des nappes et, éventuellement, d'une subduction; enfouissement qui a déterminé une élévation tant de la pression que de la température.

For a long time the extension of the zone of alpine metamorphism was thought to be more or less coincident with the Pennine domain. Typical crystalline schists derived from sedimentary rocks (mostly Bündnerschiefer) and from eruptive rocks (ophiolites) of Mesozoic, possibly Lower Tertiary age, are characteristic of the hulls of the Pennine Nappes.

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In the external part of the Western Alps located to the North and West of the Pennine domain (Helvetic Nappes, Prealps, Autochthon) textural and structural signs of metamorphism seemed to be lacking. Assuredly secondary minerals had been described by several authors in Helvetic rocks, but they were considered to be the result of either authigenic transformations or weathering. Moreover schistosity, sometimes well developped in pelitic beds, is more or less lacking in coarser detritic rocks except near tectonic accidents (faults, thrust planes, etc.); the slaty cleavage of many Flysch shales, for instance in Canton Glaris, wa not considered to result from true regional metamorphism. Finally, accepted ideas on the p-T conditions necessary to induce metamorphism and on the evolution of the alpine orogen seemed to preclude the development of true regional metamorphism in the external zones.

During the last ten years however several observations led to the conception that these so called external zones of the Western Alps had indeed been submitted during the Tertiary to weak metamorphic actions. This view rests mainly, but not only, on the discovery and interpretation of mineral assemblages in the Tertiary volcanic graywackes of the Taveyanne Formation (J. Martini et M. Vuagnat 1965) and on the nature and properties of clay minerals in pelitic rocks, limestones and sandstones, of the Flysch and of the Mesozoic sequence of the Autochthone and Helvetic Nappes (M. Frey and E. Niggli, 1971, B. Kubler, 1969).

Observations of a different kind in the same zones also contributed to establish the idea of a region of weak metamorphism outside the Pennine domain: presence of stilpnomelane in rocks of appropriate chemical composition, content of volatile constituents of coal beds, "rejuvenated" radiometric ages, nature of fluid inclusions in quartz crystals, etc. However, data arrived at by different kinds of methods are not everywhere coherent, in the Helvetic zone, even when restricted to the two main classes of observations: mineral assemblages of volcanic graywackes and nature of clay minerals in pelitic sediments; much work remains to be done.

VOLCANIC GRAYWACKES

The Taveyanne Formation of Uppermost Eocene to Lowermost Oligocene age terminates the stratigraphic sequence of the lower Helvetic Nappes and, in France, of the Autochthon. It is made up of alternating beds of volcanic graywackes and shales often showing a slaty cleavage; the whole formation has a flysch-like character. The graywackes, sometimes very coarse grained, contain up to 90% of basaltic andesite fragments and derivated minerals (F. de Quervain, 1928; M. Vuagnat, 1952). This andesitic magma presumably originated when the North alpine plate was subducted under the South alpine one (J. Martini, 1972). Some remnants of volcanic rocks are known along the

Insubric line; their age is Tertiary but somewhat younger than that of the deposition of the Taveyanne graywackes (H. Ahrendt, 1972). They may be indirectly related to the Taveyanne andesites.

The presence of secondary minerals such as chlorite, albite, several species of lime-silicates was known since a long time (see for instance F. de Quervain, 1928). These parageneses, however, were explained as the result of weathering or of diagenetic transformations on the bottom of the sea. Albite was, in some cases at least, considered as primary albite derived from spilitic lavas.

The recognition that thick sequences of volcanic graywackes in New Zealand had been submitted, as a result of burial, to weak regional metamorphism resulting in extensive development of lime silicates, mostly zeolites, without any deformation (D. S. Coombs, 1954), lead to reconsider the meaning of "alteration" minerals in the Taveyanne graywackes.

Detailed mapping of these rocks between the Arve and Giffre rivers in Haute-Savoie (France) showed that the different kinds of secondary mineral assemblages do not have a haphazard distribution. Firstly laumontite rich graywackes predominate in the outer and central part of the region. However near the inner (Eastern) limit, pumpellyite and prehnite partly replace zeolites.

Secondly, basaltic andesites with fresh basic plagioclases have been found only in restricted zones or structural features: upper and lower margins of thick graywacke beds, calcareous concretions. All these "loci" have in common a strongly calcitic cement. It should be noted that these relics of fresh plagioclases dispose of the hypothesis that albite-rich graywackes are derived from pre-existing spilitic flows rich in this mineral (M. Vuagnat, 1952); it seems that, in most cases, albitization was postdepositional.

Thirdly, a special type of graywacke, rich in albite and chlorite, but almost devoid of secondary lime-silicates was found to have a rather aberrant distribution. These rocks occur in both the laumontite and the pumpellyite-prehnite zones, generally high in the stratigraphic sequence not far from the thrust-plane of the Ultrahelvetic Nappes. The name "facies vert" has been proposed for these graywackes (J. Martini, 1968). However the term "spilitic Facies" would probably be more appropriate if by spilite we mean a basic volcanic rock poor in lime and rich in soda without any genetic implication. This lime-poor facies may partly be the result of tectonic over-pressure but it is more probably related to the nature of the fluid phase present in the pores of the rock during the metamorphism. It is interesting to note that graywackes of this type occur mainly in zones where there is a discrepancy between the nature of the phyllites and the associations of lime-silicates.

In a later phase of study the stage of "alteration" of the Taveyanne graywackes was re-examined along the alpine arc, to the North-East of the Arve-Giffre region. Here again the distribution of rocks of different mineral associations was found to obey a definite pattern. There is an increase in the grade of transformation toward the North-East. In central Switzerland (Uri and Glaris Cantons) graywackes contain prehnite, pumpellyite and some epidote to the exclusion of laumontite except in the most external fringe. In some sectors, in the Kiental for instance, this last mineral was found in the northernmost outcrops of the Taveyanne formation, elsewhere pumpellyite and prehnite are present. Thus here as in the Arve-Giffre region there is an increase in metamorphism toward the internal margin of the Helvetic domain.

All these observations point to the existence of load metamorphism in the Helvetic domain as a result of the piling up of the Prealpine Nappes on top of the Helvetic ones. This edifice of nappes thickened, on the whole, toward the internal part of the domain and also, along the alpine arc, toward the Aar-Gothard tectonic culmination. To this cause of metamorphism we must add the effect of a possible subduction of the Helvetic domain under the already formed Pennine Nappes (Martini, 1972; R. Trümpy, 1973).

This picture of a zone of very weak metamorphism in the external zone of the Western Alps which emerged some ten years ago has since been completed by the discovery of other mineral assemblages in the graywackes of the Taveyanne Formation or in equivalent volcanic sediments. Just south of the Arve-Giffre area, in the Thônes Syncline, graywackes with relic heulandite-clinoptilolite besides laumontite were found, in a limited region laumontite is even absent (G. Sawatzki and M. Vuagnat, 1971, G. Sawatzki, 1974); this means no doubt that where we expect the overburden of Nappes to decrease, we find the limit between the heulandite and the laumontite facies.

Further to the South, in the Clumanc Syncline (Basses-Alpes, France) volcanic graywackes contemporaneous with the Taveyanne Formation but located in a more external position do not contain albitized plagioclases but fresh labradorite. However the glassy volcanic groundmass has already been entirely devitrified into a chlorite-like mineral.

In the tectonic saddle between the Aiguilles Rouges-Mont Blanc and the Aar-Gotthard Massifs, remnants of Taveyanne Formation outcrop not far from Loèche (Valais) near the "root zone" of the Helvetic and Ultrahelvetic Nappes. Here the graywackes show a distinct cleavage. Under the microscope we see the development of fine needles of an actinolitic amphibole associated with abundant pumpellyite (see D. S. Coombs, Y. Nakamura and M. Vuagnat, in preparation). It is clear that near the "root zone" either the thickness of the nappes pile was highest or, more probably the depth of subduction of the Helvetic domain was at a maximum and that stress effects were also important. Therefore it is not surprising to find in this position graywackes characterized by the pumpellyite-actinolite assemblage which represents a link between very low grade and low grade metamorphism. Here the greenschist facies could even be locally represented.

Thus investigations during the last decade reveal in the external zone of the Western Alps the existence of very low grade mineral assemblages. Very similar to those found in other orogenetic zones of the world and ascribed to the effect of very weak regional metamorphism. Moreover the distribution of most of these assemblages obeys a definite pattern: there is an increase in what is considered the metamorphic grade toward regions where we expect the load and hence the pressure and temperature, to have been high. We may already note that in the Alps the load is not due exclusively or even mainly as in the South Island of New Zealand, for instance, to the thickness of the sediment sequence but mostly to the piling up of several nappes and to some extent also to subduction.

PELITIC BEDS AND CLAY MINERALS

The second group of observations leading to the idea of very low grade metamorphism in the external part of the Alps stems from the study of clay minerals either in pelitic beds of the stratigraphic sequence or as constituents of sandstones and graywackes.

In Central Switzerland we must refer to the work of M. Frey and E. Niggli on the Upper Triassic and Lower Liassic pelitic sediments of the Mesozoic stratigraphic sequence (M. Frey, 1969, 1970, M. Frey and E. Niggli, 1971 and M. Frey this issue, p. 489). In a transversal section from the Jura Mountain to the sedimentary cover of the Aar and Gotthard Massifs the use of different criteria: nature of clay minerals, crystallinity of illite, textural changes, gives a rather coherent image of metamorphism increasing from simple diagenesis in the Jura to true greenschist in the Gotthard region. However as there are no volcanic sediments or tuff beds in the Mesozoic it is impossible to correlate the data on the pelitic rocks with the very low grade assemblages of the zeolite facies.

In Western Switzerland and in France work has been done on clay minerals of Jurassic rocks of the Nappe de Morcles roots, of the sedimentary cover of the Aiguilles Rouges Massif, and of the Liassic shales of Bourg-d'Oisans (Pelvoux Massif) and also of the Taveyanne Formation (B. Kübler, 1969, 1974; J. Martini, 1972).

The clay mineral of the fine fraction of the laumontite volcanic graywackes has been recognized as corrensite, a mixed layer phyllitic mineral with alternating talc-like and adsorbed cations layers and chlorite-type layers (F. Lippmann, 1954; B. Kübler, 1973). Corrensite disappears in the pumpellyite-prehnite rocks where we find a slightly abnormal chlorite in the fine fraction. Thus in the Taveyanne Formation there is a strong positive correlation between laumontite and corrensite; the same relation obtains in the Niigata oil field in Japan (A. Iijima and M. Utada, 1971). It is however possible that this correlation depends to some extent on the overall composition of the sediment. We do not know as yet the nature of the precursor mineral of corrensite; it could be derived from a preexisting smectite, from the ferromagnesian minerals or directly from basic volcanic glass.

The criterion of illite crystallinity must be used with caution when applied to rocks of the Taveyanne Formation. In the graywackes, it cannot be used as the geochemical evolution of the rock leads to the destruction of micas. In the intercalated shales the admixture of corrensite and also of detritic mica to authigenic illite makes the interpretation of data very difficult.

Illite crystallinity has been measured in pelitic and calcareous beds located in the stratigraphic sequence below the Taveyanne Formation, such as the Globigerina Shales and the Diablerets Beds of Eocene age and the limestones of the Senonian. From these data it seems that illite from strata situated below the laumontite graywackes still has a low crystallinity indicating that the upper limit of the anchizone has not been reached.

In Central Switzerland some data indicate that the crystallinity of illite from shales intercalated between pumpellyite-prehnite graywackes is distinctly higher, corresponding to the limit between anchizone and epizone. In the Loèche region the crystallinity is high, in agreement with a position in the upper part of the epizone although some people consider that the upper limit of the epizone coincides with the appearance of the greenschist facies.

Illite crystallinity data confirm thus the general trend of increasing depth of burial from laumontite to pumpellyite-actinolite assemblages. However there is some conflicting evidence; we would expect the laumontite graywackes with their original mineralogical composition extensively transformed to be already in the anchizone. We have seen that the upper limit of this zone lies somewhere in the pumpellyite-prehnite zone. It seems thus that there is some kind of shift between the two transformation scales based, one on illite crystallinity, the other on secondary lime-silicates associations. The fact that stilpnomelane has been found in glauconitic Albian beds of the Nappe de Morcles, where illite crystallinity is still low, points to the same lag. As yet we do not know if this situation is general or restricted to the region under investigation. More work is necessary to elucidate this problem.

CONCLUSIONS

The mineral assemblages of the Taveyanne graywackes clearly indicate that these rocks have been submitted to extensive transformations the grade of which increases from Haute-Savoie in France toward Central Switzerland to the Northeast and, in a given sector, toward the inner margin of the Helvetic domain. This gradual change to higher grade conditions is confirmed by the study of clay minerals showing the replacement of corrensite by chlorite and the increase in the degree of illite crystallinity. The same succession has been found in several regions of the earth in relation to increasing depth of burial.

How great was the effective depth of burial of the Taveyanne formation? What is the age of the transformations?

Concerning the first question we must admit that we still lack experimental data on the lower limit of the stability field of laumontite. Thus we must rely on field observations to establish this limit. Except in typical hydrothermal environment, laumontite like corrensite has not been found under superficial conditions, either at the surface of the earth or on the bottom of the sea. D. S. Coombs (1971) gives the lowest temperature limit for laumontite formation as about 190° C. This is in agreement with the geologic conditions found in the Taringutara hills in New Zealand. On the other hand, in the Niigata oil field (Japan) laumontite already appears below a depth corresponding to a temperature of 90°–120° (A. Iijima and M. Utada, 1971). However, from the description given by these authors it seems that laumontite is present in amygdules of volcanic rocks; it is not mentioned as a rock forming mineral. This could maybe explain the lower temperature of formation.

The depth of crystallization of secondary minerals depends of course also on the geothermal gradient. In the Western Alps this gradient is supposed to have been moderate during the Tertiary as a result of the rapid accumulation of the Flysch sediments, of the rather abrupt arrival of the higher Nappes at the end of the Oligocene and possibly of subduction. It seems that a value near 30° C/km would be a maximum. This means that depending on the admitted lower limit of stability of laumontite, the depth of burial of the zeolite rich Taveyanne graywackes was between 3 and 6 km or even more if subduction determined a very low geothermal gradient. Illite crystallinity data would point to the lower of the two values. On the other hand we mentioned that stilpnomelane has been found in the Albian of the Nappe de Morcles (J. Martini und M. Vuagnat, 1970). More exactly the find is located at the Chalets des Sales (Haute-Savoie) about 200 m below Taveyanne graywackes which seem to be at the limit between the laumontite and the pumpellyite-prehnite facies. In Central Switzerland, the occurrence of stilpnomelane in sedimentary rocks of the Helvetic zone was mentionned already fifteen years ago (Niggli, E. et al., 1956). We shall also mention that according to H. A. Stalder and J. C. Touray (1970) fluid inclusions in quartz crystals of the Val d'Illiez Molasse, below the North-Helvetic Flysch indicate temperatures of formation of at least 200° C.

Concerning the pumpellyite-prehnite and the pumpellyite-actinolite facies their lowest temperature of formation is expected to be respectively 240° C and 340° C. This would give minimum depths of burial of 7 and 10–11 km if we take a geothermal gradient of 30° C/km. The experimental work of J. G. Liou (1971) on the stilbite-laumontite equilibrium agrees rather well with these field data, pointing to a lower stability limit for laumontite around 190°

in presence of an alpine geothermal gradient (low temperature / rather high pressure); if however pH_2O is less than p_{total} this limit may be drastically lowered maybe down to about 100° in hot spring regions.

When did these transformations take place? The Taveyanne Formation has a terminal position in the North-Helvetic stratigraphic sequence, its upper limit being either erosional or tectonic. It is doubtful that the primary thickness of the formation was anywhere more than 1 km, in fact it was probably thinner. This precludes burial metamorphism due to simple accumulation of sediments as in most other regions where zeolite facies rocks have been recognized. The burial is mainly due partly to overthrusting or gliding of the Prealpine Nappes which during the Tertiary formed a pile much thicker than the remnants we see totay, partly also to subduction. It is interesting to notice that microscopic data point to the fact that the laumontite facies developped during or after the arrival of the nappes (J. Martini, 1968). The increase in metamorphic grade encountered toward Central Switzerland may be explained by a thickening of the pile of Nappes or/and a deeper subduction. It could also be argued that there was a steeper geothermic gradient near the thermal dome that many geologists see in the Central Alps or more exactly in the Lepontine area of the Pennine domain.

Finally there is a question of nomenclature to mention. Should we use the name of diagenesis or of metamorphism for the transformations that affected the Taveyanne Formation? Most people would agree that the pumpellyite-prehnite and the pumpellyite-actinolite graywackes are true metamorphic rocks. The situation is however different for the laumontite graywackes. In this case some geologists speak of metamorphism, others of diagenesis. The authors of this paper consider that the distinction between diagenesis and metamorphism is essentially a problem of nomenclature; the limit between the two processes depending on rather arbitrary criteria. This problem will not be debated here. Nevertheless we should like to stress that there is a continuity in the progressive transformation of the volcanic graywackes as evidenced by gradual transition between the different assemblages. No doubt accessory factors like porosity, nature of connate water, CO_2 and H_2O activities played their part, but the dominant factor was a gradual increase in depth of burial determining an augmentation in temperature and pressure.

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Manuscript received December 7, 1973.