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Age Relations in the Bergell Region of the South-East Swiss Alps: With some Geochemical Comparisons

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ABSTRACT

Rb-Sr isotope data are presented for the rocks of the Tambo nappe (including the Truzzo granite gneiss), the Gruf migmatites, the Bergell granodiorite, Novate granite and aplites.

The Tambo rocks define an isochron proportional to an age of 293 ± 14 m.y. (1.47×10^{-11}/yr) with an initial Sr^{87}/Sr^{86} ratio of 0.704 ± 0.003. The age of the Truzzo granite gneiss (293 ± 14 m.y.) considered in the present work to be of sub-volcanic origin, is taken to be the time of sedimentation of the Tambo rocks; Hercynian metamorphism followed soon there after. The Gruf migmatites show a much greater scatter about a single line and could be of similar age, or older, than the Tambo rocks. Their time of formation is definitely not related to Alpine events as was previously suggested. Mica-rich phases in both the Tambo rocks and Gruf migmatites show varying degrees of response to later Alpine metamorphisms.

A meaningful Rb-Sr age was not obtained for the Bergell rocks because of their low Rb/Sr ratios, young age and the presence of apparent excess radiogenic Sr in certain samples. The same problems were encountered with the aplites which cut both the Bergell and country rocks. A poorly-defined whole-rock Rb-Sr isochron and Rb-Sr muscovite ages indicate that the Novate granite crystallised around 25 m.y.

Uranium, Th, Rb, Sr, K, Ca and Mg concentration data and Rb-Sr and U-Pb isotope data indicate the Truzzo granite gneiss and similar gneisses in the Tambo nappe are not the source of the Bergell granodiorite as was previously thought.

The Truzzo granite gneiss contains more Rb, one third the Sr and less Th than the granodiorite. The Th and U data, in contrast to the Rb-Sr results, do not support a genetic relationship between the Novate granite and Bergell granodiorite and the tonalite. Unusually low Th/U ratios, less than or equal to 1, were found in the Novate granite and cross-cutting aplites.

Introduction

The rocks described in this paper are divided into three main units: the Tambo nappe (including the Truzzo granite gneiss), the Gruf masse (migmatite complex) and the granitic rocks of the Bergell massif (the Bergell granodiorite and tonalite, and the younger Novate granite). They are located in the easternmost portion of the sillimanite zone (E. Wenk 1956) in the Lepontine metamorphic terrain of the Central Alps and surrounded by high grade isograds.

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The initial aim of the geochronological study was to date the time of formation of the migmatites which were previously thought related to the Lepontine (late Alpine) metamorphism. E. WENK (1956) considered the Novate granite, the migmatite formation and Lepontine metamorphism to be the result of the same orogeny. However, as field observations indicated some difficulty in clear separation of the migmatites and Novate granite, the study was extended to include the Bergell rocks. The latter have been the centre of controversy for more than 100 years and a detailed U-Pb study on zircons and other minerals is described in a previous paper (GULSON and KROGH, 1973). Because of a postulated relationship between the Bergell granodiorite and certain rocks of the Tambo nappe (H.-R. WENK 1970), the work was further extended to include these rocks.

Geological setting

Tambo nappe

The Tambo Nappe (GANSSER 1937, WEBER 1966) is one of the middle Penninic nappes located in south-east Switzerland and northern Italy (Fig. 1). WEBER (1966) has subdivided the Tambo nappe into the lower Corbet group (Southern gneiss zone of BLANC 1965), the Truzzo granite gneiss, and the upper Corbet group (Northern gneiss zone of Blanc); the upper Corbet group occupies the highest part, tectonically and topographically, of the Tambo nappe in this region. The lower Corbet group consists mainly of garnet-mica schists (with staurolite), muscovite-(biotite)-phengite gneisses with or without K-feldspar augen, and concordant basic rocks metamor-

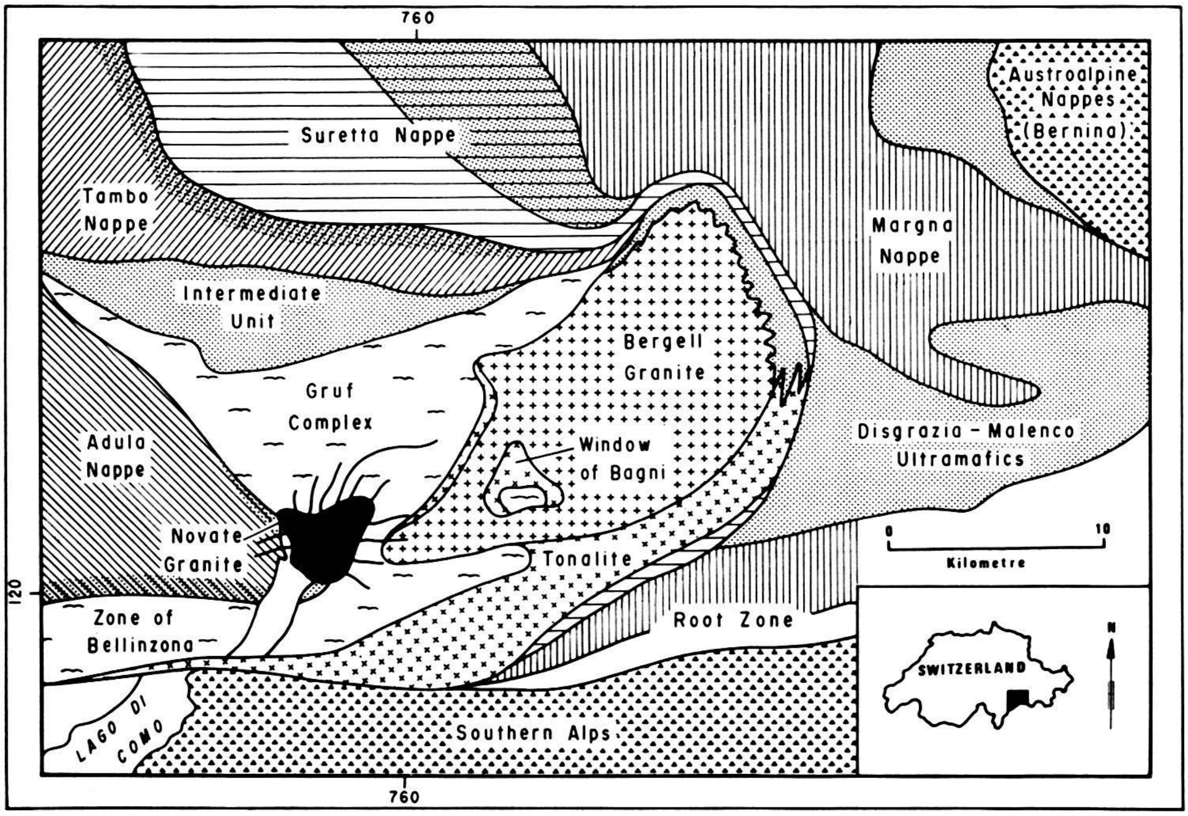

Fig. 1. Geological and tectonic sketch maps of the Bergell area after H.-R. WENK (1973). Intermediate unit consists of pelitic, mafic, ultramafic and calcareous rocks which may represent remnants of geosynclinal deposits and oceanic crust.

phosed to amphibolite facies. At lower metamorphic grade, the upper Corbet group comprises biotite and chlorite-rich gneisses and schists, phengite-K-feldspar gneisses, amphibolites, granite and carbonate-bearing schists. Locally, migmatites occur.

The Truzzo granite gneiss was thought by WEBER (1966) to be a synkinematic, porphyritic, two-mica, microcline granite intruded (under stress) during the Hercynian orogeny into the higher parts of the crust. WEBER (1966) recognised only a weak contact effect of the Truzzo granite with the surrounding country rock. In the author's opinion, thin sections of relatively underformed Truzzo gneiss show a stronger resemblance to a quartz-feldspar porphyry (metavolcanic rock) than a coarse-grained granite and as such may be related to the Roffna porphyry in the overlying Suretta nappe as described by HANSON et al. (1969).

The rocks of the Tambo nappe show effects of Alpine over printing with varying intensity in different localities.

Gruf migmatites (Gruf complex)

The Gruf migmatite complex occurs in the eastern part of the so-called Lepontine gneiss region of E. WENK (1956). It consists mainly of isoclinally folded quartzo-feldspathic, banded gneisses with mafic inclusions. The main areas studied were at the western margins of the Bergell massif but also in a window to the east at Bagni di Masino (MOTICSKA 1970). The amphibolites, marbles and migmatites of the Gruf masse are considered to underlie the Bergell granodiorite (H. R. WENK 1970). An excellent summary of the structure and tectonic setting of the Gruf masse is given by H.-R. WENK (in press). It is these migmatites which were considered Alpine by E. WENK (1956) and to have formed at the same time as the Novate granite and late Alpine metamorphism.

Bergell massif and Novate granite

The age and origin of the Bergell massif has been the centre of controversy for more than 100 years. It has been described as a post-Alpine intrusion (GYR 1967, MOTICSKA 1970), a product of metasomatic transformation of pre-existing material (DRESCHER-KADEN 1969), and the youngest phase (Novate granite) was suggested to be the result of anatexis related to Lepontine metamorphism (E. WENK 1956). Recently, MOTICSKA (1970) and H.-R. WENK (1970) suggested on the basis of structural observations, that the Bergell granodiorite was embedded concordantly in an anticline structure of the Margna, Suretta and Tambo nappes, although they noted local discordances. H.-R. WENK (1970) proposed that the Bergell granodiorite was a pre- or syntectonic granite, overthrust during Alpine folding and probably related to the granites and augen gneisses of the Tambo nappe. This is in contrast to previous workers who described that the Bergell cut across nappe structures and so gave a minimum age to the formation of the nappes (CORNELIUS 1915, STAUB 1918).

The Bergell massif is a composite of granitic rocks, covering some 50 km^2, and consisting of a central core of granodiorite, more or less enveloped by tonalite (Fig. 1). MOTICSKA (1970) described a granite-granodiorite zone, sometimes showing flow banding, between the granodiorite and tonalite. A younger granite body (Novate granite) occurs to the west of the granodiorite, considered by MOTICSKA (1970) and H.-R. WENK (1970) unrelated to the granodiorite and tonalite. The contact of the granitic rocks of the Bergell is generally concordant with the structures in the country rock except in the Forno region (in the east) where local discordances occur. Here, WEIBEL and LOCHER (1964) and H.-R. WENK and MAURIZIO (1970) described contact effects of the Bergell granodiorite whilst EVANS and TROMMSDORFF (1970) and TROMMSDORFF and EVANS (1972) discussed contact metamorphism associated with the tonalite which was superimposed on Alpine metamorphism. The rocks exhibit a weak to strong foliation delineated by K-feldspar phenocrysts in the granodiorite, hornblende and mica in the tonalite, and mica in the Novate granite. Banding on the centimetre scale is present in the Novate granite near its western contact with the Gruf migmatites.

In places a clear separation of the Novate granite and surrounding migmatites is not possible.

The granodiorite is a heterogeneous mass consisting dominantly of a porphyritic variety with areas of essentially homogeneous rock. Numerous inclusions (up to many metres across) are found in the granodiorite; these are mainly country rock gneisses, schists, amphibolites and calc-silicate bands, often occurring in swarms (WEIBEL 1960). In the Novate granite, tonalite and country rock gneisses and migmatites are abundant. The Novate granite is unusual in that it contains two micas and garnet of supposed almandine-pyrope composition (ALM 73 Py 27; MOTICSKA 1970). Garnet is more abundant near its contacts with the country rock migmatites whereas away from the contact, it is only visible in thin sections. Swarms of aplites with some pegmatites (both garnet-bearing) extend from the Novate granite, cutting other granitic types of the Bergell massif and surrounding country rocks. There are, however, other aplites located far from the Novate cutting the granodiorite, which are also sometimes garnet-bearing.

Analytical methods

Rb-Sr

Whole-rock samples were run for Rb, Sr and Sr isotopic composition on an Atlas CH4 mass spectrometer extensively modified by Mr. Rolf Brunner. Strontium was spiked with a double 86–84 spike and usually run with electron multiplier whereas a Rb aliquot was mixed with 87 spike, dried down and run with Faraday cup. Ages were calculated with the MCINTYRE et al. (1966) program using a coefficient of variation for Rb 87/Sr 86 of 0.7% and 0.2% for Sr 87/Sr 86.

An indication of reproducibility may be gained from the duplicates in Table 1. The Rb decay constant of 1.47×10^{-11}/yr was used. Three analyses of the E & A standard run during this work give an average value of 0.711 ± 0.001 when normalised to 88/86 of 8.432 (as are all spiked runs), or 0.708 ± 0.001 when normalised to 8.3752. Thus the initial ratios given in the regression table (Table 4) have been scaled down to an arbitrary value of 0.7080 for the E & A standard.

U-Pb

Zircons from the granitic rocks of the Bergell massif were analysed using the Krogh hydrothermal method at the Carnegie Institute of Washington. Sphenes, monazite, allanite, apatite and xenotime from these rocks were also analysed for U and Pb. Details of these analyses are given in GULSON and KROGH (1973).

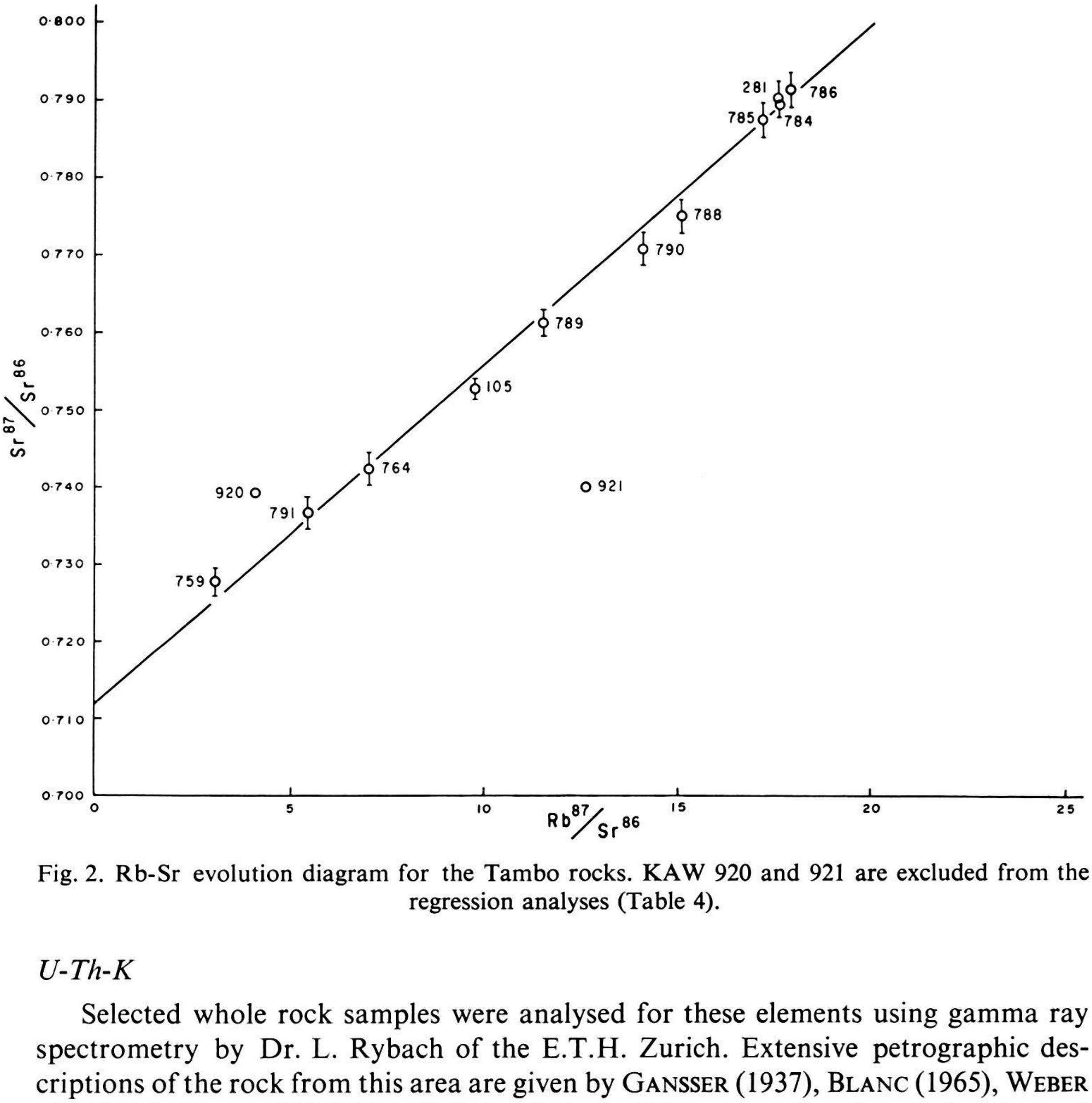

Fig. 2. Rb-Sr evolution diagram for the Tambo rocks. KAW 920 and 921 are excluded from the regression analyses (Table 4).

U-Th-K

Selected whole rock samples were analysed for these elements using gamma ray spectrometry by Dr. L. Rybach of the E.T.H. Zurich. Extensive petrographic descriptions of the rock from this area are given by GANSSER (1937), BLANC (1965), WEBER (1966), MOTICSKA (1970). Detailed descriptions of the analysed rocks may be obtained from the author.

Previous age determinations

Age determinations in the Tambo rocks are mainly Rb-Sr and K-Ar dates on micas and rocks and a U-Pb analysis of zircons from the Truzzo granite gneiss. GRÜNENFELDER (in WEBER 1966 and HANSON et al. 1966) obtained a 207/206 age on a zircon fraction of 339 ($\pm$ 70) m.y. and JÄGER and HUNZIKER (1969) determined a 305 m.y. Rb-Sr age for a whole-rock Truzzo granite gneiss. In contrast, biotite from the same rock gave a Rb-Sr age of 24.4 (JÄGER and HUNZIKER 1969) and a K-Ar age of 29.0 m.y. (ARMSTRONG et al. 1966), whereas the muscovite gave a Rb-Sr age of 238 m.y. (JÄGER and HUNZIKER 1969). HANSON et al. (1966) obtained a K-Ar age of 173 m.y. on muscovite from a pegmatite cutting the Truzzo granite gneiss and 297 m.y. on a pegmatite muscovite cutting the upper Corbet group. These mica ages were inter-

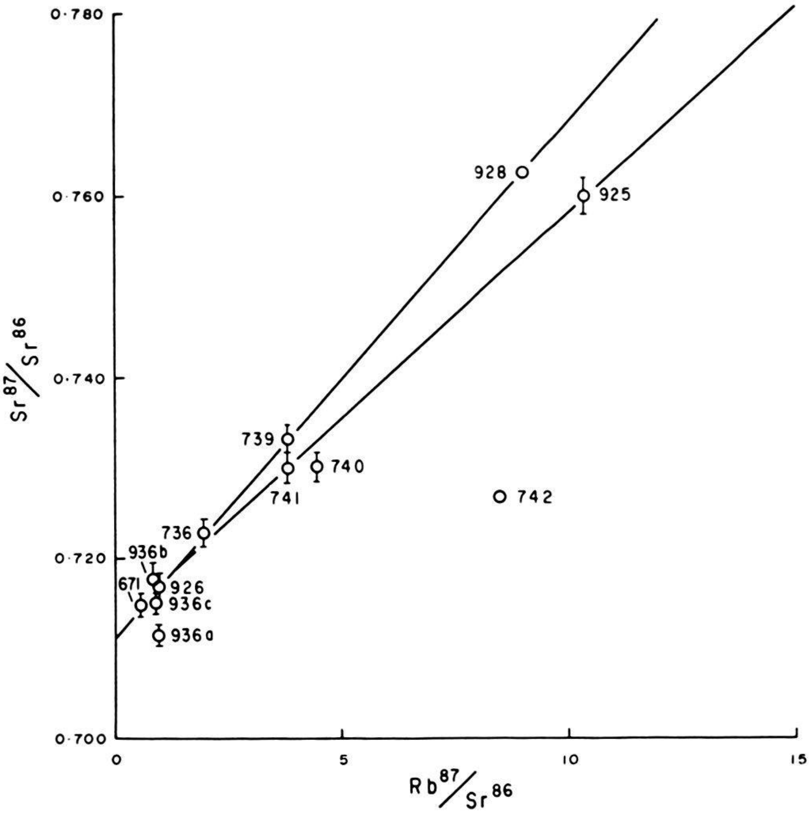

Fig. 3. Rb-Sr evolution diagram for the Gruf migmatites. KAW 742 is excluded from the regression analyses. (925 at upper right should be 929).

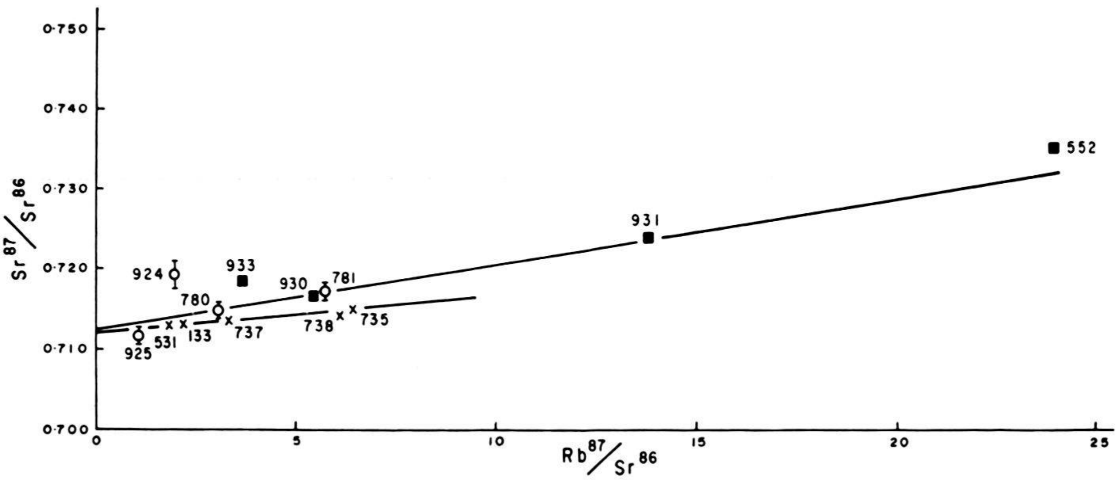

Fig. 4. Rb-Sr evolution diagram for the Bergell granodiorite (○), Novate granite (×) and aplites (■) and a pegmatite 552).

preted as due to a partial loss of radiogenic argon during Alpine orogeny. Closer to the Bergell granodiorite, JÄGER and HUNZIKER (1969) determined Rb-Sr ages of 305 m.y. for a whole rock Tambo gneiss, 35.5 m.y. for its muscovite and 24.0 for the biotite. They interpreted the biotite as a cooling age, and that of muscovite, its time of formation representing the climax of the last intensive phase of Alpine metamorphism.

Undeformed, late to post-kinematic Alpine pegmatites discordantly cutting the lower Corbet group and Gruf migmatites give K-Ar ages of 25 to 27 (± 2) m.y. (HANSON et al. 1966). Rb-Sr analyses on muscovite and biotite from a pegmatite cutting the Gruf migmatites also give ages of 25 and 20.3 m.y. respectively (JÄGER and HUNZIKER 1969).

U-Pb ages of zircons and other minerals from the Bergell rocks are given in GULSON and KROGH (1973).

Results and discussion

1. Ages

Tambo nappe

Eleven samples analysed from different units of the Tambo nappe, including 5 rocks of the Truzzo granite gneiss, define an isochron to within experimental error proportional to an age of 293 ± 14 m.y. with an initial ratio of 0.704 ± 0.003 (Fig. 2). This agrees, within the experimental error limits, with the 339 ± 70 m.y. 207/206 age obtained by GRÜNENFELDER (in WEBER 1966) on the zircon from the Truzzo granite gneiss. However, the data for the Truzzo zircon plot exactly on a chord through the 7 zircons analysed by GRÜNENFELDER (in HANSON et al. 1969) from the Roffna porphyry and which are interpreted as the time of emplacement of the porphyry at 310 m.y. (in JÄGER and HUNZIKER 1969). WEBER (1966) interpreted the zircon age as close to the time of crystallisation of the Truzzo "granite" and has suggested its intrusion (on the basis of scanty evidence) under stress during the Hercynian orogeny. As such, the identical zircon and whole-rock Rb-Sr ages place severe constraints on the time of Hercynian metamorphism in this area i.e. at 293 to 310 m.y. (or 312 m.y. if the 1.39×10^{-11}/yr decay constant is used for the Rb-Sr data). On the basis of Weber's interpretation it is impossible to decide whether the age of sedimentation of the Tambo rocks is very close to the time of metamorphism, or much older.

If however, the Truzzo "granite" was formerly of volcanic or subvolcanic origin, comparable to the Roffna porphyry, the approximate 300 m.y. age could be dating the minimum time of sedimentation. On the basis of field observations (e.g. absence of high grade contact minerals, sharp contact with country rock, concordance between "granite" contact and structure of the country rocks), WEBER (1966) suggested that crystallisation of the Truzzo "granite" took place under low temperatures in the higher parts of the crust. These observations and the similar petrography, similar major and Rb-Sr trace element chemistry, and identical 310 m.y. age of the Roffna porphyry and Truzzo granite gneiss, suggest a close genetic relationship even though they now occupy different tectonic levels. If a sub-volcanic origin of the Truzzo granite gneiss is correct, the age data give the *time of sedimentation* of the Tambo rocks. This would then necessitate a very short time interval between sedimentation and the Hercynian metamorphism.

Shear zones: In addition to the above samples, two 20 cm-wide muscovite- and phengite-schistose layers (shear zones) in the Tambo gneiss plotted far below the 300 m.y. isochron and when joined with their respective "host rocks", give ages of 50 and 77 m.y. ARMSTRONG and HILLS (1967) suggest that similar mica-rich layers in the Southern Idaho rocks have exchanged and equilibrated Sr with their enclosing rocks. JÄGER (pers. comm.) has obtained 65–70 m.y. phengite ages in the Margna nappe to the east of the Bergell massif, which she interprets as the time of early (Upper Cretaceous–Lower Tertiary) high pressure Alpine metamorphism in this area. The micaceous shearzones at Promontogno probably also date the early movements.

Local migmatites: Neither of the analyses of a 5 cm wide ptygmatically-folded granitic vein (KAW 920) in a biotite schist (KAW 921) plot near the 300 m.y. Tambo isochron and indicate a lack of equilibration of isotopes over this short interval. This effect may be the result of later Alpine events whereby the mica in the biotite schist either lost radiogenic Sr or new young mica crystallised. The radiogenic Sr released from the mica may have migrated into the feldspars of the gneiss (giving an apparent older age) by a similar mechanism which occurs sometimes in granite rocks (e.g. ARRIENS et al. 1966). This lack of equilibration over short distances contrasts with the apparent equilibrium reached over the whole of the Tambo nappe. That is, the colinearity of all the "normal" rock types constituting the Tambo nappe could be interpreted as "closed-chemical" system behaviour (for Rb and Sr). They cannot be interpreted, in the case of granitic rocks, as coeval and cogenetic because of the very nature of the metasediments and meta-igneous rocks constituting the nappe.

"Bergell-type" gneisses and remobilisation: Two samples from the Tambo nappe were analysed as a check for remobilisation: one was a porphyritic augen gneiss (KAW 764), termed "Chiavenna granite" (E. WENK and H.-R. WENK, pers. comm.), and the other an augen gneiss (KAW 759) from close to the contact of the Bergell granodiorite. H. R. WENK (1970) suggested that these rocks, along with the Truzzo granite gneiss, may be the source rocks of the Bergell granodiorite. H.-R. WENK (pers. comm.) also suggested that the augen gneiss (KAW 759) should show effects of remobilisation if it was related, by over thrusting and recrystallization, to the granodiorite. The 300 m.y. age of both samples precludes any simple hypothesis of overthrusting and recrystallization to form the Bergell granodiorite.

Gruf migmatites: Samples of the Gruf masse generally have poor Rb/Sr ratios and show a much greater scatter around a line than the Tambo rocks (Fig. 3). Most of the data occupy the lower end of a Rb-Sr evolution diagram and could be fitted to a line proportional to 306 ± 30 m.y. and initial ratio of 0.705 ± 0.002. Alternately some of the data just as easily fit a line through the uppermost sample (KAW 928) proportional to the age of 365 ± 30 m.y. with an initial Sr 87/Sr 86 ratio of 0.702 ± 0.003. However, 4 samples fall well below this older line. One of these (KAW 742) is a biotite schist and so may show the effects of Alpine events, but no simple explanation can account for the others.

The scatter in results, however, does not effect the unequivocal fact that the migmatites are earlier than, or related to, the Hercynian metamorphism and are not the result of late Alpine metamorphism as suggested by E. WENK (1956). Variable but old ages (i.e. $\sim$ 300 and 350 m.y.) have also been obtained on the migmatites to the west of the Bergell (HÄNNY and GRAUERT, pers. comm.).

A layered block of migmatite (Fig. 8) was analysed to check the time of migmatisation (given by the central, apparently, remobilised part) and distribution of isotopes between the different layers. When stained for easy identification of K-feldspar and plagioclase, the 3 main layers (apart from the biotite-rich layer which was not analysed) are found to have almost identical mineralogy with approximately equal proportions of the feldspars and quartz and less than 10% biotite. Within each layer these feldspars and quartz show a random distribution both in concentration and grain size with some parts consisting of 70–80% plagioclase (and quartz) in contrast to other areas of 70–80% K-feldspar (and quartz). A detailed map of the block is given in the Appendix (Fig. 8). The similarity in mineralogy is reflected in similar Rb and Sr concentrations (Table 2) but not the Sr isotopes. Th analyses for the central and one outer layer plot on a 300 m.y. (or older) isochron in keeping with the other migmatites, whereas the other outer layer (KAW 936a; B 110a) plots on a 30 m.y. reference line. The results may be explained by a lack of equilibration of Sr isotopes between the layers or, because of its very close proximity to the Bergell granodiorite, a resetting due to the intrusion. A resetting is considered untenable because of the similarity in mineralogy and hence all layers might be expected to respond equally to a resetting, and because a feldspar-biotite schist (KAW 736) less than 5 metres from the Novate granite shows no contact effect. Alternatively, if the zone adjacent to the "30 m.y." layer was of different chemistry, diffusion of isotopes between the layers may have given rise to the apparent younger age (e.g. see KROGH and DAVIS 1968), perhaps in response to Alpine events.

Granitic rocks of the Bergell massif: Because of the very low Rb/Sr ratios of less than 1 (see also Fig. 6) and young age of the Bergell granodiorite and tonalite, it was impossible to do any detailed work in this direction with the existing facilities. A similar position applies to the Novate granite where the highest Rb/Sr ratio was also less than 1. Analyses of a number of samples from the granodiorite and Novate granite resulted in a confusing array of points which may be bracketed between 2 reference lines from 25 to 70 m.y. with one sample (KAW 924) lying on a 300 m.y. line.

Aplites: In an endeavour to extend the range of Rb/Sr ratios, a number of aplites were analysed which cut both the granodiorite and country rocks. The aplites definitely related to the Novate (KAW 738 – a K-feldspar concentration in the Novate and KAW 735 – cutting the neighbouring banded gneiss [KAW 739]) fall on a line with other Novate samples, proportional to an age of 25 ($\pm$ 80) m.y. with an initial ratio of 0.705 $\pm$ 0.005. The sample of sapphirine gneiss (KAW 554) analysed by JÄGER and HUNZIKER (1969) also falls on this line. This age agrees well with the Rb-Sr muscovite ages of 24 $\pm$ 9 m.y. from the Novate granite at Codera and 22 $\pm$ 2 m.y. on a pegmatite from Novate.

Two aplites (KAW 930, 931) cutting the Bergell granodiorite some 20 km east of the Novate granite fall on a line with an aplitic phase of the granodiorite (KAW 781) and the normal granodiorite (KAW 780) whereas the aplite cutting the amphibolite (KAW 933) plots far above this line (Fig. 4). Except for KAW 933, the other samples define a line which passes through a pegmatite sample (cutting the Gruf magmatites), proportional to an apparent age of 65 m.y. and apparent initial ratio of 0.703. Such a simple closed system, may not be the explanation for the results because of the apparently older ages of the aplite cutting the amphibolite and that of a granite-granodiorite sample (KAW 924). If these older ages are due to incorporation of radiogenic Sr then this may also be a plausible explanation for the pegmatite in the Gruf migmatites and the other aplite cutting the granodiorite. These older ages are geologically impossible if the age of the Bergell is taken to be 30 m.y. (see following).

U-Pb data: Zircons from the Bergell granodiorite and tonalite and Novate granite and sphene, monazite and allanite from the granodiorite were analysed. Sphene was also analysed from the tonalite.

A detailed discussion of the results is given in GULSON and KROGH (in press). Briefly, the zircons from all three granitic rock units of the Bergell massif seem to contain an old lead component with the youngest intrusive phase (Novate granite) giving the oldest apparent age (206/238 of 65 m.y.). The time of crystallisation of the rocks was taken as 30 m.y. based on a concordant monazite, a chord joining the monazite and zircons, and U-Pb sphene and allanite ages.

The data may, however, be interpreted in another way particularly in light of the Rb-Sr data. If a chord is drawn through all the zircon data from the granodiorite and tonalite (omitting the zircon from the Novate granite) the upper intersection is near 120 m.y. (90–150 m.y. – it is impossible to obtain a precise intercept because of the cluster of data in the 30 m.y. region). The zircons may then be interpreted as having crystallised at about 70 m.y. (to tie in with the apparent Rb-Sr age) with a strong subsequent event at around 30 m.y. which led to the recrystallisation of sphene, allanite and monazite with associated Pb loss in the zircons. Recrystallisation of sphene and allanite is a common phenemon (e.g. see HICKLING et al. 1970). However, the chord would then be expected to pass through 30 m.y. (and not zero) indicative of the episodic event (WETHERILL 1956). Also, it is difficult to explain the cluster of all the zircon data in the 32–38 m.y. "field", which would require an equal response (resetting and Pb loss) of all zircons to the proposed 30 m.y. "event".

In view of these difficulties, the time of crystallisation of the Bergell granodiorite and tonalite is taken to be 30 m.y. and the fit of the Rb-Sr data for the granodiorite and aplites to one line is taken to be fortuitous. It is interesting to note the apparent anomaly in the U-Pb and Rb-Sr data. The Novate granite appears to contain more country rock inclusions (and garnet) than the granodiorite and tonalite, its zircon has the greatest amount of old lead component and yet there is no excess radiogenic Sr in the granites and aplites analysed.

Another interesting point of the Bergell data is in regard to the Lepontine metamorphism. If, as proposed by E. WENK (1956), the Bergell was the result of the young (Lepontine) phase of Alpine metamorphism, then it is several million years younger than the "blocking" temperature of muscovite (e.g. at Promontogno – see JÄGER and HUNZIKER 1969). This also means that the Bergell must have intruded in the cooling period, and not during the climax of metamorphism.

Po Boulders

One important aspect and use of the U-Pb data concerns the abundant granitic boulders found in the molasse of the Po plain. Many of these are thought to have been derived from the Bergell massif. Zircons were analysed from 2 granodiorite boulders and the results indicate that they are indubitably from the Bergell massif. Their physical properties are the same and the very high U concentrations, presence of an apparent old Pb component and the fact that they lie on the same chord as the Bergell zircons clearly point to a common source. The stratigraphic age of the molasse is given as lower to middle Oligocene (CITA 1957) corresponding to an absolute time scale from about 38 to 31 m.y., *assuming the fossil control is correct.* As some of the boulders in the molasse are from the Bergell, erosion and deposition of the massif must have been extremely rapid. An extremely interesting result has recently been obtained by Prof. E. JÄGER (pers. comm.) on a biotite separated, along with the zircon, from one of the boulders. The Rb-Sr cooling age of 28 m.y. fits in perfectly between the time of crystallisation at 30 m.y. (indicated by the U-Pb data) and the younger cooling ages of 22–25 m.y. (JÄGER and HUNZIKER 1969) from the deeper, now exposed parts of the Bergell granodiorite.

2. *Other chemical data*

Rb and Sr concentrations

In the search for samples suited to isotope dilution analysis, over 185 approximate X-ray fluorescence spectrographic determinations were performed on the Tambo rocks, Gruf migmatites and granitic rocks of the Bergell massif. Gneiss and schist samples to the west of the Bergell massif, also forming part of the Gruf migmatites and studied by BLATTNER (1965) were checked for their Rb and Sr concentrations. The data, plotted on a Rb vs. Sr diagram (Fig. 5) show a clear separation into two fields for the Bergell rocks (including the Novate granite) and the Tambo samples. On histograms (Fig. 6), the Tambo rocks have a 3 times lower Sr concentration (average ~ 100 ppm) than the Bergell and Novate rocks and there is *no overlap*. Consequently, the Tambo rocks have significantly higher Rb/Sr ratios (see also Fig. 2 and 4). There is a closer correlation between the Bergell rocks and Gruf migmatites with the average Sr concentration falling somewhere between the Tambo and Bergell rocks. An overlap exists in the Rb concentrations for the various rocks but there is a distinct tendency for slightly higher concentrations in the Tambo rocks compared with the Bergell types and Gruf migmatites (Fig. 5).

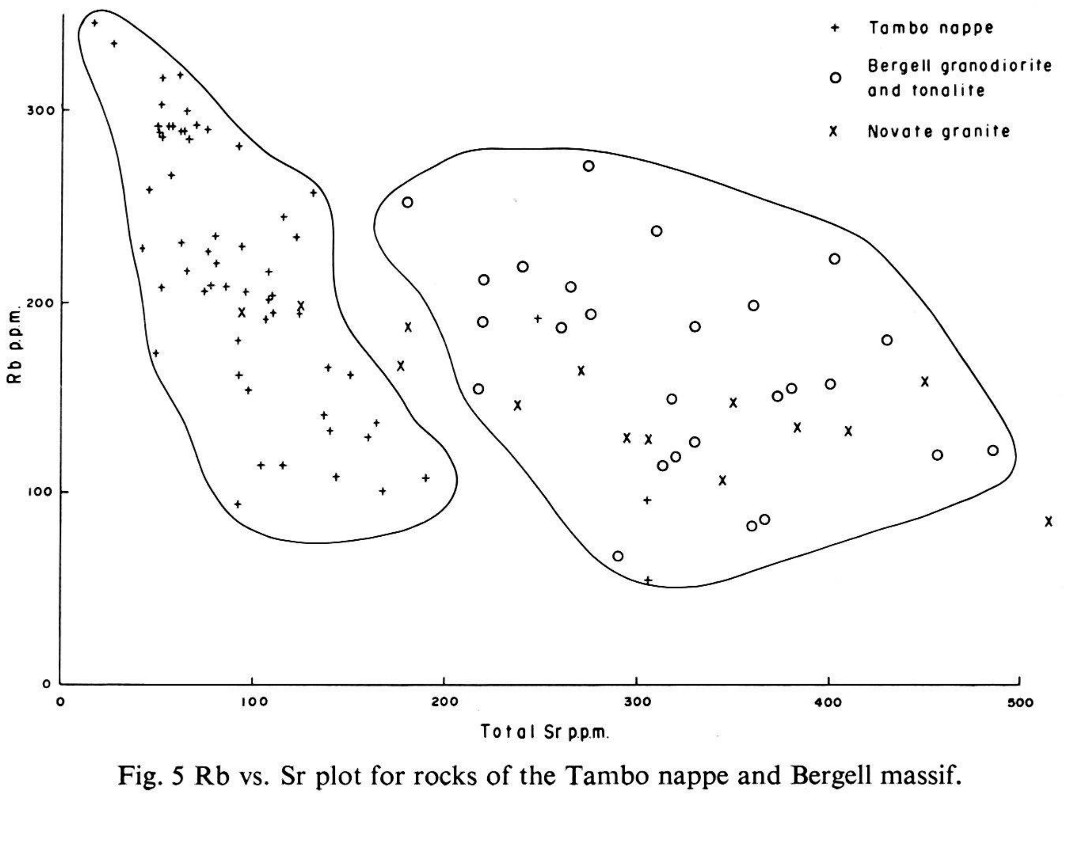

Fig. 5 Rb vs. Sr plot for rocks of the Tambo nappe and Bergell massif.

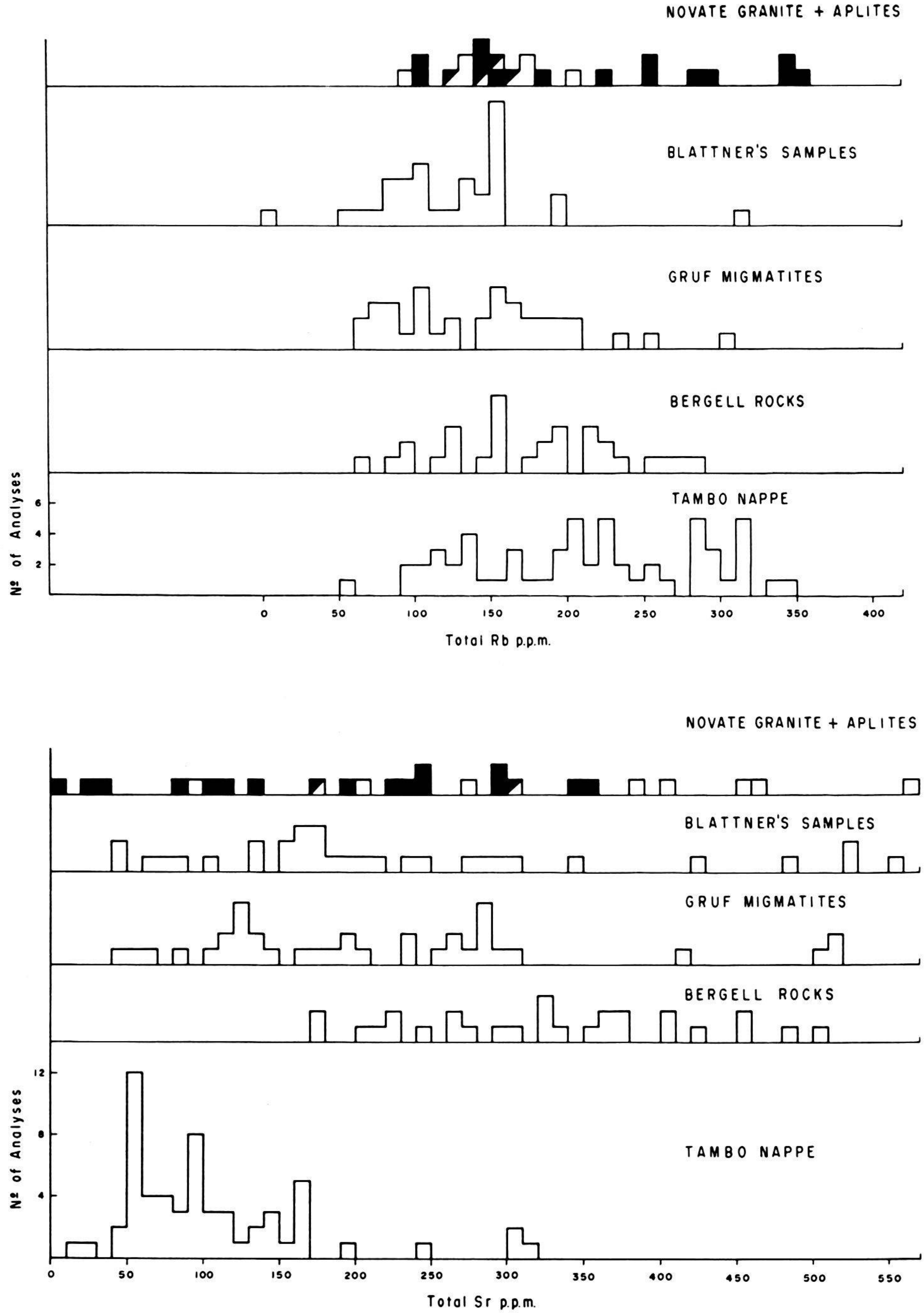

Fig. 6a and 6b Rb and Sr histograms for rocks from the Bergell region. Blackened squares are aplites.

The difference in Sr (and Rb) concentrations of Bergell and Tambo rocks would seem to place definite constraints on a genetic relationship between these two rock units. However, it may be argued that certain of the Bergell rocks have been contaminated by calcium-rich material (with expected high Sr concentrations), of which there is an abundance in the surrounding country rocks. Samples which were analysed by isotope dilution for Rb and Sr were also checked for their Ca and Mg contents by Atomic Absorption Spectroscopy. In combination with data from WEIBEL (1960) and MOTICSKA (1970), the Bergell granodiorite has a Ca content at least 3 times higher than the Tambo rocks, which in turn is reflected in their Sr contents. Either way, it is not possible to differentiate between a contamination hypothesis or basic differences in bulk composition in order to decide whether a genetic relationship exists between the Tambo and Bergell rocks. However, if the contamination hypothesis operates, one might expect to find uncontaminated parts of the Bergell granodiorite with higher Rb/Sr ratios. No samples of granodiorite (or any rocks from the Bergell massif except the aplites) with a Rb/Sr ratio greater than 1 were found.

U-Th-K concentrations (Table 5)

Bergell rocks, Novate granite and Aplites: In contrast to the overlapping K, Ca, Rb and Sr concentrations, the U and Th values are more definitive in establishing relationships between the Bergell rocks and Novate granite. The Th concentrations are at least 5 times lower, and the U almost half the value in the Novate granite compared with the Bergell granodiorite; the Th/U in the Novate is $\leqslant 1$ in contrast to the average value of 2.9 in the Bergell; the K/Th is at least 4 times higher in the Novate, whereas the K/U shows an overlap. Aplites cutting migmatites (KAW 735) and the Bergell granodiorite, and a K-feldspar "aplitic" concentration in the Novate (KAW 738) have U and Th concentrations more closely resembling the Novate granite than the Bergell and usually exhibit the unusual feature of a Th/U less than 1. Various authors (HEIER and ADAMS 1963, AHRENS 1965, TAYLOR 1966, KOLBE and TAYLOR 1966, GULSON 1972) have pointed out that U and Th concentrations generally increase during differentiation. HEIER and ADAMS (1963) and AHRENS (1965) also suggested that within a given suite of igneous rocks, the rate of increase of Th with respect to some index of differentiation may be greater than U.

The U and Th values show clearly that the Novate granite could not have differentiated from the Bergell granodiorite and supports the other data given previously, pointing to an absence of a genetic relation between these two rock units.

Within the Novate there is a trend of increasing U concentration with differentiation (using the K content as an indicator) shown by the K-feldspar concentration and the aplite vein whereas there is little change in the Th, and in one sample, a decrease. An aplitic phase of the Bergell granodiorite (KAW 781) shows a marked increase in U but a sharp decrease in Th concentration compared with other samples. These few results suggest that the postulated Th enrichment during differentiation does not apply to the supposed very-late stage differentiates such as aplites (in the rocks under discussion).

The lack of any systematic trend (with K) and variability of U concentration in the Bergell granodiorite may be due to the formation of the mobile hexavalent U ion. The presence of uraninite and other U-minerals in vughs and along joint planes in the Bergell granodiorite attests to a later movement of U-bearing solutions.

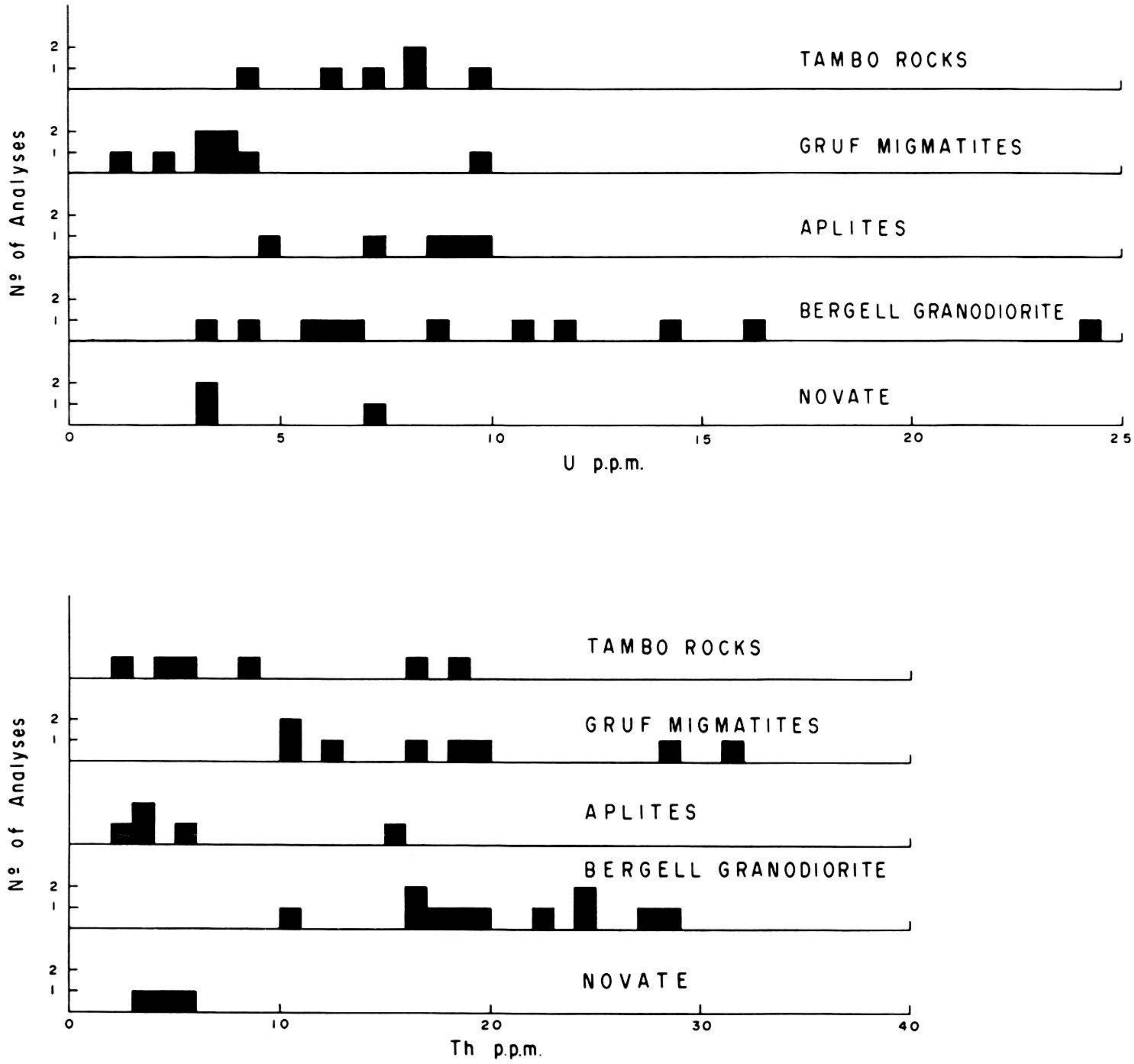

Fig. 7a and 7b U and Th histograms for rocks from the Bergell region.

The almost identical U and Th values of the aplitic parts of the Novate granite (and similar Th/U, K/Th, K/U ratios) and sharp contrast with any rocks of the Bergell granodiorite, suggests that the analysed aplites cutting the Bergell granodiorite and country rocks were derived from the Novate and not the Bergell. There is a possible exception in the aplite cutting amphibolites (KAW 933) near the north eastern contact; this has a high Th concentration, similar to that of the Bergell rocks.

A similar argument may apply to rocks found cutting migmatites near the western part of the Novate granite. As mentioned previously (p. 294), in these localities, granitic rocks cutting gneisses and schists of the Gruf masse closely resembled the Novate granite, and in places, it was not possible to define lithological boundaries between the Novate and migmatites. Two samples (B 26, B 28) of the granitic material cutting the migmatites have such different (high) Th concentrations (and Th/U, K/Th, K/U ratios) that it is highly improbable they are Novate material.

In chondrites, mantle or crustal rocks, the Th/U ratio is approximately 4 or greater (Heier and Adams 1963, Ahrens 1965) but in the Novate granite the Th/U is less than

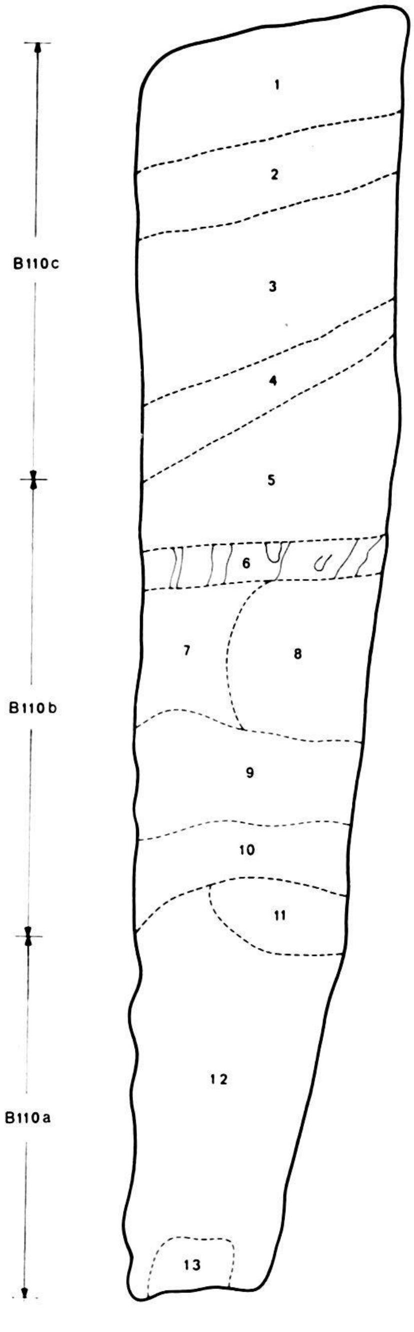

Fig. 8 Detail of a layered block of Gruf migmatite after staining for feldspar identification. Approximate quartz and feldspar compositions for stained block (biotite amounts to less than 10% in all except in the mica-rich layer). Block is ~ 36 cm long.
1. K–F + plag + qtz equal amounts. 2. Plag (60%) + qtz (40%). 3. K–F (60%) + Plag (20%) + qtz (20%). 4. Plag (80%) + qtz (20%) + K–F (trace). 5. Biotite (40%) + Plag (50%) + qtz (10%). 6. Plag (90%) + interstitial qtz (10%). 7. Variable grainsize – Plag (40%) + K–F (40%) + qtz (20%). 8. Fine grained K–F (60–70%) + Plag (20%) + qtz (< 10%). 9. Coarser grained (up to 6×3 mm) – Plag (40%) + qtz (30%–40%) + K–F (20%) 10. K–F (80%) + qtz (20%) + Plag (<5%). 11. Fine grained Plag (90%) + qtz (10%). 12. Variable grainsize–K–F (30%) after forming small porphyroblasts (up to 8 × 7 mm) + Plag (40%) + qtz (30%). 13. K–F porphyroblast.

or equal to 1 and in the Bergell granodiorite the ratios range from 1.24 to 4.72 with an average of 2.9.

Gruf migmatites: In keeping with other elements, the variety of rock types (mica schists, banded and non-banded gneisses, migmatites) constituting the Gruf migmatite complex, show a wide range in their K, U and Th concentrations. Overall, they have a lower U concentration than the Bergell granodiorite and consequently, a higher K/U ratio: other values are similar. The low U values are comparable to the Novate granite but the Th concentrations are considerably higher. An interesting feature of the last five migmatite samples listed in Table 5 is that although the K contents are almost identical, the U, and particularly Th, values vary markedly. The Th/U ratio (average of 5.7, range 1.97 to 8.78) is significantly higher than in any of the other rock types from this area.

Tambo rocks: Except for a phengite schist (KAW 788), the samples analysed are from units originally proposed by H.-R. WENK (1970) as possible source material for the Bergell granodiorite. The higher K and lower Th concentrations (except for one sample of porphyritic gneiss) argue against such a relationship, whereas the U values (and particularly Th/U ratios less than one in 3 samples) are more reminiscent of the Novate granite.

An interesting feature of the results is that identical composition of the micaceous shear zones (KAW 782) and host rock augen gneiss (KAW 784). These shear zones developed in response to the early Alpine metamorphism (i.e. much later than the time of formation of the host rock) and yet they still apparently retain their K, U and Th whereas they have lost much radiogenic Sr.

It is obvious that a realistic discussion of relationships between the Bergell granodiorite and Tambo rock is hampered by sampling problems (i.e. small number of samples) and it would be necessary to carry out the K, U and Th work to the extent of the Rb and Sr data.

SUMMARY

The results of the isotope and geochemical study of the Tambo nappe rocks, the Gruf migmatites and granitic rocks of the Bergell massif may be summarised as follows:

1. The different units constituting the Tambo nappe define an isochron proportional to an age of 293 ± 14 m.y. Assuming WEBER'S (1966) theory of time of emplacement, the Truzzo granite gneiss gives the age of Hercynian metamorphism in this area, i.e. 293 m.y. If the Truzzo "granite" gneiss is of volcanic origin, as proposed by the present author, the 310 m.y. 207/206 zircon age of GRÜNENFELDER (HANSON et al. 1966) and Rb-Sr whole-rock data give the minimum time of sedimentation of the Tambo rocks, which were shortly thereafter metamorphosed during the Hercynian orogeny. Locally, strontium isotopes in granitic (migmatitic) layers have not equilibrated with the surrounding mica schists over a scale of centimeters. Phengitic bands along shear zones in the Tambo gneiss, probably formed in response to the early (Upper Cretaceous–Lower Tertiary) Alpine metamorphism. Varieties of augen gneiss, previously thought related to the Bergell granodiorite (H.-R. WENK 1970), show no evidence of recrystallisation or remobilisation, a necessary condition for a genetic relationship between the rocks of the Tambo nappe and Bergell granodiorite.
2. The Gruf migratites are of a similar, or older, age to the Tambo rocks and indicate a lack of equilibrium of Sr isotopes over both short and long distances. Their formation is probably related to the Hercynian orogeny and no evidence was found in the isotope work of any connection with the Alpine metamorphism(s) as previously suggested by E. WENK (1956). Mica schist samples from the Gruf masse show varying degrees of response to Alpine events.
3. It was not possible to obtain a satisfactory Rb-Sr whole-rock age for the rocks of the Bergell massif and Novate granite due to their unfavourable Rb/Sr ratios and young age. Rb-Sr data for 2 samples of Bergell granodiorite fall on a line through 3 aplites and a pegmatite of an apparent of about 70 m.y. Because of the geological impossibility of this age in the light of the zircon data, apparent excess radiogenic Sr in a sample of Bergell granite-granodiorite and in an aplite, this "false" isochron is considered untenable. A poorly-defined isochron of approximately 25 m.y. for 3 samples of Novate granite and 2 aplites agrees with the muscovite ages (Rb-Sr) on these rocks and places a minimum limit on the time of intrusion of the older Bergell granodiorite and tonalite.
4. U-Pb ages on monazite, sphene and allanite indicate a time of crystallisation of the Bergell granodiorite and tonalite of about 30 m.y., whereas the zircons all apparently contain an old lead component, with the younger Novate granite giving the oldest *apparent* age (206/238 about 65 m.y.). If the time of crystallisation of the Bergell granodiorite and tonalite at 30 m.y. is taken

to be correct, then it post-dates the older (Upper Cretaceous–Lower Tertiary) Alpine metamorphism in this area placed at about 60–70 m.y. by JÄGER (pers. comm.) and the younger Alpine phase at approximately 35 m.y. This agrees with the field observations of a contact metamorphism due to the Bergell intrusion being superimposed on the regional metamorphism.

5. The geochemical data shed new light on the controversial question of the formation of the Bergell rocks, particularly the granodiorite and perhaps the Novate granite. Similar initial Sr 87/Sr 86 ratios of ~0.705 for the Tambo rocks, the Bergell granodiorite and Novate granite, and the presence of an old lead component in the zircons could argue for a genetic relation between the Tambo rocks and Bergell granodiorite as proposed by H.-R. WENK (1970). However, the different Sr (and Rb), U, Th, K and Ca concentrations and different U concentrations in the zircons, in conjunction with the age data which show no evidence of remobilisation or recrystallisation in the Tambo augen gneisses, preclude a genetic relationship. The U and Th data show that the Novate granite could not have formed from the Bergell granodiorite by differentiation and that many of the aplites cutting different rock units in this area were probably derived from the Novate.

Acknowledgments

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Mrs. C. Kerr-Joplin kindly drew the diagrams. Mrs. L. Parry typed the manuscript.

Table 1. Rb and Sr isotope dilution analyses of rocks from the Tambo nappe.

Sample No.	Rb ppm	Sr ppm	Rb^{87}/Sr^{86}	Sr^{87}/Sr^{86} calc.	Sr^{87}/Sr^{86} meas.
KAW 759	168	159	3.02	0.7276	
KAW 791	255	131	5.46	0.7365	
KAW 764	229	93.5	7.02	0.7423	0.7421
KAW 105/4[1])	305	89.5	9.72	0.7520	
105/7	315	91.1	9.86	0.7534	
KAW 789	207	51.8	11.51	0.7627	
789/1	208	51.2	11.59	0.7597	
KAW 790	266	56.6	13.98	0.7706	
790/1		56.4	14.19	0.7707	
KAW 788	318	60.7	15.07	0.7728	0.7749
KAW 785	304	51.0	17.16	0.7873	
KAW 281[1])	292	47.0	17.73	0.7905	
281/4	336[2])	48.0	17.23	0.7895	
KAW 784	317	51.8	17.64	0.7903	0.7887
784/1	316	51.5	17.65	0,7893	
KAW 786	300	48.4	17.83	0.7912	
KAW 782[3])	335	26.8	36.08	0.8033	
782/1	332	26.6	35.95	0.8040	
KAW 920	112	78.3	4.09	0.7393	
KAW 921	396	90.1	12.62	0.7399	
KAW 783[3])	345	16.7	59.10	0.8372	

88/86 normalised to 8.432; 85/87 to 2.591.

[1]) Analyses by E. JÄGER (pers. comm.). [2]) Poorly spiked. [3]) Not plotted in Figure 2.

Table 2. Rb and Sr isotope dilution analyses of rocks from the Gruf masse (Gruf migmatites).

Sample No.	Rb ppm	Sr ppm	$\frac{Rb^{87}}{Sr^{86}}$	$\frac{Sr^{87}}{Sr^{86}}$ calc.	$\frac{Sr^{87}}{Sr^{86}}$ meas.
KAW 671	100	511	0.56	0.7155	0.7148
KAW 936a	127	381	0.96	0.7113	
936b	94	330	0.82	0.7175	
936c	110	349	0.90	0.7162	0.7149
KAW 926	130	372	0.97		0.7167
KAW 736	175	253	1.97	0.7252	0.7228
KAW 740	201	129	4.46	0.7283	0.7300
KAW 741	192	144	3.82	0.7306	0.7300
KAW 739	183	137	3.81	0.7317	0.7329
KAW 742	307	103	8.54	0.7266	
KAW 929	262	72.4	10.34	0.7601	0.7595
KAW 928	242 } 241 }	75.5	9.15	0.7615	
	233	75.4	8.81	0.7642	

Table 3. Rb and Sr isotope dilution analyses of rocks from the Bergell massif, Novate granite and aplites.

Sample No.	Rb ppm	Sr ppm	$\frac{Rb^{87}}{Sr^{86}}$	$\frac{Sr^{87}}{Sr^{86}}$ calc.	$\frac{Sr^{87}}{Sr^{86}}$ meas.
Bergell massif					
KAW 925	164	443	1.06	0.7116	
KAW 924	178	258	1.97	0.7194	
KAW 925a					
KAW 780	219	206	3.03	0.7148	0.7149
KAW 781	265	133	5.71	0.7182	0.7170
					0.7168
Novate granite					
KAW 553	153	245	1.78	0.7132	
KAW 133/2[1])	158	224	2.05	0.7138	
133/3	159	210	2.16	0.7131	
KAW 737	179	156	3.28	0.7156	0.7135
KAW 738	210	98.8	6.06	0.7155	0.7145
Aplites					
KAW 735	187	84.6	6.31	0.7150	0.7152
KAW 933	225	179	3.60	0.7185	
KAW 930	200	106	5.38	0.7164	
KAW 931	238	49.3	13.76	0.7238	0.7237
Pegmatite					
KAW 552[1])	193	23.1	23.84	0.7346	

[1]) Analyses by E. JÄGER (pers. comm.).

Table 4. Regression parameters for rocks from the Bergell area.

Rock unit	No. of samples	Age (m.y.)	Initial S 87/S 86	MSWD	Model
Tambo Nappe incl. Duplicates	11	293±14	0.704±0.003	1.6	1
Migmatites (lower line excl. KAW 742)	8	306±30	0.705±0.002	0.3	1
Migmatites (upper line)	7	365±35	0.702±0.003	0.7	1
Novate granite (incl. aplitic phases)	5	25±80	0.705±0.005	0.0	1
Bergell granodiorite (plus aplites and pegmatite)	6	65±17	0.703±0.003	0.3	1

Table 5. K. U, and Th determination of rocks from the Bergell region.

Sample No.	K	U	Th	Th/U	K/U	K/Th
Novate						
KAW (B 79)	3.03	3.2	3.7	1.17	9,490	8,200
73+	3.39	7.4	5.4	0.76	4,590	6,280
KAW 1040	3.43	3.1	4.4	1.42	11,000	7,600
Bergell granodiorite						
72+	3.20	8.7	24.3	2.70	3,680	1,320
KAW 924 (B 81)	3.30	11.5	24.5	2.14	2,870	1,350
KAW 919 (B 17)	3.35	4.2	17.1	4.06	8,000	1,960
KAW 925a (B 83)	3.49	5.6	18.8	3.35	6,230	1,860
KAW 753	3.50	14.0	28.0	2.00	2,500	1,250
KAW 935 (B 109)	3.50	10.5	27.8	2.65	3,340	1,260
KAW 925 (B 82)	3.78	3.4	16.0	4.72	11,120	2,360
B 33	4.63	6.2	22.4	3.60	7,470	2,070
KAW 780 (B 37)	4.67	16.0	19.9	1.24	2,920	2,350
B 34	5.57	6.9	16.9	2.47	8,070	3,300
KAW 781 (B 39)	5.25	24.3	10.4	0.43	2,160	5,050
Aplites						
KAW 930 (B 104)	3.55	4.8	3.4	0.71	7,400	10,450
KAW 735 (B 1)	4.01	7.2	2.8	0.39	5,570	14,320
KAW 931 (B 105)	4.06	9.5	5.5	0.58	4,280	7,400
KAW 933 (B 107)	3.56	9.1	15.6	1.71	3,920	2,280
KAW 738 (B 6)	4.36	8.7	3.1	0.35	5,000	14,080
Bergell tonalite						
KAW 918 (B 18)	1.84	2.2	4.3	1.95	8,360	4,280
Gruf masse						
KAW 671	1.48	3.4	10.5	3.08	4,350	1,410
KAW 736 (B 4)	2.80	3.6	31.5	8.78	7,780	890
B 26	3.17	1.4	10.7	7.46	22,640	2 960
KAW 739 (B 11)	4.18	9.7	19.0	1.97	4,310	2,200
KAW 741 (B 25)	4.20	2.4	18.3	7.72	17,500	2,300
B 28	4.22	3.5	28.1	8.12	12,060	1,500
KAW 928 (B 89)	4.27	4.0	12.5	3.08	10,680	3,420
KAW 740 (B 16)	4.31	3.1	16.2	5.19	13,900	2,660
Tambo rocks						
KAW 782 (B 44a)	4.43	8.2	4.7	0.57	5,400	9,430
KAW 784 (B 44c)	4.54	8.0	5.0	0.63	5,680	9,080
KAW 764	4.68	6.1	18.2	2.98	7,670	2,570
KAW 788 (B 56)	4.89	9.6	16.0	1.66	5,090	3,060
KAW 790 (B 60a)	4.97	7.2	2.9	0.40	6,900	17,140
KAW 789 (B 59a)	5.25	4.0	8.0	1.98	13,130	6,560

Table 6. Localities of analysed samples.

Co-ordinates refer to the Swiss National Topographic Maps 1:50,000, quadrangles 267, 268, 277, 278.

Sample No.	Locality	Sample No.	Locality
KAW 759	764.7, 132.5	KAW 925	765.6, 124.4
791	748.5, 135.0	924	765.7, 124.2
764	750.8, 132.3	925a	768.7, 123.0
105	748,6, 134.6	780	774.0, 136.2
789	748.4, 136.7	781	774.0, 136.2
790	748.3, 136.3	553	757.2, 123.1
788	747.4, 139.1	133	755.5, 121.3
785	763.4, 134.4	737	755.3, 121.5
281	763.7, 134.3	738	755.3, 121.5
784	763.2, 134.4	735	755.1, 121.4
786	763.7, 134.3	933	774.5, 136.8
782	763.2, 134.4	930	772.6, 133.7
920	746.5, 138.7	931	772.8, 133.7
921	746.5, 138.7	552'	760.7, 127.3
783	763.4, 134.4	1,040	756.3, 121.3
671	765.7, 131.9	919	766.9, 123.4
936	764.8, 131.3	753	770.5, 133.6
926	760.0, 125.7	935	769.8, 134.2
736	755.1, 121.4	918	767.1, 123.4
740	766.4, 123.9	B 79	754.0, 122.7
741	755.2, 117.3	33	774.0, 136.2
739	754.2, 121.8	34	774.0, 136.2
742	753.8, 119.8	26	753.4, 119.7
929	757.2, 124.6	28	753.4, 119.7
928	757.2, 124.6		

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(SMPM = Schweiz. Miner. Petrogr. Mitt.)