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Potassium-Argon age studies across the southeast margin of the Tauern window, the Eastern Alps

By E. R. OXBURGH *), R. ST. J. LAMBERT *), H. BAADSGAARD **) & J. G. SIMONS *)

With 5 figures and 1 table

Kalium-Argon-Altersbestimmungen am Südostrand des Tauernfensters (Ostalpen)

Von E. R. OXBURGH, R. ST. J. LAMBERT, H. BAADSGAARD und J. G. SIMONS

Mit 5 Abbildungen und 1 Tabelle

Abstract

Twenty six new K-Ar ages on samples from the eastern Tauern are presented (24 mica ages, 2 whole rock ages). The majority of these are concentrated across the edge of the Tauern window near Obervellach, Mölltal, Kärnten; the remainder come from a nearby area in the Zentralgneis. The edge of the window, established by previous workers on geological criteria, is marked by an abrupt break in the pattern of ages. Within the window ages range from 17.5 to 37 my, but there is a strong concentration near 20 my. This age of about 20 my is interpreted as the age of the cooling associated with and following the development of the gneiss domes of the eastern Tauern. Ages outside the window range from 60 to 91 my. The spread is greatest near the edge of the window and it is suggested that in this zone ages have been modified by partial loss of argon, caused by some later thermal event, possibly the rise of the gneiss domes mentioned

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*) Dept. of Geology and Mineralogy, University Museum, Oxford.

**) Dept. of Geology, University of Alberta, Edmonton.

above. Further from the margin, the rocks outside the window (Altkristallin), give concordant ages of about 80 my. It is argued that at this time and/or some time earlier (91 my) the Altkristallindecke may have begun to move northwards and undergone erosion and consequent cooling. Support for this hypothesis comes from the geology of the Late Cretaceous Gosau beds, which make their first appearance in the Coniacian and subsequently first contain abundant metamorphic debris in the Upper Campanian.

Zusammenfassung

Sechsundzwanzig neue K-Ar-Altersdatierungen von Proben aus den östlichen Tauern werden vorgelegt (24 Glimmer-Alter, 2 Gesamtgesteins-Alter). Die Mehrzahl dieser Proben liegt konzentriert um den Rand des Tauernfensters bei Obervellach, Mölltal, Kärnten. Der Rand des Fensters, von früheren Bearbeitern aus geologischen Gründen festgelegt, ist durch eine abrupte Veränderung der Altersdaten gekennzeichnet. Innerhalb des Fensters liegen die bestimmten Werte zwischen 17,5 und 37 Millionen Jahre, bei starker Häufung der Werte um 20 Millionen Jahre. Das Alter von ungefähr 20 Millionen Jahre wird als jenes Altersstadium interpretiert, in welchem eine Abkühlung im Zusammenhang mit der Ausprägung der Gneisdome im östlichen Tauernfenster erfolgte.

Die Altersdaten außerhalb des Fensters reichen von 60 bis 91 Millionen Jahre. Sie sind nahe dem Fensterrand am unterschiedlichsten, wobei angenommen werden kann, daß die Alter in diesem Bereich durch teilweise Argon-Verluste modifiziert werden. Letztere wurden möglicherweise durch spätere thermische Vorgänge in Zusammenhang mit dem Aufsteigen der erwähnten Gneiskuppeln verursacht. Weiter entfernt vom Fensterrand ergaben die altkristallinen Gesteine übereinstimmend Werte von ungefähr 80 Millionen Jahre. Es wird angenommen, daß zu dieser Zeit und/oder etwas früher (91 Millionen Jahre) die Nordbewegung der altkristallinen Baueinheiten eingesetzt hat, die dabei der Erosion ausgesezt und damit einer Abkühlung unterworfen wurden. Diese Hypothese wird durch die Ergebnisse geologischer Studien an den spätkretazischen Gosausedimenten gestützt: Die Gosau-Sedimentation beginnt im Coniacien und anschließend ab Obercampan wird erstmals reichlich Detritus aus metamorphen Gesteinen eingestreut.

Contents

Introduction

The margins of the Tauernfenster offer considerable scope for age determination studies. Previous work in the area has been by the rubidium-strontium method and has been confined to Zentralgneis series within the window (Lambert, 1964). The main result of this work was to establish an age of 243 ±

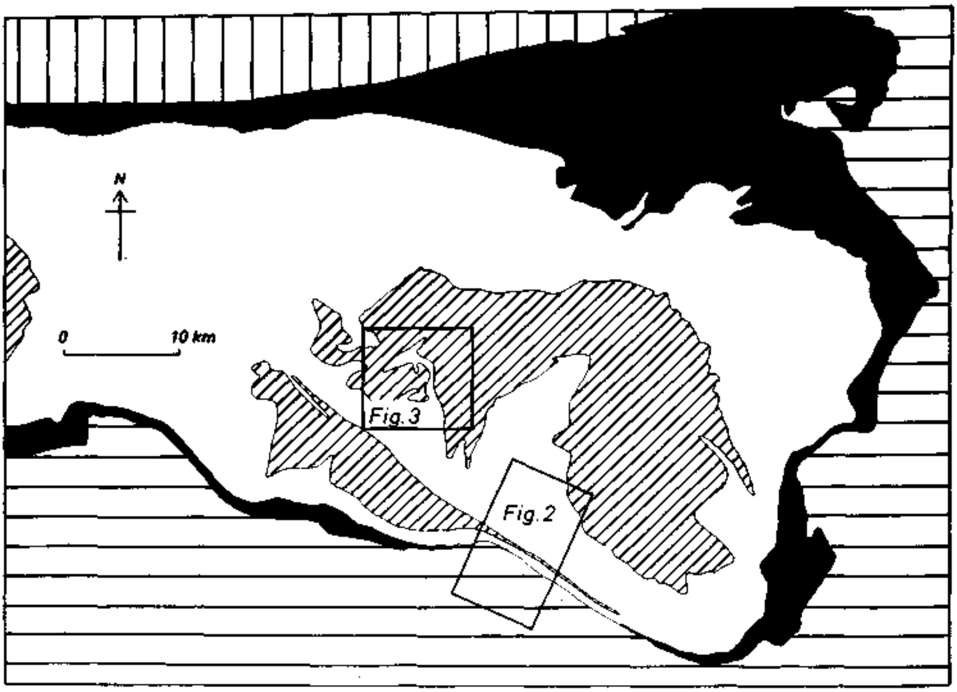

Fig. 1. Geological sketch map of the eastern Tauern to indicate areas studied in detail. Explanation of symbols: vertical lines = Grauwacke zone; horizontal lines = Oberostalpin Altkristallin; oblique lines = Zentralgneis; black = Unterostalpin; white = Schieferhülle and Altkristallin of the Tauern. All after EXNER (1956).

11 my (Middle Permian?) for the probable age of intrusion of the granites which now form the Zentralgneis.

For the present study, samples have been collected from a strip about 13 km long which cuts across the southern edge of the Tauernfenster (Fig. 1). The northeast end of this strip lies within the area of outcrop of the Zentralgneis and its cover of metamorphosed Mesozoic sedimentary rocks, the Schieferhülle. The southwest end of the strip lies within the metasedimentary rocks of the Altkristallin series. The age of this series is unknown but at Innerkrems and elsewhere, slightly recrystallized sedimentary rocks of Triassic age are reported to rest unconformably upon the Altkristallin (EXNER, 1954). The Altkristallin rocks are believed to belong to the Oberostalpin thrust sheet which forms the margin of the window and which is believed to have moved northwards, overriding the Schieferhülle and Zentralgneis.

The potassium-argon method of age determination allows an investigation of the most recent thermal events in an area. Thus it was hoped that the present study would establish the minimum age of the most recent metamorphism within the Zentralgneis and Schieferhülle. In addition it was hoped to discover whether the margin of the window as established by field geology showed up clearly in the pattern of ages; this has important implications for the time of movements involving the Altkristallin and for the thermal situation at the time of the movements. Finally, it was desirable to establish the minimum age of the most recent metamorphism of the Altkristallin rocks and if possible to relate all these results to other known thermal and stratigraphic-structural events.

Samples

The majority of the samples were collected during 1963 and 1964 from the Overvellach area, in which one of the authors has been mapping for the last three years; sample localities are shown an Fig. 2. Specimens were chosen to provide a good geographic spread and to be representative of the main rock units. Detailed descriptions of the samples are given in Appendix A. Analyses were made of separated muscovite or biotite concentrates and in two cases of whole rocks. The remaining samples came from the Böckstein-Mallnitz area (Fig. 3) and were mostly separated from specimens already used for whole rock rubidium-strontium analysis (LAMBERT, 1964).

Analytical procedures

About half of the analyses were carried out at the University of Alberta, Edmonton and about half at Oxford University.

Those at the University of Alberta were analyzed using the methods described by BAADSGAARD, GOLDICH, NIER and HOFFMAN (1957) for argon; this involves fusion of the sample with sodium hydroxide *in vacuo* at a moderate temperature. The potassium analyses at Edmonton were carried out by A. STELMACH,, using either the potassium tetraphenylborate method or flame photometry using a Perkins-Elmer photometer with Li internal standard.

At Oxford, argon was extracted by direct fusion *in vacuo* at a high temperature using induction heating, and all potassium analyses were made by R. GOODWIN on an EEL flame photometer using standard procedures. Interlaboratory comparisons between Oxford and Edmonton, carried out immediately before the present series of analyses, showed potassium analyses to agree within ½ per cent and argon analyses within 1 per cent. In Table 1 errors have been quoted at ± 3 per cent, rounded off to the nearest 0.5 my where relevant, as are the ages themselves. Errors of more than 3 per cent are quoted on analyses containing unusually low percentages of radiogenic argon.

The significance of K-Ar "ages" in metamorphic rocks

Before discussing these results in detail a few brief comments should be made on the comparability and geological significance of K-Ar results.

In the simplest situation, the K-Ar age of a system represents the time which has elapsed since it cooled below some critical temperature at which the rate of argon escape from the system became negligible and radiogenic argon began to *accumulate* from the radioactive decay of potassium. (The case of potassium-rich minerals which form diagenetically at low temperatures will not be considered here.)

The system upon which the measurements are made may be a simple phase within a rock (e. g. biotite, muscovite) or in some cases the whole rock itself. It is evident both on the basis of experimental work (e. g. EVERNDEN, CURTIS, KISTLER and OBRADOVITCH, 1960) and field studies (HART, 1964) that different kinds of system become closed with respect to argon at different tempe-

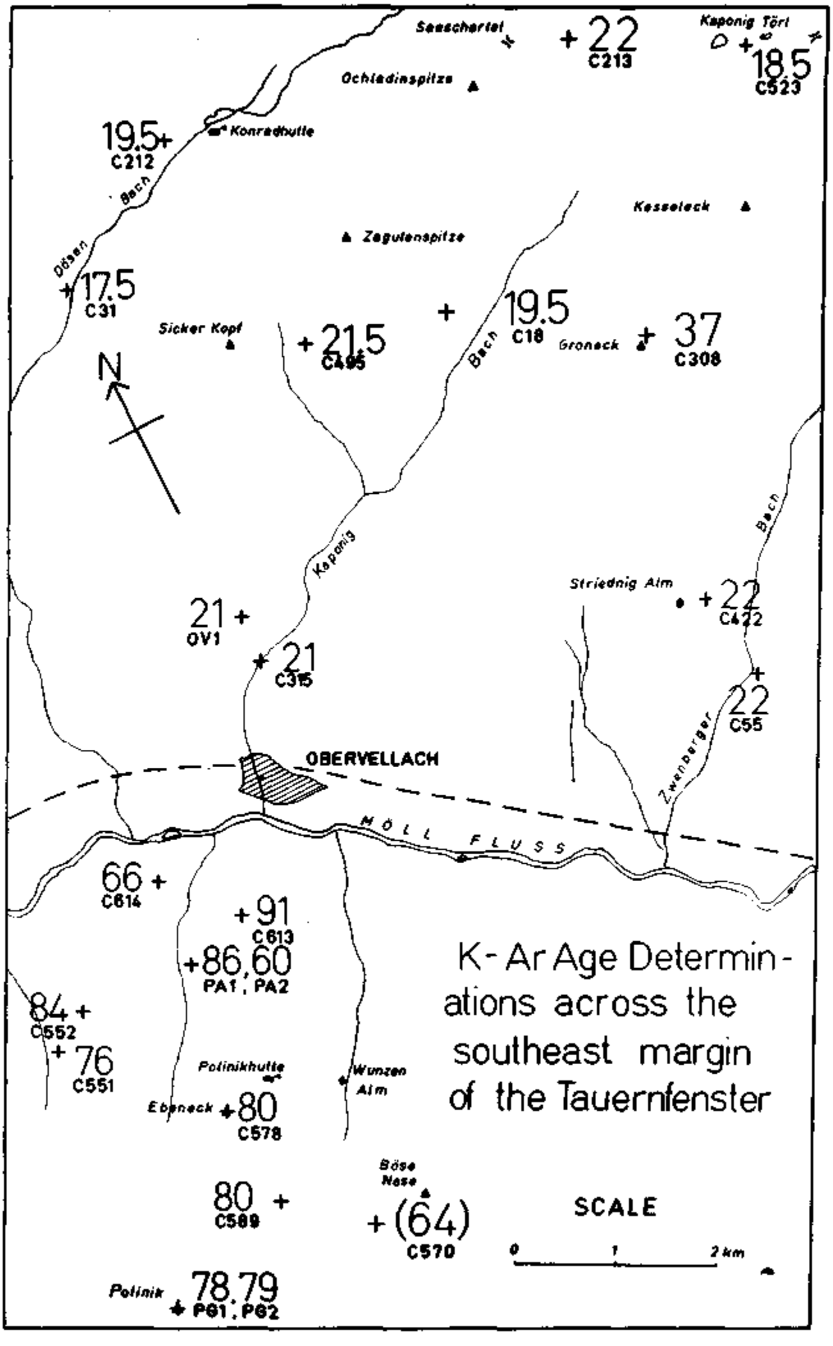

Fig. 2. Sketch map showing localities of specimens near Obervellach. Explanation of numbers and symbols: crosses indicate the localities of analysed specimens; the large numerals near each cross give the K-Ar age for that specimen in millions of years, while the small numerals preceded by a letter or letters give the sample number. The heavy dashed line indicates the edge of the Tauernfenster (after Exner, 1956, 1962).

ratures, and therefore that unless the fall in temperature within an area is relatively rapid, measurements on different minerals within the same rock may yield different ages, irrespective of assumptions about the mechanism of argon escape.

Other factors being equal, the order muscovite, biotite, triclinic K-feldspar represents a sequence with successively lower temperatures for the beginning of retention of argon; amphiboles and pyroxenes probably retain argon better than biotite (HART, 1961).

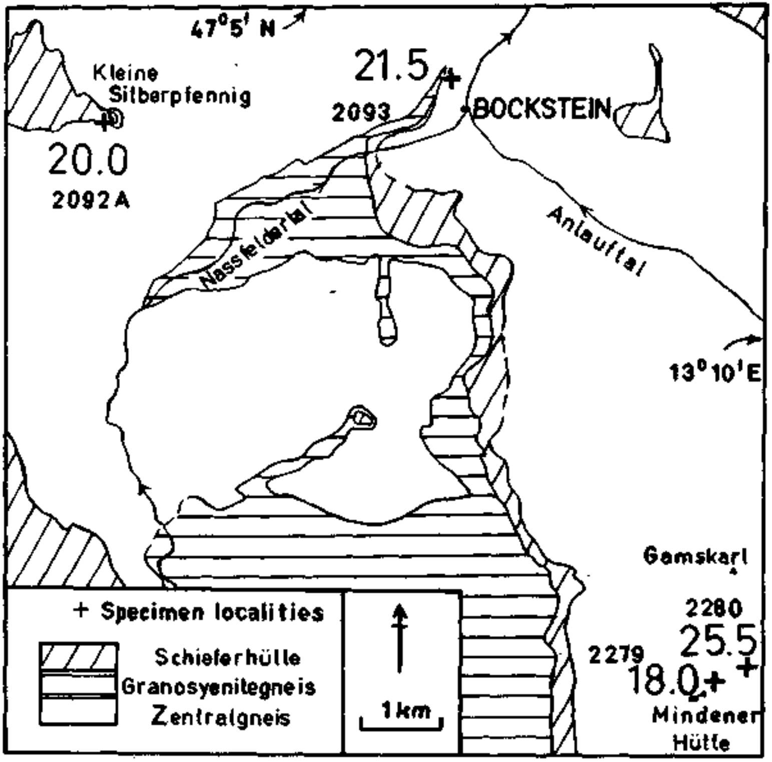

Fig. 3. Sketch map showing the localities of analysed specimens in the vicinity of Böckstein. Localities and ages indicated as in Fig. 2. Boundaries after EXNER (1956).

If it should happen that a system which has already begun to accumulate radiogenic argon experiences a reheating, there may result a loss of argon, which, depending on the amount and duration of the temperature rise, may be partial or complete. In the case of partial loss, the system becomes closed once more while still retaining some proportion of the previously accumulated radiogenic argon; thus the total radiogenic argon contained in the mineral today comprises part of that retained after the first cooling and all that retained after the second cooling; such a mineral would give an age intermediate between the time of the two coolings. In the case of total argon loss as a result of reheating, the age derived would simply be that of the second cooling.

In addition to differences of behaviour between different minerals, differences are to be expected between crystals of the same mineral but of different size. Large grains have a smaller ratio of surface area to volume than small grains, and thus, other factors being equal, argon will escape more readily from the latter.

The effect of variations of total pressure on the diffusion rates of argon through crystal lattices is not known; it is probable that pressure is much less important than temperature. At very high argon pressures, however, argon (including a radiogenic component) may be included in crystal lattices at the time of their formation. Ages on minerals formed under these conditions and containing "excess" radiogenic argon would be spuriously high. Indisputable examples of "excess" argon are, however, confined to potassium-poor minerals such as pyroxenes.

Physical disruption of a crystal lattice by tectonic activity may possibly bring about the loss of radiogenic argon from the crystal, but this is likely to be important only in situations where the system has not cooled very much below the temperature of beginning of rentention of argon. At lower temperatures deformation is not likely to cause significant argon loss from crystal lattices unless it also brings about a recrystallization.

In summary, it may be said that K-Ar ages are only strictly comparable when they have been determined on the same mineral species and on materials of approximately the same grain size. Further, in so far as the ages are related to metamorphic events, they can only provide a minimum age for the metamorphic recrystallization because this will generally be complete by the time the metamorphosed area has cooled sufficiently for its minerals to begin to retain radiogenic argon. No exact figure is known for the latter temperature, but muscovite is known to lose all its argon in a geologically short time at 300° C under laboratory conditions (EVERNDEN, CURTIS, KISTLER & OBRADOVITCH, 1960), a temperature below that probable for all but the lowest grades of metamorphism.

Results

The results are presented in Table I and are classified according to the rock unit from which the samples were collected. Included in the term "Schieferhülle" are all metasedimentary rocks inside the Tauernfenster. The areal distribution of the ages obtained is shown in Figs. 2 and 3 and their cumulative frequency has been plotted in Fig. 4.

It will be observed that values from within the Tauernfenster range from 17.5 to 37 my. The errors on the majority of these results do not exceed 1 my and thus it appears that this range of values represents a true time difference between events in different areas within the Tauernfenster; it would not be legitimate to average these results to derive an "age" for the rocks which yield them.

It will, however, be seen that of the nine muscovite ages from within the window, seven are between 20 and 22 my. Differences of this order between ages are probably not significant. Interpretation of the two remaining muscovite ages, one of 25 my and the other of 17.5 my must await confirmation by analysis of further material from the same localities, but it may be noted that the 25 my age came from a rock of coarser than average grain size.

TABLE I.

	Analysis No.	Sample No.	Laboratory	Rock Type	Mineral	K_2O Wt. %	Ar^{40} CC STP/gm x 10^{-5}	% radiogenic Ar^{40}	Age-millions of years
Zentralgneis	492	2280	E	phyllonitic gneiss	Mu	9.63	0.819	81	25.5 ± 1.0
	756	2092 a	O	muscovite — phyllonite	Mu	8.75	0.579	91	20.0 ± 0.5
	493	2279	E	coarse augen gneiss	Bi	8.63	0.517	58	18.0 ± 1.0
	775	C 18	O	fine grained aplitic gneiss	Bi	8.58	0.553	82	19.5 ± 1.0
	507	2093	E	coarse augen gneiss	Bi	9.02	0.645	81	21.5 ± 0.5
	773	C 213	O	coarse augen gneiss	Bi	8.06	0.596	84	22.0 ± 0.5
	774	C 308	O	biotite augen gneiss	Bi	7.16	0.892	75	37.0 ± 2
Schieferhülle	763	C 212	O	biotite pegmatite	Bi	8.55	0.558	81	19.5 ± 0.5
	570	C 31	E	garnet muscovite schist	Mu	8.39	0.486	78	17.5 ± 0.5
	563	C 315	E	mica schist	Mu	10.23	0.721	61	21.0 ± 1.0
	569	OVI	E	muscovite dolomite quartzite	Mu	9.24	0.646	82	21.0 ± 0.5
	571	C 495	E	tourmaline quartz muscovite schist	Mu	10.53	0.755	51	21.5 ± 1.0
	568	C 55	E	muscovite schist	Mu	9.63	0.704	79	22.0 ± 0.5
	566	C 422	E	muscovite schist	Mu	10.02	0.746	58	22.0 ± 1.0
	573	C 523	E	biotite kyanite schist	WR	4.84	0.300	24	18.5 ± 2.0
Altkristallin of Polinik	564	PA 2	E	biotite schist	Bi	8.39	1.696	52	60 ± 3
	771	C 551	O	biotite schist	Bi	8.91	2.295	94	76 ± 2
	567	PG	E	garnet mica schist	Bi	7.09	1.863	96	78 ± 2
	764	C 589	O	biotite amphibolite	Bi	8.38	2.270	94	80 ± 2
	759	C 614	O	sheared augen gneiss	Mu	10.40	2.319	91	66 ± 2
	572	PG	E	garnet mica schist	Mu	6.51	1.744	85	79 ± 2
	765	C 578	O	mica schist	Mu	9.08	2.453	92	80 ± 2
	760	C 552	O	coarse pegmatite	Mu	9.29	2.655	82	84 ± 3
	565	PA 1	E	coarse pegmatite	Mu	8.84	2.586	88	86 ± 2
	770	C 613	O	coarse pegmatite	Mu	10.19	3.145	76	91 ± 3
	772	C 570	O	microcline augen gneiss	WR	4.25	0.923	83	64 ± 2

"O" = indicates Oxford analyses; "E" = indicates Edmonton analyses.

The biotite results from within the window show a wider range of values (37—18 my). If C 308 (37 my) is disregarded, however, the range is reduced to 22.5—18 my. Taking into account the relatively poor argon retentivity of biotite, the difference between the main group of biotite ages and the main group of muscovite ages is probably not significant.

It is extremely difficult to explain the high value (37 my) given by C 308 — a sample collected within a short distance of the top the Gröneck. Although a variety of accidental factors may combine to produce an anomalously low age, it is less usual for them to make an age anomalously high. It is improbable that the mineral analysed (biotite) contains excess radiogenic argon as there is no evidence in the mineralogy of the rocks to suggest the existence of the high argon pressures necessary for this effect to be important. In the absence of any other determinations from the neighbourhood of the Gröneck, it is suggested that C 308 represents a rather older age which has been modified by partial argon loss some time later than 37 my ago. If this is the case, the rocks at the top of the Gröneck could represent allocthonous Altkristallin. This interesting possibility clearly requires further study.

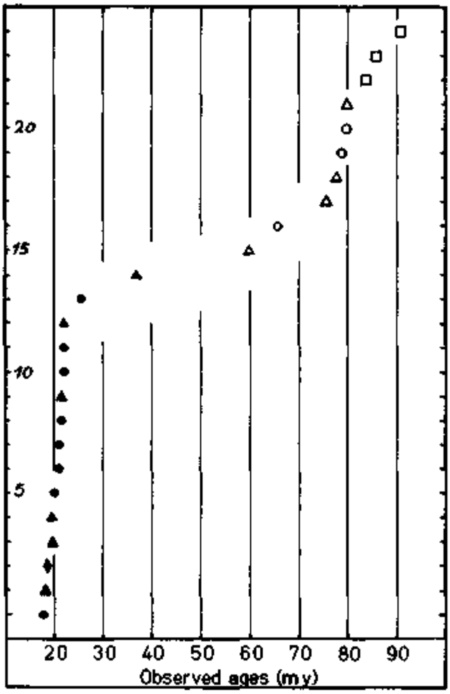

Fig. 4. Cumulative frequency diagram of 25 measured ages. Measured ages are placed in an order of ascending age and each age is then assigned a number corresponding to its place in the order (i. e. 1—25). Points are plotted for which the value on the abscissa is the age of the sample and the value on the ordinate is the number assigned to the sample in the order. A concentration of similar ages is indicated by steep slope in the sequence of points, while an interval for which no or few ages are found is indicated by a low (flat) slope. Open symbols indicate samples from outside the Tauernfenster and solid symbols, samples from inside the Tauernfenster. Circles indicate muscovite ages, triangles biotite ages, squares muscovite-pegmatite ages, and the diamond a whole rock age. (C 570 is omitted from this diagram because its value is not strictly comparable with the others.)

As is shown on both Fig. 2 and Fig. 4, there is a marked difference between the ages within the window and those outside. Whereas the oldest age within the window is 37 my, the youngest outside the window is 60 my. It is highly significant that the edge of the window, a boundary mapped by earlier workers on geological criteria, corresponds to a break in the pattern of ages. Discussion of this, however, is deferred until later.

Within the Altkristallin rocks outside the window, the pattern of ages is not simple. Values range from 60 to 91 my. Fig. 5 shows these ages plotted as a function of their distance from the edge of the window. Consider first those ages which are found at distances of more than 2 km from the margin of the window. Three muscovite ages give results of 79—80 my and two biotite ages give values of 76 and 78 my. The differences within each of these groups are not significant as all of these results are ± 2 my; nor, taking into account the lower argon retentivity of biotite by comparison with muscovite, can any significance be attached to the difference between the groups. Thus all ages further than 2 km from the edge of the window may be considered as concordant. (The sample C 570 is not included in this discussion; it cannot be compared directly with the mica ages as the age was measured on the whole rock, which was poor in micas and rich in microcline and thus likely to suffer argon loss.)

At distances of less than 2 km from the margin of the window, however, there is a much more irregular pattern of ages. All ages are either distinctly

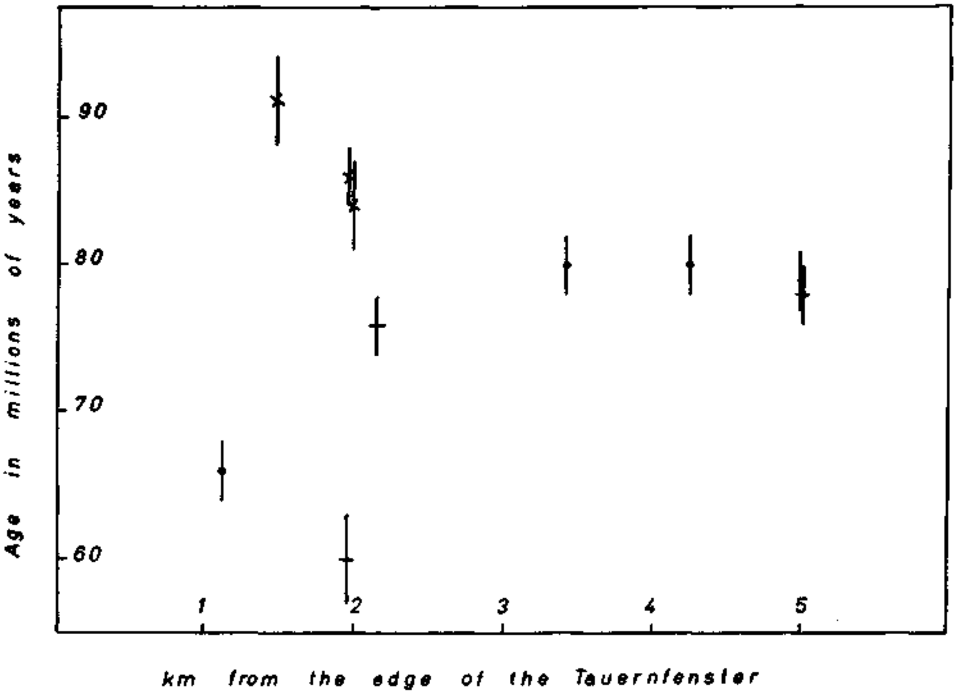

Fig. 5. The measured age of samples from outside the Tauernfenster plotted against the distance of their localities from the present edge of the window. The length of each vertical line corresponds to the error on the age of that sample. Crosses indicate muscovite-pegmatite ages, dots groundmass-muscovite ages, horizontal lines biotite ages.

older or younger than the concordant group described above. The three ages which exceed that of the concordant group have all been yielded by coarse muscovite from discordant pegmatites which cut across the foliation of the Altkristallin schists. At one of these localities (PA 1) where the pegmatitic muscovite gives an age of 86 my, the biotite of the country rock (PA 2) gives 60 my. A difference of this order is unlikely to result solely from a single cooling episode, even though different minerals of different grain size are involved; it is more probable that a reheating has taken place which brought about partial argon loss from the fine grained biotite of the country rock and a much smaller or negligible loss from the coarse pegmatitic muscovite. Such a reheating could have produced the other low age in the marginal zone (66 my, on muscovite) and could have produced the spread of 7 my in the muscovite pegmatite ages.

If such a reheating and partial argon loss be accepted as the cause of the discordant ages in the marginal zone of the Altkristallin, it remains to explain the discrepancy between the concordant group of ages of about 80 my from the outer zone and the highest (and therefore least modified by reheating) of the ages in the marginal zone (91 my). The problem is whether the pre-Tertiary thermal histories of the two areas are actually different or whether the *same* early thermal history has been recorded differently by minerals in different parageneses. This problem cannot adequately be solved without further work, in particular, analyses of muscovite from pegmatites in the area further south from the margin. If these give ages of 90 my or more there is probably no difference in the main cooling history of both marginal and outer zones.

It does seem safe to conclude, however, that the Altkristallin rocks did as a whole experience a cooling episode some 80—90 my ago, although this time interval may contain either one or two events. Subsequently the marginal zone underwent a reheating and suffered a partial loss of argon. These ages are discussed further in the next section, in the light of nearby stratigraphic evidence.

Discussion

It remains to discuss the interpretation of the results as applied to the geological evolution of the southeast Tauern.

It has been suggested above that K-Ar ages represent some point in time during the cooling history of a body of rocks. The most usual reason for such a cooling is that an area has undergone differential uplift and that the upper rock units have been removed by erosion, thus exposing units which were previously deeply buried, to cooling at or near the surface. Such an explanation seems appropriate for the main group of ages within the Tauernfenster. It is known on geological grounds that late differential vertical movements of the basement took place within the eastern Tauern (Exner, 1954, 1957, 1962 a); these movements were responsible for the development of the present striking pattern of gneiss domes separated by deep and sinuous tectonic troughs within which the Schieferhülle is preserved. These vertical movements seem to postdate important horizontal movements because many of the tectonic features produced by the horizontal movements, *e. g.* gneislamellae, are themselves domed or depressed. It is suggested, therefore, that elevation of the gneiss domes and the relative depression of the troughs was in progress 20 my ago although the process certainly began before and went on after this time.

It has already been pointed out that the boundary mapped on lithological criteria as the margin of the Tauernfenster corresponds to a sharp break in the pattern of ages. Thus although the Altkristallin rocks and those inside the window are now in close contact, their thermal histories are quite different. This means that originally the two areas must have been spatially separated but brought into their present juxtaposition relatively recently. The present relationship cannot be very much more than 20 my old. If it were much older, no sharp break in ages would be expected across the edge of the window, and at least the marginal part of the Altkristallin would be expected to have suffered total argon loss during the thermal event from which the Schieferhülle and Zentralgneis were cooling 20 my ago.

As was recorded earlier, there is evidence of partial argon loss from some of the minerals in the Altkristallin near the edge of the window (*i. e.* in the lowest part of the Oberostalpindecke). This suggest that the Altkristallin of Polinik assumed its present relationship to the Schieferhülle and Zentralgneis shortly before 20 my ago, when, altough these rocks were cooling, there still remained sufficient heat to cause partial loss of argon in the marginal part of the Altkristallin.

There remains the question of the nature of the movements which took place shortly before 20 my ago, and brought about the present situation. In that differential vertical movements have already been suggested to occur about this time, there seems to be no reason why differential vertical movements along the line of the Mölltal should not have brought up warm Tauern rocks from depth to lie against the cooler and structurally higher rocks of the Altkristallin.

It should be pointed out, however, that the present age relationships could equally well be satisfied by large scale horizontal movements a little earlier than 20 my ago, which transported cool Altkristallin rocks from the south against and over rocks of the Tauern while the latter were cooling but still warm. These horizontal movements would have had to have been followed very shortly by the differential vertical movements which were described earlier.

The main group of ages within the Altkristallin rocks gives a most interesting and geologically rather surprising result. Although, as discussed in the previous section, the significance of the difference between the age of the oldest pegmatite (91 my) and the main concordant group of groundmass mica ages (80 my) is not clear, the overall degree of consistency is so high that it is hard to escape the conclusion that these values are a true indication of the age of the cooling after some thermal event. It would be most interesting to know whether this was the event which brought about the slight recrystallisation of the Triassic sedimentary rocks at Innerkrems which are reported to lie unconformably upon the Altkristallin rocks (Exner, 1954).

It is clear that it is both hazardous and speculative to extend the results of a study of a few square kilometres to problems which relate to many thousands of square kilometres. There are, however, some points of interest in this respect. An elevation of the Altkristallin rocks of the Oberostalpindecke must have begun 91 my ago, or perhaps earlier, in order that their upper layers should be stripped off, allowing the lower zones to cool. This elevation could have been associated with the northwards movement of the Oberostalpindecke up an inclined thrust plane. Thus 91 my could be the time of the main northward movement of the Oberostalpindecke and other associated thrust sheets.

Although the correlation between the absolute time scale and the stratigraphic sequence is not yet good (Casey, 1964), the highest age measured outside the window (91 my) is close to the age of 92 my reported for sanidine from a bentonite at Coleman, Alberta (Folinsbee, Baadsgaard and Lipson, 1961), now regarded as of probable Albian age (Folinsbee, Baadsgaard and Cumming, 1963). The latter authors also analysed sanidines and biotites from the Mowry shale and Frontier Formation, Wyoming and Montana (Upper Albian or Lower Cenomanian, Casey, 1964) and found a mean age of 94 my excluding one lower biotite age. Taking both sets of data into account, an age of 91 my therefore suggests the Upper Albian or Lower Cenomanian.

Although it is uncertain whether the measured age of 91 my is a real age, it is noted that pre-Cenomanian disturbances are known to the north of the Tauern window (Zeil, 1956, 1959) and Gosau sedimentation begins in the Coniacian (Weigel, 1937, Kühn, 1947, and Kollmann, 1964). These events might be connected with movements in the southern Tauern area which caused the uplift and cooling recorded in the 91 my (minimum) age.

A possible second link with stratigraphy and sedimentation is suggested by the 80 my ages. On the evidence of an age of 76 my found for the Upper Campanian Bearpaw Shale, Alberta by Folinsbee et al. (1961) the 80 my ages could indicate a mid-Campanian age. Woletz (1963) and Kollmann (1964) record the first incoming of metamorphic detritus (garnet, epidote and chloritoid) in the Upper Campanian Gosau beds of Gams. It is tentatively suggested that this change in the nature of the detritus might be the sedimentary expression of tectonic activity at 80 my. Oberhauser (1964) has discussed this problem in detail.

Recently a considerable number of age determinations have been carried out in the Western Alps. Jäger (1962), using the Rb/Sr method, showed an age range from 21 to 16 my northwards from the root zone into the Pennine nappes and the Gothard massif. She explained the time interval of 5 my by progressively later times of erosional uncovering from south to north. This range of ages corresponds surprisingly closely with that reported here from the Schieferhülle and Zentralgneis. It is not possible, however, to see any comparably simple explanation for the spread of ages recorded in this paper as there is no systematic variation corresponding to variation in location, altitude or geological unit.

Some other results of Jäger which have a bearing on the present study are those from rocks of the Silvretta which is regarded as the western part of the Mittelostalpindecke (Tollmann, 1963) and is thus the tectonic equivalent of the Polinik Altkristallin. Two micas and a whole rock analysis gave ages of 306 ± 13, 293 ± 12 and 356 ± 21 my. Thus it is clear that the western part of the thrust sheet has a rather different thermal history from that part immediately south of the Tauern.

There is only one figure similar to the 80 my group known elsewhere in the Alps; an age of 77 my is given by biotite from the Mittagfluh granite, Aar massif (Jäger and Faul, 1959). This result, obtained by K-Ar and Rb-Sr analyses, was regarded as an intermediate or mixed age between a Hercynian and an Alpine event, but the authors commented "we may not ignore the possibility of a complete recrystallisation 77 million years ago". However, Jäger et al. (1961) in a detailed petrographic study of the same biotite, preferred the intermediate age theory.

Steiger (1964) has employed K-Ar analysis on hornblendes from rocks to the south of the Gothard massif. A number of different generations of hornblende are recognised petrographically and the ages on each group show a different pattern. Steiger concludes that 46 my (the age given by his N—S oriented hornblendes) is the minimum age for the main tectonic phase in the Gothard massif. Ages of 23 to 30 my, from randomly oriented hornblendes, he regards as indicating the episodic rise of thermal domes in the Lepontinic region. It is to be noted that all Steiger's ages on amphiboles are older than those of Jäger on micas from the same area (16 my). There is no obvious correlation between the events established by Steiger and those of the present area.

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Appendix A.

2280 Point 2321 m on Hohenweg, NE of Mindener Hütte, near Mallnitz. In a band of contorted muscovite phyllonite underlying coarse argen gneiss. Euhedral, granular quartz 70%; muscovite in 2 mm flakes, concentrated in thin foliae, crystals not distorted, 25%; remainder rare untwinned microcline and pale brown biotite.

2092 a Muscovite from „muscovitite" lenticle 0.6 m thick at contact between Zentralgneis and Schieferhülle, about 200 m SW of summit of Kleine Silberpfennig, near Bad Gastein; pure muscovite, less than 1 mm maximum grain size. The material when collected was a soft, friable and uncompacted powder.

2093 See Lambert (1964).

2279 See Lambert (1964).

C 18 Fine-grained aplitic gneiss. — 0.5 km W of Jägerhütte on N side of Kaponigbach. Average grain size 0.2 mm; granular texture in groundmass of quartz and untwinned K-feldspar in about equal proportions and subsidiary albite. Set in the groundmass are numerous small laths of biotite and muscovite (together ≯ 5%) with strong preferred orientation. Concordant veinlets of quartz and K-feldspar.

C 213 Augen gneiss — 0.5 km SE of the Seescharte1.

A coarse augen gneiss with 1 cm augen of untwinned K-feldspar in a granular groundmass of albite, orthoclase and quartz within which are granules of epidote and partially resorbed garnet. Biotite (pleochroic pale green to mud grey) and muscovite are about equal in proportions and make up about 15% of the rock. There are patches of myrmekite associated with untwinned K-feldspar.

C 308 Biotite augen gneiss — 0.1 km NE of the summit of the Gröneck on the ridge crest.

Fine grained schistose gneiss with small (0.5 cm) rounded augen of K-feldspar; fine laminations of alternately light and dark components. Total mica 15% (biotite $\gg$ muscovite). Other constituents quartz, and albite. Accessory sphene and garnet.

C 212 Biotite pegmatite — at foot of cliffs 0.3 km WNW of Konradhütte.

A semi-concordant pegmatite within biotite-rich melanocratic augen gneiss. Principal minerals of the pegmatite; quartz, K-feldspar and books of biotite.

C 31 Garnet muscovite schist — NE side of lower Dösenbach where track crosses from NE to SW side of the river.

Coarse (0.5—1.0 cm) garnets in a coarse muscovite-rich ($>$ 40%) quartzo-feldspathic schist. Both quartz and muscovite show strain.

C 315 Mica schist — 0.25 km E of Obervellach railway station; SE bank of Kaponigbach.

Muscovite and quartz-rich schistose rock close to the margin of a gneiss lamella; it is uncertain whether this fine grained rock ($<$ 0.1 mm) is a sheared derivative of Schieferhülle or of gneiss lamella.

OV 1 Dolomite quartzite breccia — Kaponig.

Typical dolomite quartzite breccia of the Schieferhülle. Elongate rolled spindles of pale grey dolomite (1—40 cm long) in a granular matrix of muscovite and quartz. Quartz shows undulose extinction and muscovite laths have deformed cleavage. Dolomite aggregates composed of 2 mm crystals. Dolomite 15%, muscovite 5%, quartz 80%.

C 495 Tourmaline quartz muscovite schist — 0.5 km E of top of Sicker Kopf.

Light coloured, schistose rock extremely rich in coarse muscovite. Conspicuous tourmaline needles ($\sim$ 1 cm long) randomly oriented in the foliation plane. About equal proportions of quartz and muscovite, both strongly deformed.

C 552 Muscovite schist — 0.5 km ENE of Feistritzer Alm, in the bed of Zwenbergerbach.

Extremely coarse muscovite schist. The rock is predominantly muscovite, with discrete and irregularly dispersed albite porphyroblasts and lenticular patches which are rich in quartz.

C 422 Muscovite schist — 0.17 km of Striednig Alm.

Extremely coarse ($>$ 1 cm) muscovite-rich schist which locally becomes almost a monomineralic rock. Elsewhere albite porphyroblasts ($\sim$ 1 cm) and quartz make up 40% of the rock.

C 523 Kyanite biotite schist — 0.15 km WNW of the Kaponigtörl.

A coarse-grained rock with biotite (0.25—0.75 cm flakes) as the dominant mineral ($>$ 50%). Large, deformed and partially resorbed crystals of kyanite (0.25—1.25 cm long) prominent but $\ngtr$ 5% and enclosed by large albite crystals. Muscovite and chlorite present. Both muscovite and biotite crystals are strongly deformed.

PA 2 Coarse muscovite pegmatite — 0.4 km NNW of Jägerhütte (1346 m); a few metres from the track to the Polinikhaus.

Discordant pegmatitic vein ($\sim$ 25 cm wide) comprising predominantly quartz, K-feldspar and books of muscovite.

C 551 Biotite schist — 0.25 km NNW of triangulation point (1665 m); at side of new logging road.

A melanocratic granular and schistose rock in which there is incipient separation of the components into discrete dark and light layers. Main constituents are quartz, albite and untwinned K-feldspar with mica (biotite $\gg$ muscovite) comprising about 15%. Large, deformed biotite laths are enclosed in unstrained albite. Average grain size 1 mm.

PG 1, PG 2 Garnet mica schist — the top of Polinik.

A fine grained schist (grain size 0.25 mm); a granular groundmass of quartz and albite within lie deformed laths of muscovite and biotite with strong preferred orientation. Accessory garnet, calcite, epidote and sphene; groundmass grain boundaries are extemely sutured and irregular. The muscovite and biotite were analysed from the same rock.

C 589 Biotite amphibolite — 0.4 km due N of the Ochsenhütte, on the path to the Ochsenhütte.

Principal constituent ($\sim$ 80%) is an almost non-pleochroic amphibole ($\sim$ 1.0 mm grain size) which occurs with random orientation. Biotite laths (pleochroic — pale yellow to foxy brown) with preferred orientation cut across the amphibole groundmass ($\sim$ 15%, laths $\sim$ 3 mm long). Accessory quartz and garnet.

C 614 Sheared augen gneiss — 0.35 km NW of Rauchkopffall on NW side of track.

Sheared leucocratic gneiss with rare small K-feldspar augen ($\sim$ 0.5 cm). Main constituents quartz, microcline and albite, together $\sim$ 90% of rock. Muscovite in laths deformed round augen $\ngtr 10\%$. Accessory epidote and apatite. All groundmass grain boundaries extremely denticulate.

C 578 Mica schist — top of the Eberneck.

A medium grain size (0.5—1 mm) mesocratic schist with tight microfolds in the schistosity. Mica (predominantly muscovite, some biotite) about 20% of the rock. Quartz and plagioclase make up the rest of the rock, with accessory garnet. Quartz and plagioclase have strongly sutured boundaries. Micas, quartz and feldspar show straining effects.

C 552 Muscovite pegmatite — on new logging road at a point 0.35 km WSW of triangulation point 1302 m.

Sample from a discordant pegmatitic vein ($\sim$ 10 cm wide) consisting predominantly of quartz, K-feldspar and coarse „books“ of muscovite.

PA 1 Biotite schist — same as PA 2.

Mesocratic medium grained ($\sim$ 0.5—1.0 mm) schist with deformed biotite ($\gg$ muscovite) comprising 15% of the rock. Other constituents are quartz, albite and untwinned K-feldspar (quartz $>$ feldspar). Grain boundaries highly denticulate.

C 613 Muscovite pegmatite — 0.5 km SW of Rauchkopffall on the Wunzen Weg.

Coarse discordant pegmatite $\sim$ 20 cm wide. Principal constituents quartz, K-feldspar and coarse (4 cm) „books“ of muscovite.

C 570 Microcline augen gneiss — $\sim$ 0.6 km due W of Böse Nase in the cliffs at the head of the Wunzen Alm.

1 cm diameter augen of microcline are set in a fine-grained groundmass ($\sim$ 0.5 mm) of quartz, albite and K-feldspar. Subordinate amounts of mica ($\ngtr 5\%$, biotite $>$ muscovite). Micas are deformed round the augen and the groundmass shows highly sutured and denticulate grain boundaries. Accessory apatite.

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Superimposed Fold Systems in the Altkristallin Rocks on the Southeast Margin of the Tauernfenster

With 8 Figures

By E. R. OXBURGH *)

Faltungsphasen im Altkristallin am Südostrand des Tauernfensters

Mit 8 Abbildungen

Von E. R. OXBURGH *)

Abstract

Detailed studies of fold types and measurements of S planes and B directions have been made in an area of Altkristallin rocks immediately southwest of Obervellach, Mölltal. This area lies just outside the Tauern window. It is shown that there have been three main phases of folding in the area. An episode of early isoclinal folding was followed by a period of buckle folding. Finally the area underwent gentle flexure folding and at the same time there was incipient development of a new schistosity, parallel to the axial planes of microfolds associated with the flexures. The geometry of the three groups of folds is discussed. It is shown that deformation throughout the area has been homogeneous except for that part which is nearest the edge of the Tauernfenster. This result is disscussed.

Zusammenfassung

Im Bereich des Altkristallins unmittelbar südwestlich von Obervellach im Mölltal wurden Detailstudien an Faltentypen und Gefügemessungen von S-Flächen und B-Achsen ausgeführt. Das bearbeitete Gebiet liegt knapp außerhalb des Tauernfensters. Es wird gezeigt, daß sich hier drei Hauptfaltungsphasen

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*) Department of Geology and Mineralogy, University Museum, Oxford.