RENDICONTI Società Italiana di Mineralogia e Petrologia, 38 (2): pp. 543-548
Comunicazione presentata alla Riunione della SIMP in Abano (Padova) il 3 giugno 1982

THE MEDIUM GRADE – HIGH GRADE TRANSITION IN THE REGIONAL METAMORPHISM: An example from the Ivrea-Verbano Zone (Italy)

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RIASSUNTO. — Grado alto, migmatiti, granuliti vengono spesso trattati separatamente, quasi sfuggisse il legame stretto che li unisce.

La formazione « Diorito-kinzigitica Ivrea-Verbano » offre un esempio di come questo legame sia perfettamente accertabile sul terreno.

La P_{H_2O} è superiore a 3 kb nel grado medio in quanto si ha comparsa di sillimanite in presenza di Mus + Qz per la reazione Stt + Mus + Qz → Bio + Sill + H_2O e similari. Nella zona a sill (+ mus + qz) si ha la comparsa di una certa quantità di filoni e sacche pegmatoidi la cui genesi è certamente anatettica (Val d'Ossola, Val Strona). In Valsesia, in Val Strona di Postua, in Val Sessera e in Val del Cervo i mobilizzati possono avere fino a composizione granodioritica. In Val d'Ossola i mobilizzati pegmatoidi scompaiono al break-down della muscovite in presenza di quarzo. Il minimum melt formatosi ha consumato gran parte dell'H_2O la cui pressione parziale scende al di sotto dei 3 kb uscendo dal solidus del granito. La P_{tot} rimane elevata ma la fase fluida è ormai prevalentemente costituita da CO_2; con l'aumentare della temperatura le paragenesi diventano vieppiù anidre e si ha la transizione alto grado-granuliti. Almeno in questo caso non vi era acqua disponibile in grandi quantità perchè si sviluppasse un'estesa anatessi; si può pensare che questa sia possibile solo ove vi sia un apporto consistente di H_2O dal di sotto, come previsto dalla tettonica delle zolle nelle aree in cui avviene subduzione di crosta oceanica ricca d'acqua.

ABSTRACT. — High-grade, migmatites, granulite facies are often considered separately, as if the intimate links among them were not realized.

The « Ivrea-Verbano Formation » of Northwest Italy is a good example of how this connection is clearly ascertainable in the field.

In medium grade terraines P_{H_2O} exceeded 3 kb since sillimanite coexists with the muscovite + qz pair and is formed through the reaction Stt + Mus + Qz → Biot + Sill + H_2O or similar reactions.

In this zone there is a considerable amount of pegmatoid lenses or dykes whose origin is anatectic beyond any doubt (Val d'Ossola, Val Strona di Omegna). More westerly the mobilizates reach a granodioritic composition. In the Ossola Valley the mobilizates disappear rather abruptly at the muscovite + quartz breakdown. The formed minimum melt has drained most of the available H_2O whose partial pressure descends below 3 kb leaving the granite solidus. P_{tot} remains high but, by now, the fluid phase consists mostly of CO_2; as T increases, parageneses become more and more anhydrous till the granulite facies is reached.
The water available, at least in this case, was not enough abundant to allow the development of an extensive anatexis; this is possible only where there is a significant supply of H_2O from below; it is likely that this process may be important only above subduction zones.

The sillimanite - K-feldspar isograd is commonly considered (WINKLER, 1979) the lower temperature boundary of the high grade metamorphism, whilst its higher temperature boundary is represented by the minimum melting curve of granite.

In most cases the sillimanite — K-feldspar isograd is not reached at $P_{tot} = P_{H_2O}$ conditions since P_{tot} commonly exceeds 3.5-4 kb in regional metamorphism; at such condition the disappearance of muscovite would occur by melting in presence of quartz and plagioclase + H_2O.

Moreover, in presence of graphite and Fe-oxides, P_{fluid} does not coincide with P_{H_2O}, even if their influence is higher at low P_{tot}, which is not the case in regional metamorphism (EUGSTER & SKIPPEN, 1967; YUI, 1966).

KERRICK (1972) experimentally determined the temperature shift of the muscovite + quartz = sillimanite + K-feldspar + H_2O isograd for X_{H_2O} between 1 and 0.5 and calculated the corresponding displacement of the minimum melting curve. His results indicate that the lower X_{H_2O}, the larger is the high grade field since the muscovite + quartz — out isograd moves to lower tem-

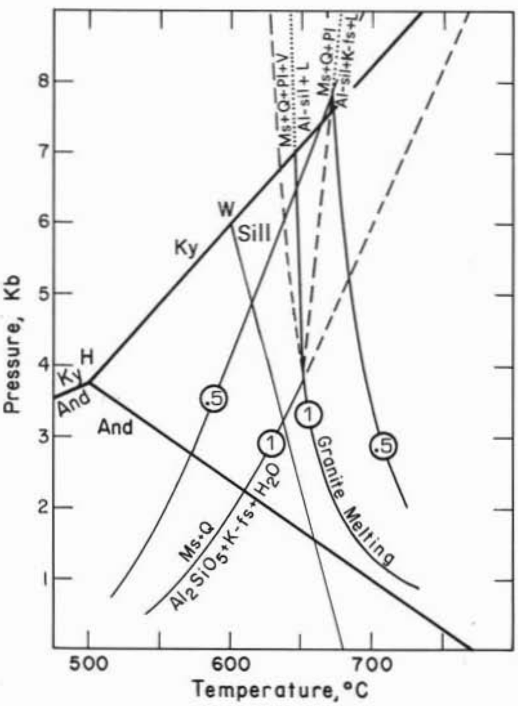

Fig. 1. — *PT* diagram (simplified and modified from KERRICK, 1972) showing equilibrium for the reaction: $Ms + Q = Al_2SiO_5 + K\text{-}fs + H_2O$, for $X_{H_2O} = 1$ and .5 (circled numbers); granite solidus for the same X_{H_2O} values. Stability relations of Al_2SiO_5 polymorphs from HOLDAWAY, 1971 (triple point H) and from WINKLER, 1979 (triple point W).

peratures and the minimum melting curve moves to higher temperatures.

What we can see in the field is that the appearance of anatectic migmatites is commonly connected with the occurrence of sillimanite but in the stability field of muscovite plus quartz. This means that P_{tot} could not exceed 7 kb (fig. 1) since beyond that pressure melting would have occurred in presence (or with production) of kyanite and that the fluid phase should have $X_{H_2O} > 0.5$.

The aims of the present paper are:

— to point out some general features of the transition between the medium and the high grade metamorphism;

— to stress the important role played by the X_{H_2O} evolution in controlling metamorphism and anatectic processes;

— to show that the effects of advanced degranitization commonly admitted in the high-grade terranes can be unrelated to partial melting.

The above considerations will be based on the natural situations occurring in the Ivrea-Verbano Zone (western sector of the southern Alps - Northern Italy), an area that shows, markedly in its eastern part, a good example of transition from medium to high grade metamorphism up to the granulite facies conditions.

The Ivrea-Verbano Zone

The Ivrea-Verbano Zone consists of metasediments (mostly metapelites) that were intruded by the Ivrea basic layered complex.

Its boundaries are mostly tectonic: to the NW it is cut by the Insubric Line, whilst to the SE it comes in contact with the para- and orthogneisses of the Strona-Ceneri Zone (Serie dei Laghi) through an old, rehealed tectonic line of pre-Alpine age (BORIANI & SACCHI, 1973). The attitude of the schistosity is nearly vertical trending NE-SW with a few, open folds with vertical axial plane.

The metamorphic grade increases towards NW (PEYRONEL PAGLIANI & BORIANI, 1967; SCHMID, 1967; BERTOLANI, 1968) and most of the authors think that the intrusion of the basic magma supplied the heat for metamorphism (fig. 2).

As far as the age of intrusion and metamorphism is concerned there is no agreement among the authors. Both ages are definitely pre-Alpine since the adjacent Serie dei Laghi (that shares the same metamorphic and deformational history) is covered by unmetamorphosed late-carboniferous and permo-triassic sediments.

Details on the geological, geochemical and geophysical features of the Ivrea-Verbano Zone can be found in the proceedings of the two symposia that were held respectively in 1968 in Locarno (S.M.P.M., vol. 48) and 1978 in Varallo (Mem. Sc. Geol., vol. 33).

In the eastern part of the Ivrea-Verbano Zone the metapelites are very abundant and prevail by far over the basic rocks. In Val Strona di Omegna and in Val d'Ossola the series begins with the sillimanite + muscovite + quartz (no staurolite) zone, whilst in Val Cannobina one can see the complete transition from the staurolite + kyanite zone to the staurolite + sillimanite and sillimanite + muscovite + quartz (no staurolite) zones since the Pogallo Line (BORIANI & SACCHI, 1973) runs here well within the Ivrea-Verbano Zone and the transition to the Serie dei Laghi is gradual.

The considerations here exposed mostly derive from studies carried out in the Val d'Ossola-Val Cannobina sector.

P, *T* conditions of metamorphism

SCHMID & WOOD (1976) give extimations of *P* and *T* conditions during metamorphism using the grossular content of garnet (in presence of plagioclase + sillimanite + quartz) as indicator of pressure, and the reaction: biotite + sillimanite + quartz = garnet + K-feldspar + H_2O as temperature indicator. In the assumption that $P_{tot} = P_{H_2O}$ the *P-T* range resulted: 9-11 kb and 700°-820° C. These *T* values were clearly too high implying that the rocks should have been completely molten. New *T*, *P* values were recalculated assuming an X_{H_2O} lower than 1 and shifting the obtained temperatures at the point of beginning of melting of a paragneiss. The new *P*, *T* data resulted: 700° C/9 kb, $X_{H_2O} = 0.6$ for the amphibolite facies zone, 710° C/8.7 kb and $X_{H_2O} = 0.5$ for the transitional zone and 710° C/9.2 kb, $X_{H_2O} = 0.4$ for the granulite zone.

SCHMID & WOOD (1976) maintain that the granulite facies affected rocks already undergoing amphibolite facies regional metamorphism. Since no significant difference of *P* resulted between amphibolite and granulite facies they concluded that the series was metamorphosed in nearly the present position and that it was not tilted later.

P conditions are consistent with the interpretation of the Ivrea-Verbano Zone like a slice of lower crust near the crust-mantle transition, but they are too high with reference to the accepted kyanite-sillimanite boundary.

HUNZIKER & ZINGG (1980) give different estimations for *P-T* conditions. Minimum and maximum pressure were recalculated using the same geobarometer as SCHMID & WOOD, assuming ideal mixing and a regular solution model (HENSEN et al., 1975). Temperatures were extimated from the Fe-Mg exchange between garnet and biotite (to be independent of H_2O pressure), using the calibrations by THOMPSON (1976) and FERRY & SPEAR (1978).

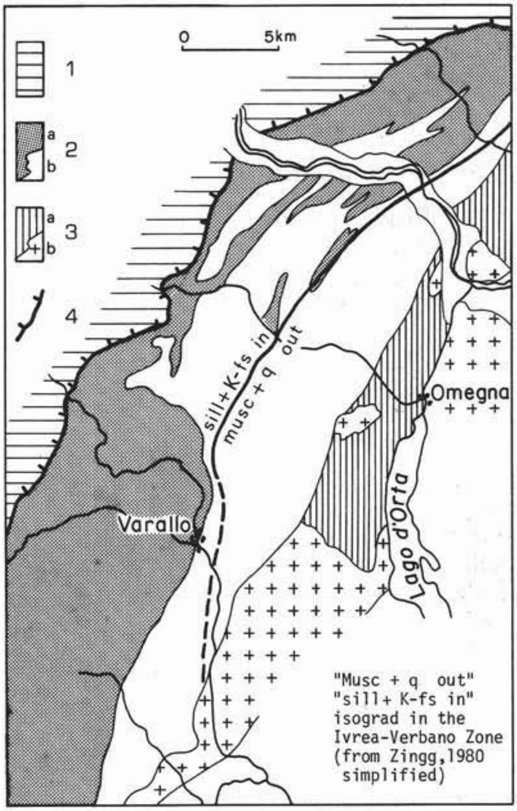

Fig. 2. — Sketch map of the central Ivrea-Verbano Zone. 1) *Sesia Zone*; 2) *Ivrea-Verbano Zone*: basic and ultrabasic rocks (*a*), and metapelites (*b*); 3) *Strona-Ceneri Zone*: gneisses (*a*), Hercynian granites (*b*); 4) Insubric Line.

HUNZIKER & ZINGG'S extimations give a wider range of *P* and *T*; nevertheless the Authors maintain that there is a regular increase in *P* and *T* from the amphibolite to the granulite facies. The cause of the metamorphism is referred to the intrusion of the basic body in nearly unmetamorphosed sediments. These processes are related to the Caledonian event (∼ 478 m.y. - Rb/Sr w.r. isochron on paragneisses) when schistosity and lithological boundaries were flat lying; the series was tilted to the present position during the Hercynian time.

Both SCHMID & WOOD and HUNZIKER & ZINGG share SCHMID'S opinion (1972) that the average pelitic gneiss of Ivrea-Verbano Zone is a restite from which up to 65 weight % of granodioritic magma was removed by partial melting (see also SCHMID, 1978-79). Also MEHNERT (1975) thinks that kinzigites and granulites of the Ivrea-Verbano Zone are restites.

Field and petrographic evidence

As already pointed out by PEYRONEL PAGLIANI & BORIANI (1967) and SCHMID (1967) one can follow a complete metamorphic sequence along the Val d'Ossola from the sillimanite (+ muscovite + quartz) zone to the granulite zone.

Crossing the SE tectonic boundary with the Strona-Ceneri zone between Mergozzo and Candoglia, we find paragneisses consisting of biotite-muscovite-sillimanite-quartz-plagioclase $\pm$ garnet showing intercalations of concordant pegmatite dikes or lenses. Proceeding westward along the northern slope of the valley, before reaching Nibbio, muscovite and quartz are no longer coexistent; at the same time the pegmatite inliers decrease and rapidly disappear.

The same sequence can be followed in Val Cannobina between P.te Gurro and Gurro or between P.te Gurro and Orasso.

Pegmatites are obviously of anatectic origin since their presence is clearly related to a well defined isogradic interval. A pegmatitic melt is beyond any doubt very rich in volatiles (mostly water) and must represent a minimum melt with a very limited amount of melting.

Since these pegmatites are very little or not schistose, the melting temperature was reached during the late or post-kinematic metamorphic stage. SCHMID'S evaluation (1978-79) of 60-65 % (weight) melt removed from the original paragneiss cannot be easily reconciled with the simple observation of the pegmatoid distribution in the eastern Ivrea-Verbano Zone. In SCHMID'S opinion (1978-79), melting occurred under $X_{H_2O} < 1$, $P_{tot} = 9$ kb and $T = 800°$ C conditions, with the production of a melt 6 to 3 times undersaturated in water.

Actually there is no trace of that melt: the only igneous looking rocks in the paragneiss are the above described pegmatites.

We don't want to argue about degranitization of the Ivrea-Verbano paragneisses or about that of many other granulitic terraines (see NESBITT, 1980), we simply state that here it did not occur through partial melting.

In our opinion, substantiated by field and petrographic observations, a P_{tot} estimation of 9 kb is unacceptably high since it is in contrast with the polymorphic transition kyanite-sillimanite, that in Val Cannobina occurs well before the appearance of the mobilizates. This means that the polymorphic boundary was crossed before the reaching of the musc + quartz + pl + H_2O melting point, i.e. under P_{tot} conditions significantly lower than 6.9 kb for $X_{H_2O} = 1$ or 7.3 kb for $X_{H_2O} = 0.6$ (KERRICK, 1972). This is in good agreement with the P_{tot} estimation of HUNZIKER & ZINGG (1980).

There is no need of proposing new P and T values; it is sufficient to point out that X_{H_2O} was close to 1 when the beginning of melting was reached because:

1) it is highly probable on theoretical grounds (WINKLER, 1979, page 21);

2) the anatexis produced a water rich pegmatitic melt.

The formation of such a melt subtracted water to the system and the X_{H_2O} in the pore fluids dropped very quickly; the thermal gradient could only partly compensate the temperature shift of minimum melting due to the lowering of X_{H_2O}. From KERRICK'S (1972) diagram we can see that it is possible to get a melt from muscovite in the stability field of musc + quartz + sill till $X_{H_2O} = 0.6$. When X_{H_2O} falls slightly below this value it becomes impossible and muscovite breaks down in the presence of quartz while anatexis stops.

BROWN & FYFE (1970) pointed out that melting in H_2O undersaturated conditions is possible at T of 800°-900° C, values that are clearly out of any reasonable estimation for our zone.

The sudden drop of X_{H_2O} caused (as also noticed by HUNZIKER & ZINGG, 1980) the rapid replacement of biotite by garnet and the subsequent transition to the granulite facies conditions through dehydration reactions in the solid state.

Mobilizates beyond the muscovite + quartz out isograd are very rare in the eastern part of the Ivrea-Verbano Zone; they could be interpreted as due to in situ anatexis at sites with abnormally high local X_{H_2O}. In the western part the mobilizates occurring in high grade kinzigites and granulites are more frequent. In our opinion also those mobilizates are the result of in situ anatexis; in this case temperatures were higher than in the eastern part maybe on account of the early stages of intrusion of the Ivrea layered basic pluton. However we must stress out that at least part of that pluton was intruded later since the contact metamorphism of the basic body is very evident, as it was noticed by ARTINI & MELZI (1900) in their excellent memory on the petrography of Valsesia.

High grade metamorphism, anatexis and generation of granitic magma

As also pointed out by PITCHER (1978) in his vast and well documented paper on granites, the connection between the generation of granitic magma and anatexis related to high grade metamorphism is not easy to be demonstrated. Many granulites show chemical evidence of having been depleted of granitophile elements during metamorphism; other granulites seem to be not affected by such depletion (GRAY, 1977).

Temperatures and water activity during high grade metamorphism seem to be unadequate to explain the production of large volumes of granitic magma through large scale anatexis.

In fact only certain migmatites are easily explained by in situ anatexis. Nevertheless a certain degree of degranitization of the Ivrea-Verbano granulites is probably consistent with chemical data (see also BORIANI et al., 1982).

A possible mechanism for a degranitization unrelated to partial melting is that proposed by JANARDHAN et al. (1982) for the formation of the charnockites of India: a flux of CO_2 coming from mantle displaces water pushing it upward together with chemicals dissolved in it. This explanation is suggested by the replacement of granite gneisses by charnockites in the transition zone, replacement that is not gradual but with patches and flames of charnockite that penetrate in the granite that is abruptly transformed in a dehydrated and partially depleted granulite.

In the case of the Ivrea-Verbano Zone the transition appears to be gradual and maybe a simple process of progressive dehydratation and migration by diffusion processes of the produced water together with the light granitic elements dissolved in it, is an acceptable explanation.

SCHMID (1978-79) and HUNZIKER & ZINGG (1980) suggested a degranitization through partial melting; the resulting magma should have formed the granites that now we find transformed into orthogneisses in the Strona-Ceneri Zone (BORIANI et al., 1977, 1982).

This interpretation is difficult to accept since the intrusion of those granites occurred $\sim$ 466 m.y. ago (BORIANI et al., 1982) into slightly or non metamorphosed sediments and their main metamorphism took place during the Hercynian cycle (325 m.y., Rb/Sr age on muscovite); how could the Ivrea-Verbano undergo a granulitic metamorphism while in the adjacent Strona-Ceneri the sedimentary rocks remained almost unaffected?

The two zones are not separated by metamorphic breaks except where they are divided by the late Hercynian Pogallo Line (BORIANI, 1970), so their metamorphic history must have been the same, at least for the last, higher temperature, event.

In conclusion in my opinion the Ivrea-Verbano main metamorphism must have been of Hercynian age as well as the intrusion of the layered basic complex. If we accept that degranitization resulted in a production of granitic magma, such magma can only be represented by the late Hercynian granites intruded at the boundary between the Ivrea-Verbano and the Strona-Ceneri zones; but this is difficult to accept both for lack of geological evidence and for geochemical reasons (their initial $^{87}Sr/^{86}Sr$ is too low).

The simplest explanation is that degranitization, if it really did occur, did not result in the production of granitic magma; dehydration reactions proceed right from the very beginning of the metamorphic process. The driven off water is certainly not pure water but contains dissolved chemicals whose species and abundances depend on P and T conditions. Degranitization can be seen as a continuous process of very limited importance that proceeds a pace with dehydration during regional metamorphism without producing spectacular phenomena untill the transition medium grade — high grade. At high grade it may occur through partial melting, but in most cases conspicuous melting is prevented by the scarcity of water. If water is continuously supplied from below in presence of an undergoing crustal slab in a subduction zone, this type of magma generation can be important, but this does not seem to be the case for the Hercynian history of the Ivrea-Verbano zone.

Acknowledgements. — The Author is highly indebted to G. PEYRONEL PAGLIANI for the fruitful discussions and for her precious advice and help in the preparation of this paper. The critical reading of A. GREGNANIN and F. SASSI was fundamental in improving the clarity of the concepts expressed in the manuscript.

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