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HEAT TRANSFER IN THE THERMO-METAMORPHIC AUREOLA OF THE NORTHEASTERN SECTOR OF MT ADAMELLO (TRENTO - ITALY)

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RIASSUNTO. — Sul versante occidentale della Val Rendena il plutone tardo-alpino dell'Adamello e i suoi corpi satelliti del Corno Alto e del Sostino si intrudono nel basamento cristallino costituito da metasedimenti che mostrano un metamorfismo prealpino J*grado cloritoide → staurolite*) seguito da un diffuso retrometamorfismo.

Il metamorfismo di contatto è molto ben sviluppato nella roccia incassante con formazione di nuova *biotite, andalusite* (talvolta anche *cordierite*) e *sillimanite,* in ordine di temperatura crescente verso il contatto. La pressione di carico durante il metamorfismo di contatto deve essersi mantenuta inferiore a 1,5 kb, dato che non sembra essersi formata nuova staurolite.

Localmente una sovrapressione di H_2O superiore a 2,5 kb, dovuta a reazioni di disidratazione ha impedito la scomparsa dell'associazione *muscovite + quarzo* nella zona della sillimanite vicino al contatto con la massa principale, dove si osserva in modo discontinuo la coesistenza di *K-feldspato + sillimanite.*

I profili termici basati sulle isograde non sembrano in accordo con il modello conduttivo di JÄGER (1957); pur escludendo fenomeni convettivi, data la non permeabilità delle rocce incassanti, pensiamo che il processo sia complicato da variazioni nella conducibilità termica, dovute alla presenza di sovrapressione di fluidi nella parte più interna dell'aureola.

ABSTRACT. — On the western slope of Val Rendena the late-alpine pluton of Mt Adamello and its satellite bodies of Corno Alto and Sostino intrude the metasedimentary rocks of the Southern basement showing a prealpine metamorphism of *chloritoid → staurolite* grade and a later retrogressive overprint.

Contact metamorphism is fairly well developped in the country rocks with newly formed *biotite, andalusite, cordierite* and *sillimanite* in order of increasing temperature towards the contact. P_{load} should have been lower than 1.5 kb since the thickness of the cover could not exceed 5 km; near the contact an H_2O overpressure, due to the dehydration reactions, prevented the breakdown of *muscovite* in the presence of *quartz* in most of the *sillimanite zone.*

Thermal profiles based on isograds are not consistent with a simple conductive model involving constant conductivity. Thermal conductivity is probably increased in the presence of a fluid overpressure.

Introduction

A growing interest has been devoted, during these last few years, to the problems of heat transfer around and above intrusive bodies from the moment of their emplacement till their final cooling down.

The process is intimately connected with the formation, under favourable hydrogeologic conditions, of geothermal fields, with their thermal configuration, their fluid dynamics and relative size in comparison to the volume and shape of the igneous body.

Several theoretical models of cooling pattern and heat transfer have been proposed, but comparatively few petrological studies have been carried out with the specific target of achieving quantitative data that could be relevant to a better understanding of the process.

For this reason we have undertaken this study which, though in its very preliminary stage, has already yielded indications that we consider are worth publishing and discussing with the scientific community.

Theoretical models as well as petrological studies deal normally with shallow intrusive bodies in rather permeable country rocks: that is the case for most of the geothermal fields in active volcanic areas.

For example LOVERING (1935) and LARSEN (1945) studied the cooling of a dyke-like mass which they assumed to be an infinite uniform solid with an initial temperature that is constant over a region and zero outside it. Later JÄGER (1957) examined the distribution of temperature in the neighbourhood of a dyke, taking into account the effect of the heat of solidification. The model dyke would have the shape of an infinite sheet with a given thickness *D*. The models of LOVERING, LARSEN and JÄGER are based on the assumption that heat transfer takes place only through conduction.

More recent studies (CHATLES, 1977; NORTON & KNIGHT, 1977; VILAS & NORTON, 1977) discuss the model of the cooling of a body of limited volume, considering the importance of fluid circulation near it. Their models of heat transfer take into consideration convective heat fluxes. NORTON & KNIGHT (1977) assume that « *fluid circulation is an inevitable consequence of the emplacement of the magma in the crust; ... the convective heat fluxes predominate over conductive heat fluxes when host rock permeabilities exceed* 10^{-14} cm^2 ». The geometries of fluid circulation and isotherms depend on the volume of the plutonic body, the nature of the magma, the level of emplacement, the permeability of host rock. The permeability of a rock, on the other hand, depends on the amount and geometry of continuous flow channels, as faults, joints, cracks and bedding planes in layered host rocks. Flow and diffusion processes play a very small role in the moving of fluids, so that the permeability of crystalline rocks may be considered nil (NORTON & KNAPP, 1977; AUMENTO, personal communication).

We chose the study of a contact aureole of a rather deep-seated Tertiary intrusion dismantled by erosion, this being the only possibility of having an accessible section through the igneous body and aureole and of having an acceptably good idea of shape and size of the intrusion.

The choice fell on the northeastern sector of the Mt Adamello aureole, because of the following main reasons:

1) the contact aureole is well exposed;
2) the country rocks are schists of rather uniform composition, whose permeability is presumably less than 10^{-14} cm^2 (NORTON & KNAPP, 1977);
3) the contact plane is nearly vertical in part of the area, as one can see from the intersection of the boundary with the topographic surface;
4) the tonalite body has a size which is large enough to be compared to a sheet of known thickness, but with infinite width and lenght in respect of the considered sections through the contact aureole;
5) in the zone under consideration dykes and fractures are nearly absent, and we can assume that no significant fluid circulation due to secondary permeability occurred.

A negative feature of the area is the presence within the contact aureola of the satellite bodies (Corno Alto and Sostino) of slightly different composition (granodiorite). Their age of emplacement is not significantly different from that of the main body since the difference of ages falls within the analytical error (CORTECCI et al., 1979).

The Mt Adamello pluton and its structural setting

The most recent studies on the Mt Adamello pluton can be found in the works of BORSI et al. (1966), BIANCHI et al. (1970), CALLEGARI e DAL PIAZ (1973), CORTECCI et al. (1979). Geological outlines are found in CASTELLARIN (1982). JUSTIN VISENTIN & ZANETTIN (1968) gave a detailed description of the metamorphic contact aureole in the zone under consideration.

We think it helpful to summarize below the geological features of the area in which the Adamello pluton intruded.

The Mt Adamello group is a rugged mountain massif of the Southern Alps with peaks of more than 3500 m of altitude, partly covered with large glaciers. The massif represents the top of a huge igneous body intruded in the pre-Westphalian schists of the South-Alpine basement and in their Permo-Mesozoic cover. The intrusion is clearly connected with the two fundamental tectonic discontinuities of the Alps, i.e. the Insubric Line and the Giudicarie Line, that run respectively NNW and ESE of the pluton. Recently CASTELLARIN (1982) confirms that the two tectonic lines seem to have been active long before the emplacement of the igneous body, since they are known to have played a very important role from late Paleozoic to Cainozoic times.

The intrusion consists of several independent and crosscutting plutonic bodies of dominating granodioritic and tonalitic composition (the term *tonalite* derives from the Tonale Pass, NW Adamello Group).

The isotopic and oxigen ratios show a systematic variation from south to north (CORTECCI et al., 1979). This fact may be related, in their opinion, to a melting of more and more shallow crustal masses with a consequent production of the magmas from which crystallized the various rocks of the Mt Adamello. The mineral age seems to decrease from 52 m.y. in the southern part to 29 m.y. in the northern part of the massif (BORSI et al., 1966).

The total thickness of the sedimentary cover is very variable from place to place, but in our area it may be evaluated to be 2-4 km (JUSTIN VISENTIN & ZANETTIN, 1968).

The crystalline basement of the Southern Alps

The crystalline basement of the Southern Alps consists primarily of metasediments of pelitic, semipelitic and arenaceous composition of unknown age of deposition. They contain granitic orthogneiss intercalations whose age of intrusion (Rb/Sr whole rocks isochrons) varies from 430 to 470 m.y.. Where the latter are present, it is obvious that the age of the original sediments predates the lower Ordovician; where granitic orthogneisses are lacking and orthogneisses, interpreted as metarhyolites, are present, some Authors (SASSI & ZANETTIN, 1980) assume a post-Ordovician age for the overlying metasediments.

The metamorphism is polyphasic and the relationships between deformation and metamorphic crystallization suggest a common metamorphic evolution (GREGNANIN, 1980) for all the basement schists of both South-Alpine and Austroalpine units.

A pre-intrusive metamorphism of disputed intensity could be inferred from the presence of schistose xenoliths in the orthogneisses.

The crystalline basement in the North-eastern sector of Mt Adamello

In the area under investigation the post carboniferous sedimentary cover is absent.

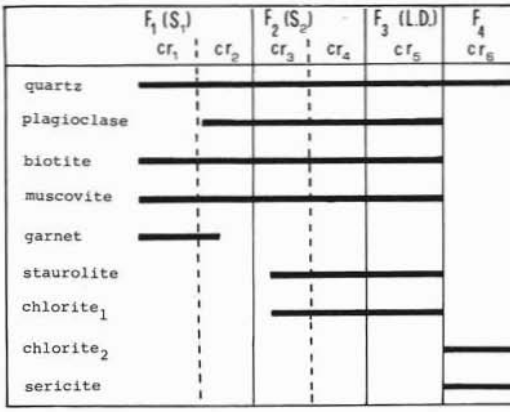

Fig. 1. — Summary diagram of the sequence of main deformations and crystallizations in the basement of Val Rendena, before the thermal metamorphism. F and Cr represent deformation and crystallization intervals: F_1 = rotation, F_2 = crenulation, F_3 = flattening, F_4 = late deformation connected with local retrogressive metamorphism (Cr_6). S_1 and S_2 as in GREGNANIN (1980).

It outcrops E of the Sarca river and in the south of Val Rendena, near Tione.

The South Alpine crystalline basement consists of phyllites, micaschists and to a lesser extent of paragneisses; orthogneiss lenses are absent.

The schistosity strikes generally N 20° E - N 60° E and dips 30°-60° SE; in the zone near the contact with the main body of Mt Adamello the schistosity plane is subvertical, whereas 4-6 km away from the contact it is gently inclined towards SE; in the zone near the Giudicarie Line it returns subvertical or even overturned.

Fracture or fault zones are absent all over the area, except near Caderzone and Pinzolo, where a system of vertical fractures and faults, with prevailing N 130° E direction is present.

All the rocks show a pre-alpine polyphasic metamorphism in which one can easily distinguish the steps represented in fig. 1.

The intrusive rocks are represented by the eastern part of the main body of Mt Adamello (*tonalite* of the Mt Re di Castello-

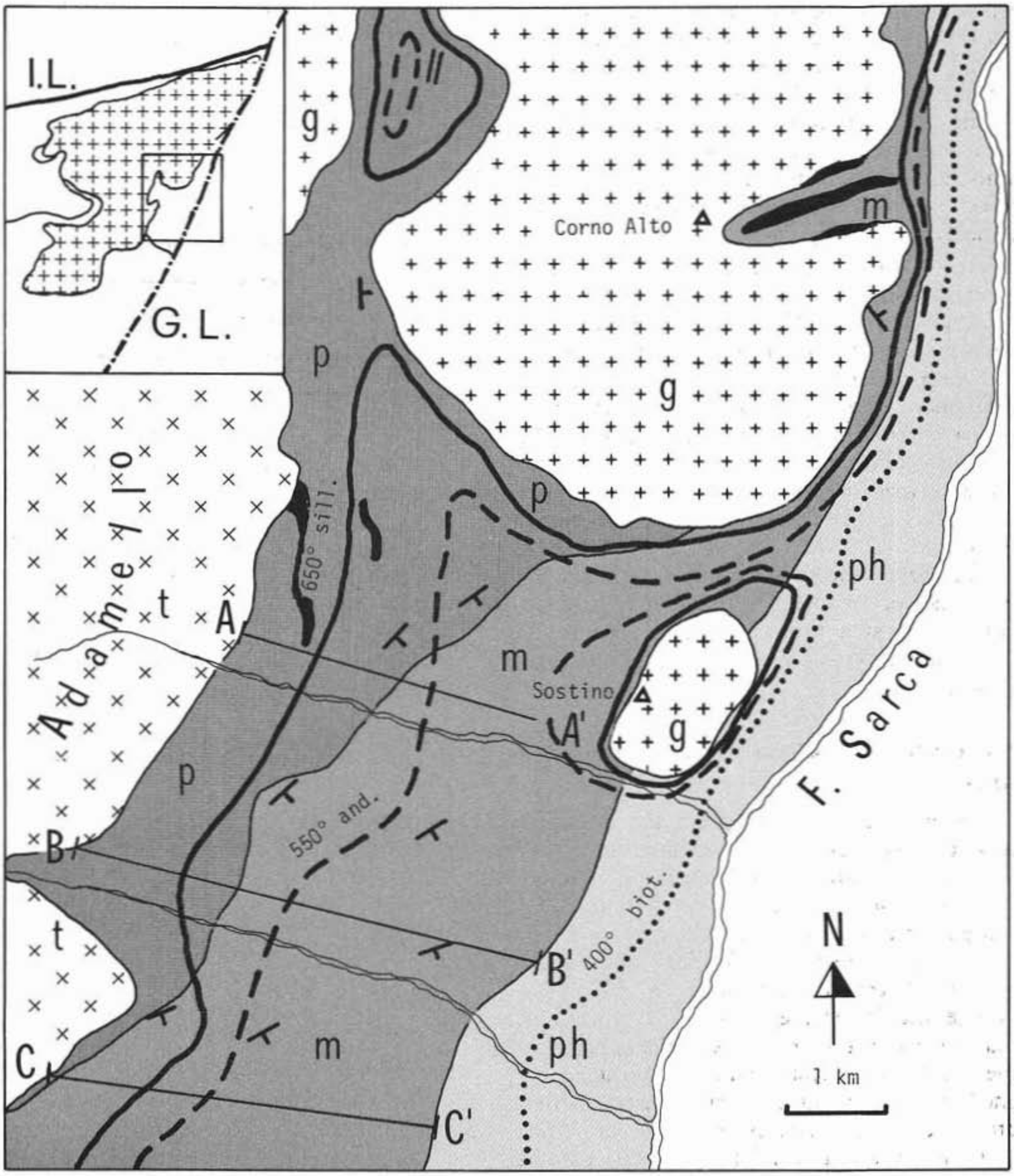

Fig. 2 *a.* — Schematic map of the northeastern sector of Mt Adamello. 1) Granodiorite (Corno Alto-Sostino); 2) Tonalite (Mt Adamello main body); 3) *ph* = phyllites and phyllonites; 4) micaschists; 5) *p* = paragneisses; 6) gabbrodiorite dikes: *a*) « biotite in » isograd; *b*) « andalusite in » isograd; *c*) « sillimanite in » isograd. *I.L.* = Insubric Line; *G.L.* = Giudicarie Line. *A-A'*, *B-B'*, *C-C'* = traces of the thermal profiles.

type, Bianchi et al., 1970) and by the satellite bodies of Corno Alto and Sostino (*granodiorite*). Gabbrodiorite dykes are present only near Pinzolo, in the eastern sector of Corno Alto and in the upper Val Borzago. The distribution of rock types is shown in fig. 2.

The contact aureole

The study of the contact metamorphism

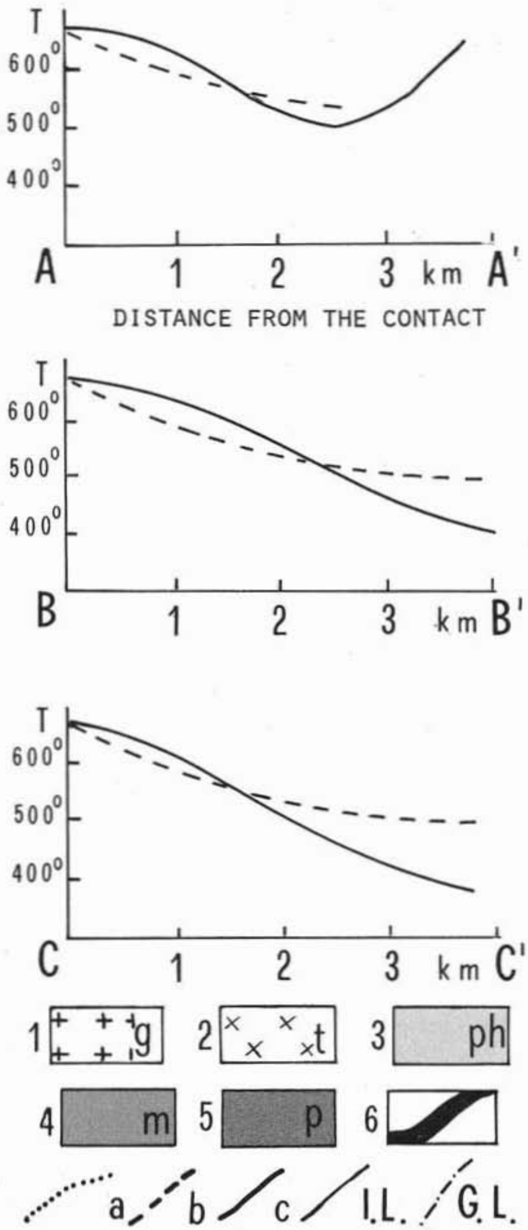

Fig. 2 *b*. — Some representative thermal profiles, E of Mt Adamello. *Solid lines*: temperature distribution based on mineral isograds. *Dashed lines*: temperature distribution calculated for an infinite dyke (15 km thick) with an intrusion temperature of 850° C, following the conductive model of JÄGER (1957).

has been possible only because of the intense retrograde metamorphism that affected the schists well before the intrusion. These phenomena are not homogeneously distributed and the regional metamorphic parageneses persist almost unaltered even in the innermost part of the aureole: this is the reason why we considered, for the identification of the isograds only the samples of rocks that underwent a severe retrograde metamorphism before the intrusion.

In the lowermost part of the western slope of Val Rendena the phyllites and the phyllonitic schists contain *chloritoid* relics near Pinzolo and *staurolite* relics in the rest of the area. *Staurolite* is more or less replaced by *sericite-chlorite* aggregates; *garnet* is deeply altered to *chlorite*.

For this reason it is very easy to recognize the first appearance of newly formed *biotite* out of the chlorite aggregates, due to the contact metamorphism, and trace the appropriate isograd if, as we did, one consideres an adequate number of samples.

The new biotite becomes more and more abundant towards the contact and then *andalusite* appears as product of the reaction:

chlorite + *muscovitte* + *quartz* $\leftrightarrows$ *cordierite* + *biotite* + Al_2SiO_5 + H_2O (HIRSCHBERG & WINKLER, 1968). (1)

It must be stressed out that andalusite seems to be pseudomorphic after staurolite, but this is only due to the fact that it grows out of the products of a previous alteration of staurolite, i.e. out of the chlorite-muscovite aggregates.

No new staurolite seems to have been formed during contact metamorphism; this can also be deduced from the ubiquitous stable coexistence of green iron-rich chlorite and muscovite.

In the andalusite zone, *cordierite* is also present, but only rarely because of the unfavourable Fe/Mg ratio of most of the rocks. *Cordierite* presumably resulted from the reaction:

chlorite + *muscovite* + *quartz* $\leftrightarrows$ *cordierite* + *biotite* + Al_2SiO_5 + H_2O (HIRSCHBERG & WINKLER, 1968). (2)

This scarcity compelled us to use the reaction 1) for tracing the isograd instead of that of the « *cordierite in* ».

The highest temperature isograd we could trace is that of the first appearance of *silli-*

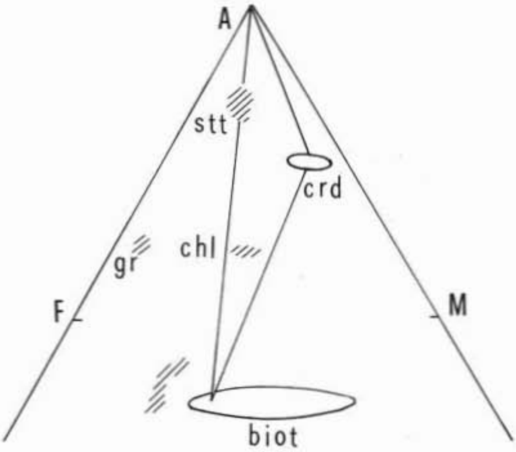

Fig. 3. — *AFM* diagram representing the standard topology of cordierite-medium grade metamorphism (from WINKLER, 1979, p. 225). Hatched areas indicate the compositions of relic staurolite and garnet and of new chlorite and biotite, as determined by microprobe analyses.
Sample VR 107 (24 mineral analyses) *Mt. Palette 31960832. Main regional metamorphism mineral association: quartz, muscovite, biotite, plagioclase, staurolite, garnet, chlorite; retrogressive metamorphism: chlorite, sericite; contact metamorphism: biotite, andalusite. Sample VR 131* (16 mineral analyses) *Dossone 33681168. Main regional metamorphism mineral association: plagioclase, quartz,* (*biotite*), *garnet, muscovite; contact metamorphism: biotite, andalusite, cordierite* (*altered*), *sillimanite.*

manite, at first in rare tiny needles and then in more and more abundant crystals of bigger size.

Fig. 3 represents the *AFM* triangle for the conditions of contact metamorphism in the inner part of the aureole. Hatched areas indicate the compositions of the phases analyzed by means of the microprobe (courtesy of G. GARUTI, Istituto di Mineralogia e Petrografia, Università di Modena).

Another important feature is the gradual variation of microstructure through the whole metamorphic aureole that leads to the formation of a typical hornfels texture only very close to the contact.

The isograd pattern is disturbed by the presence of the two satellite bodies of Corno Alto and Sostino (fig. 2).

The considerations about T_{max} distribution that follow, are mostly based on the sections *S* of the Sostino stock, in the Borzago and San Valentino Valleys.

P conditions in the various parts of the contact aureole during the thermal metamorphism

a) Before the intrusion total pressure was exclusively dependent on the depth and can be estimated from the thickness of the volcanic and sedimentary cover plus the thickness of the crystalline basement below the Hercynian unconformity (in total about 5 km). Reasonable estimations give a figure of about 1.5-2 kb and $T = 125\text{-}130°$ C for a gradient of $T = 25\text{-}30°$ C/km.

b) During and after the intrusion significant variations of P_{H_2O} conditions in the external part of the aureole («*biotite zone*») cannot be expected, since important dehydration reactions, that could produce water overpressure, did not take place.

c) In our « *andalusite zone* » there is no clear evidence of formation of new staurolite; staurolite relics do not show accretionary rims and a *green iron-rich chlorite* coexists with *muscovite*. We could observe only in one thin section the presence of euhedral staurolite included in cordierite, but the euhedral habit could be inherited from the previous regional metamorphic crystallization.

Again we have no evidence of higher P_{H_2O}, since staurolite seems to be stable only above 2 kb (GREENWOOD, 1976). Unfortunately HOSCHEK's (1969) experiments do not cover the low pressure region and the Mg/Fe ratio can influence the low pressure boundary of the staurolite + quartz stability field.

On the other hand we did not find *andalusite* coexisting with K-feldspar; *muscovite + quartz* coexist along with this Al_2SiO_5 species; this indicates a P_{H_2O} overpressure developed in the higher temperature part of the « *andalusite zone* », due to the increased amount of water resulting from the dehydration reactions producing Al_2SiO_5.

d) In the « *sillimanite zone* » *muscovite + quartz* coexist over a considerable area; alternatively the *sillimanite + K-feldspar* association is stable. The two parageneses are inhomogeneously distributed.

This indicates that the andalusite/sillimanite boundary was reached at a P_{H_2O} exceeding that of the intersection of the two isograds: « *sillimanite in* » and « *K-feldspar +* Al_2SiO_5

in ». Using HOLDAWAY's experimental *andalusite/sillimanite boundary* (1971) this intersection lies at $P_{H_2O} = 2.2$ kb and $T = 610°$ C; if we consider the petrogenetic grid published in WINKLER (1979, p. 208) this intersection takes place at $P_{H_2O} = 2.7$ kb and $T = 645°$ C. Even higher P and T are proposed by GREENWOOD (1976) on the basis of petrographic evidences.

For all these reasons we think it reasonable to assume a $P_{H_2O} \approx 2.5$ kb and a $T = 650°$ C at the andalusite-sillimanite boundary in the northeastern Mt Adamello aureole. These conditions were very close to the equilibrium of the reaction:

$$\textit{muscovite} + \textit{quartz} \leftrightarrows \textit{sillimanite} + \textit{K-feldspar} + H_2O\,,$$

since the two assemblages appear in patches in the sillimanite zone, reflecting slight variations in P_{H_2O} due to different amounts of water produced by the dehydration reactions in different rock types.

A different interpretation for this area, is given by MC RAE (1982), who considers $P_{tot} = P_{H_2O}$ and justifies P inhomogeneities with the movement of a thrust sheet above the intruding Adamello pluton.

T estimations

The liquidus temperature of the tonalite can be estimated around 1000° C and the solidus temperature around 725° C at 2 kb, in analogy with the experimental determinations of PIWINSKII (1973), and CONDLIFFE & MOTTANA (1974).

Following the methods suggested by LARSEN (1945) and JÄGER (1957), the temperature of the immediate contact must be around 600° C plus the temperature of the country rock prior to intrusion. If our estimation of the depth of the considered pluton section is correct, and if we assume a gradient of T of 25°-30° C/km, the temperature in the country rock was around 125°-130° C. The total T near the contact would result 725-750° C, but these values appear unacceptably too high, because they exceed the minimum melting T of granite. There is no evidence in the contact aureola of melting, except perhaps in the first one or two meters away from the pluton. This means that we cannot accept a temperature at the contact exceeding 670°-680° C at the P_{H_2O} estimated from the parageneses and we have to admit that, at the moment of intrusion, the magma was not completely molten but in the interval of solidification, at a temperature around 800°-850° C.

CALLEGARI (1962) on the basis of petrographic evidences deduced that « at the moment of the intrusion the plutonic body was already partly crystallized » with andesinic-plagioclase, hornblende and biotite as cumulus phases.

In the attribution of the respective T to the traced isograds, we used the following criteria:

a) *sillimanite*: we attributed to the « *sillimanite in* » isograd the T of 650° C, because this appears to be a reasonable evaluation of *andalusite-sillimanite* transition, in the presence of *muscovite + quartz,* as discussed above;

b) *andalusite*: petrographic evidence shows that *andalusite* forms from the reaction:

$$\textit{chlorite} + \textit{muscovite} + \textit{quartz} \leftrightarrows \textit{biotite} + Al_2SiO_5 + H_2O\,.$$

Unfortunately experimental data are not yet available for such reaction. A reasonable estimation may be 550° C, in analogy with the temperatures determined by HOSCHEK (1969) for the *muscovite + chlorite* $\leftrightarrows$ *staurolite + biotite + quartz +* H_2O and from the irregular presence in the *andalusite zone,* of *cordierite,* which forms from the reaction:

$$\textit{chlorite} + \textit{muscovite} + \textit{quartz} \leftrightarrows \textit{cordierite} + \textit{biotite} + Al_2SiO_5 + H_2O$$

at 525° C ± 10° C and 2 kb P_{H_2O} (HIRSCHBERG & WINKLER, 1968);

c) *biotite*: we assumed a T around 400° C for the « *biotite in* » isograd extending to lower P_{H_2O} the experimental data of NITSCH (1971) on biotite formation, although in our case it is more realistic that biotite was formed by the reaction:

$$\textit{phengite} + \textit{chlorite} \leftrightarrows \textit{biotite} + \textit{Al-richer chlorite} + \textit{quartz}$$

(TURNER, 1948).

Thermal sections

In order to represent the distribution of temperatures in the neighborhood of the pluton, we traced several thermal profiles perpendicular to the contact with the main tonalitic body and the satellite granodioritic stocks. Thermal profiles indicate the $T_{max.}$ reached during contact metamorphism at different distances from the pluton.

The more representative profiles are shown in figg. 2 *a-b*: *A-A'* is traced between the main body of Adamello and the Sostino satellite stock; *B-B'* is perpendicular to the main body in Borzago Valley and *C-C'* in San Valentino Valley.

If we assume a pure conductive model and trace the curves (*dashed lines*), calculated as proposed by JÄGER, for an estimated thickness of the pluton $D = 15$ km, we find that they show a marked concavity involving a rapid T decrease near the contact. On the contrary our thermal profiles (*solid lines*) are convex, showing a sort of thermal plateau in the first one or two km; only from a certain distance they assume the shape of the JÄGER's curves.

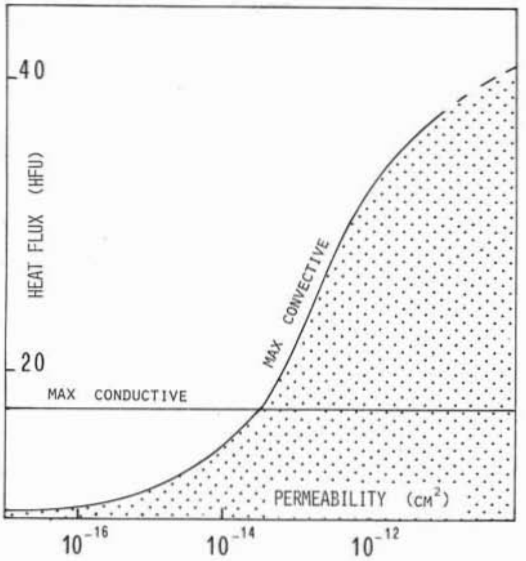

Fig. 4. — Distribution of heat fluxes calculated at the top of a pluton, as a function of host rock permeability, showing maximum model values for convection and conduction (from NORTON & KNIGHT, 1977). In rocks with a permeability below $k = 10^{-14}$ conduction prevails over convection.

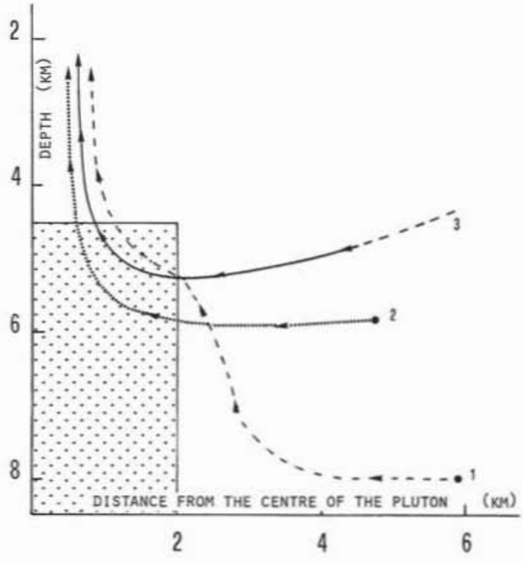

Fig. 5. — Examples of fluid pathlines aside a pluton intruded into an impermeable fractured host rock, at about the depth of 4-5 km. The starting positions are marked with small circles, arrows indicate the direction of fluid motion, time is not considered. Pathline 3) corresponds to the course of the fluids initially distant from the pluton at shallow depth; pathline 2) shows the path of fluids that move horizontally towards the pluton from a point near the side wall (4 km). In these two cases the pluton is considered relatively permeable: the fluids may flow inside the pluton and concentrate above its top. If the pluton is impermeable the fluids flow upwards along the walls (pathline 1). The stippled area represents only half pluton (from NORTON & KNIGHT, 1977) (modified).

Discussion

The T estimations of liquidus and solidus for a tonalite magma given above are based on the assumption of water saturation; if the melt is undersaturated the T would be unacceptably too high. The water content of the magma at the moment of intrusion should have probably been around 6 % weight at 2 kb P_{H_2O} (BROWN, 1970; BROWN & FYFE, 1970); the present H_2O content of the tonalite is approximately 1-1.5 (BIANCHI et al., 1970), therefore a considerable amount of water, though difficult to quantify, on account of the uncertainity about the solid-melt ratio at the moment of intrusion, was liberated during solidification.

Moreover, near the contact, dehydration reactions in the host rocks provided another notable amount of water to the pluton-contact aureole system.

NORTON & KNIGHT (1977) maintain that with a permeability below $k = 10^{-14}$ cm^2, the heat is mostly transferred through conduction and at smaller degree through convection (fig. 4), but a considerable movement of fluids took place beyond any doubt. Fluid transfer occurred by means of a diffusion process, which is very slow, since it takes place mainly along grain boundaries and intracrystalline cracks.

If we consider the pattern of fluid circulation around and above a cooling pluton (fig. 5), we may see that the shape of the convection cells, originated by the thermal anomaly implies that the fluids do not diffuse through the side walls towards the host rock, but there is a flux of water towards the magma chamber from the permeable host rocks.

The host rocks of Mt Adamello pluton did not display a significant primary or secondary permeability, in any case fluid motion took place, although it occurred by diffusion processes.

Since the fluid motion is very slow, we may reasonably assume that the water produced in the hottest part of the contact aureole caused an H_2O overpressure.

No positive contribution of convective fluid motion to heat transfer around the Mt Adamello pluton can be envisaged: we must definitely consider a pure conductive model.

When we compare our thermal profiles with the theoretical ones, calculated by JÄGER (1957), we may notice that the shape of the $T_{max.}$/distance curves is quite different.

Tentatively we may propose that the real $T_{max.}$ distribution is influenced by variations of conductivity around a cooling intrusive body, due to the presence of an H_2O overpressure in the vicinity of the contact. In fact we may see that in a section through the aureole $T_{max.}$ decreases very slowly in its hottest part, where dehydration reactions played an important role. A consequence of this interpretation is that the size of the hot body can be bigger than that of the igneous body itself, when important dehydration reactions occur in the contact aureole.

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