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Oxygen Isotope Studies on Metamorphic Rocks of the Western Hohe Tauern Area (Austria)

By *Stephan Hoernes* and *Hans Friedrichsen* (Marburg) *)

With 5 figures in the text

Abstract

Isotherms for the alpine metamorphism in the western part of the Tauern-window have been derived from oxygen isotope fractionations. During this metamorphism the oxygen isotopes reequilibrated and the equilibrium has been preserved after this event. The temperatures of formation are around 630° C in the area of the Schlegeis and Berliner Hütte. To the North and to the South of the Alpenhauptkamm lower temperatures (to 405° C) have been determined.

Only in some carbonate rich rocks the calcite and occasionally the silicate-phases do not represent the oxygen isotope equilibrium of the metamorphic event. The temperatures of some of the observed mineral reactions are known from bombexperiments. Both temperatures agree within a certain limit of error (± 10–25° C).

During a prealpine event the rocks of the Inner Schieferhülle interacted with an isotopically lighter material (magmatic liquids or meteoric water), while the rocks of the Peripheral Schieferhülle preserved their original $^{18}O/^{16}O$-whole rock coposition.

Zusammenfassung

Im West-Teil des Tauernfensters wurden Isothermen für die alpidische Metamorphose aus Sauerstoffisotopen Fraktionierungen bestimmt. Während dieses Ereignisses erfolgte eine Gleichgewichtseinstellung der Sauerstoffisotope, die in den meisten Mineralen erhalten blieb. Nur in einigen karbonatreichen Proben konnten zwischen Calcit und beteiligten Silikatphasen und auch gelegentlich zwischen den Silikatphasen, Ungleichgewichte festgestellt werden.

Das Temperaturmaximum mit Temperaturen um 630°C ± 20°C liegt im Bereich Schlegeisgrund-Berliner Hütte. Zum Rand des Tauernfensters hin wurden niedrigere Metamorphosetemperaturen bestimmt (um 400°C im Bereich Gerlos–Salzachtal–Dorfertal–Sterzing).

Von einigen beobachteten Mineralreaktionen sind die Gleichgewichtstemperaturen aus Hydrothermalexperimenten bekannt. Es zeigte sich, dass diese mit den aus der

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Sauerstoffisotopen-Methode bestimmten Temperaturen innerhalb einer Genauigkeit von 10–25° C übereinstimmen.

Aus den $^{18}O/^{16}O$-Verhältnissen der Gesamtgesteine der Inneren Schieferhülle muss man schliessen, dass diese während eines präalpinen Ereignisses mit einem Reservoir eines niedrigen $^{18}O/^{16}O$-Verhältnisses, die Sauerstoffisotope ausgetauscht haben, während in den Gesteinen der Äusseren Schieferhülle kein grossräumiger Austausch der O-Isotope stattgefunden hat.

INTRODUCTION

This paper is part of a detailed study in the Geotraverse Ia, Geodynamics of the Mediterranian area, a project initiated by the Deutsche Forschungsgemeinschaft. During the last years, many geologic, geophysical, geochemical and petrologic data have been made available of this area. One of the most interesting parts of the Geotraverse Ia is the so called "Tauern window", where rocks of the tectonic lower Penninikum are exposed. They are surrounded by the Ostalpin.

The effect of the alpine metamorphism on these rocks, the "Tauernkristallisation" (Sander, 1911) has been uncertain for a long time. Recently, whole rock and mineral ages have been published (Besang et al., 1968, Cliff et al., 1971, Jäger et al., 1969), which gave us a better knowledge on the thermal history of this area. Whole rock Rb/Sr ages indicate, that during the Permian huge granitic to tonalitic magma-bodies were intruded.

These "Zentralgneise" are enveloped by rocks of sedimentary origin, the so-called 'Schieferhüllen". The "Schieferhüllen" are partly paleozoic (Innere Schieferhülle, Habach- and Greiner-series and the Altkristallin) and partly mesozoic (Peripheral Schieferhülle, Bündner Schiefer) (fig. 1). The geologic mapping in fig. 1 is based on Frasl and Frank (1966) with some supplements from recent papers.

Parts of the Inner Schieferhülle show traces of an intense metamorphism with migmatisation (i.e. migmatic structures in the Altkristallin). From radiometric work there is no evidence for alpine magmatism in the Tauern window, but all mineral Rb/Sr and K/Ar analyses on micas yield ages around 20 m.y. We conclude, that the migmatisation must be related to a pre-alpine metamorphic event.

Typical mineral parageneses and mineral reactions during the last (alpine) metamorphic event indicate a progressive metamorphism from the lower Greenschist facies in the North and the South to the amphibolite facies in the central part.

These field observations are supported by the oxygen isotope measurements of Friedrichsen et al. (1973) on two metamorphic profiles in the eastern part of the area investigated in this paper. $^{18}O/^{16}O$-fractionations between quartz

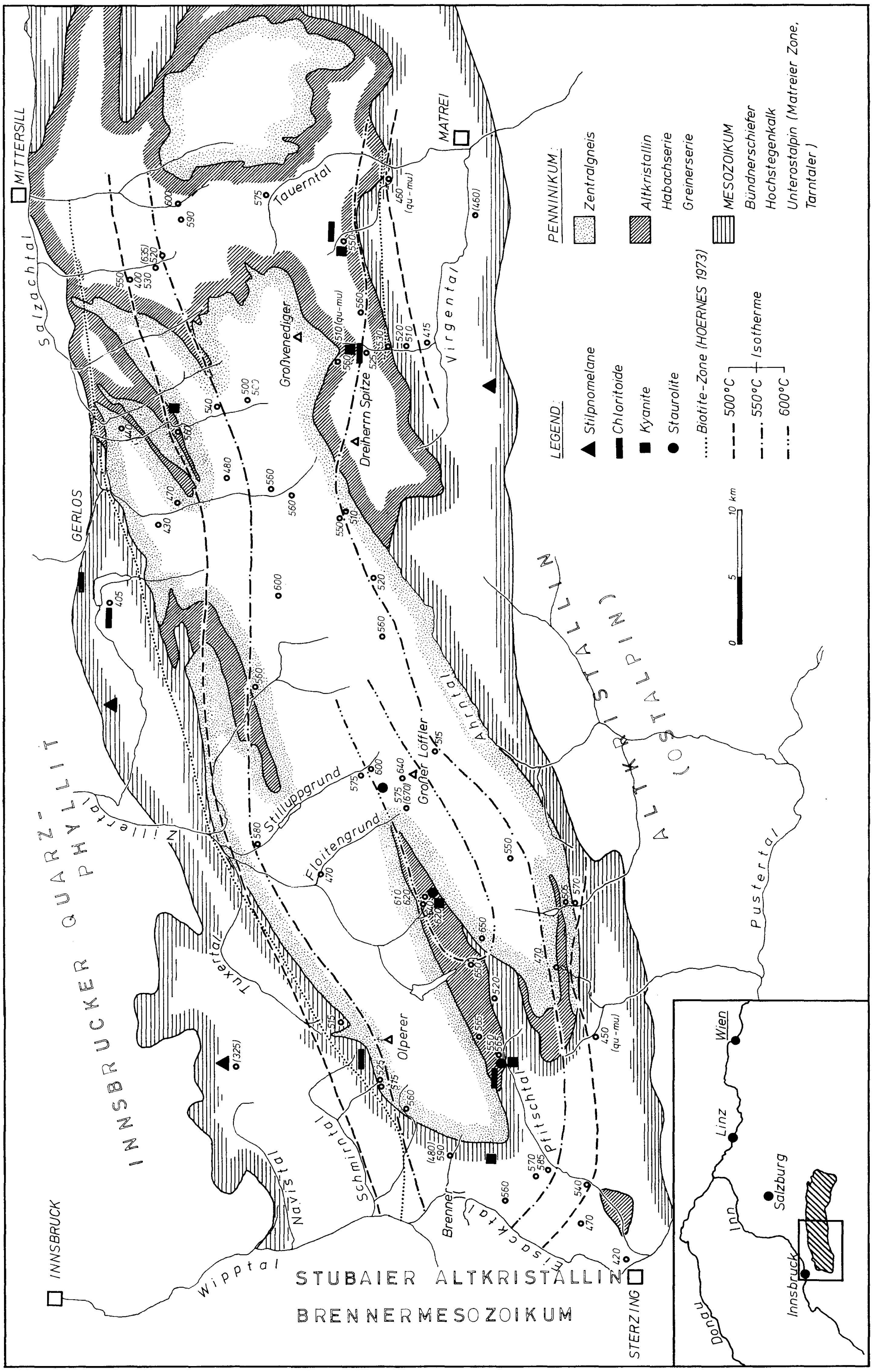

Fig. 1. Geological map of the area investigated, with the isotherms and the occurrence of some index-minerals.

and biotite as well as quartz and garnet yielded temperatures from 430 to 600° C for the alpine metamorphic event.

It is the purpose of this study to check, whether in all rock types of the Western Tauern area oxygen isotope-equilibrium has been attained. If this were so, it should be possible to derive the temperatures of the last metamorphic event from oxygen isotope fractionations between cogenetic minerals.

EXPERIMENTAL PROCEDURE

The minerals analysed were separated by standard techniques (heavy liquids, magnetic separation and hand picking etc.). The mineral fractions were checked for impurities microscopically and by X-ray diffraction analyses. 5–30 mg of the dried sample were decomposed by BrF_5. The reaction temperature was 550° C for the quartzes and feldspars, 570° C for the muscovites and biotites, 640° C for magnetites and ilmenites and 680° C for the garnets. The deliberated oxygen was converted into CO_2 (Clayton and Meyeda, 1963, slightly modified).

Calcite was decomposed by phosphoric acid. (McCrea, 1950.) For the $^{18}O/^{16}O$-correction the values of Sharma and Clayton (1965) were applied.

The mass-spectrometric analyses were carried out with a 60°, 15 cm single focussing mass-spectrometer (McKinney et al., 1950). The analytical reproducibility was better than $\pm 0.05^0/_{00}$ (2 δ) for the mass-spectrometric measurements and in general better than $\pm 0.15^0/_{00}$ for the analytical treatment. The reaction yields were 97% to 101%.

The temperatures of formation for the rocks were derived from

a) quartz magnetite fractionations, using the magnetite-water curve of Bertenrath et al. (1973),

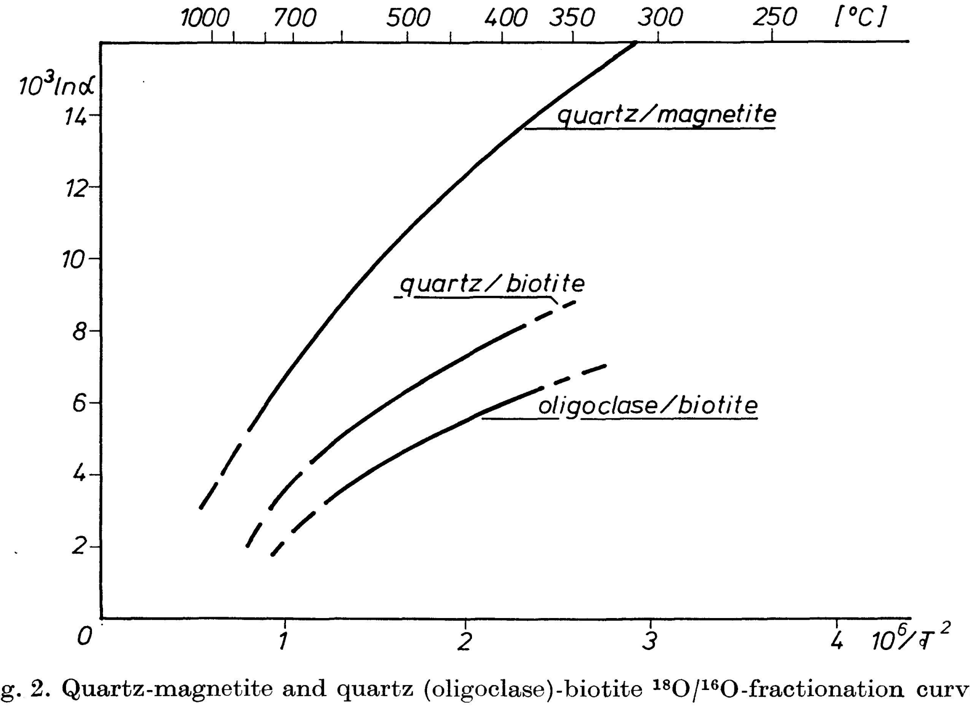

Fig. 2. Quartz-magnetite and quartz (oligoclase)-biotite $^{18}O/^{16}O$-fractionation curves.

b) quartz-biotite fractionations,
c) quartz-garnet fractionations (Taylor and Coleman, 1968),
d) feldspar-magnetite-fractionations (O'Neil and Taylor, 1967, and Bertenrath et al., (1973), and
e) feldspar-biotite fractionations.

The quartz-biotite and the feldspar-biotite curve were derived from published quartz-feldspar-biotite-magnetite fractionations, using the quartz-magnetite-curve. This curve showed very reasonable temperatures compared with typical mineral reactions (usually within ± 10 to ± 20°C) (fig. 2).

A quartz-muscovite curve derived from the quartz-water curve of Clayton et al. (1972) and the muscovite-water curve of O'Neil and Taylor (1969) yielded too low temperatures, but if we apply the estimated curve of Taylor (1967), reasonable temperatures can be derived for quartz-muscovite fractionations.

DISCUSSION

A. Whole rock data

The whole rock isotopic compositions were derived from mineral-isotope data and the modal analyses. The precision is about ± 0.5 to 1‰. These data

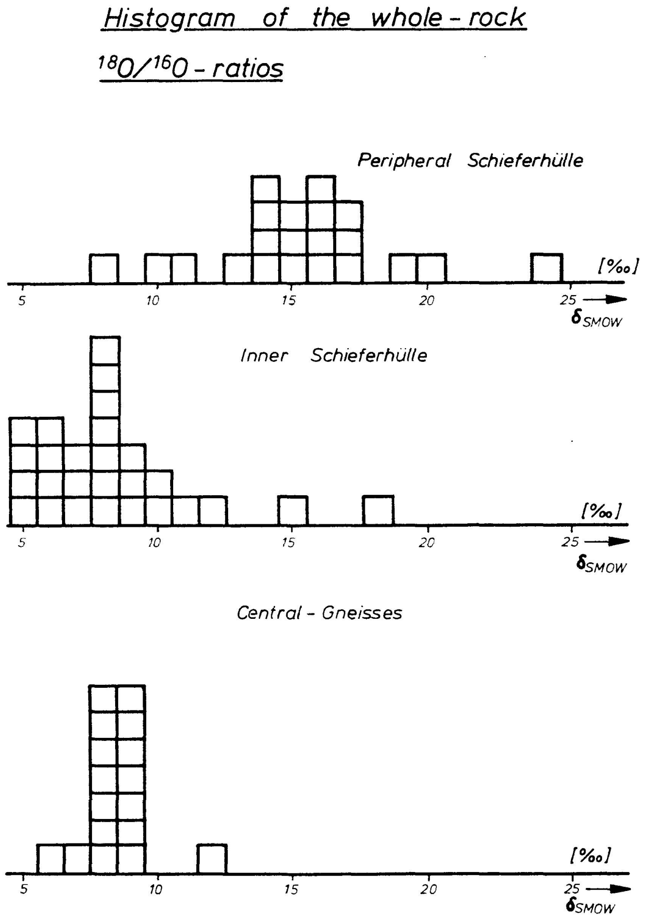

Fig. 3. Whole rock $^{18}O/^{16}O$ data, calculated from mineral data and modal analysis.

are presented in a histogram (fig. 3). The mean $^{18}O/^{16}O$-value of the Zentralgneis is about $+8$ to $+9^0/_{00}$ relative to SMOW, with very few exceptions. This $^{18}O/^{16}O$-ratio is very close to the value TAYLOR (1968) estimated for a granite of magmatic origin. During the metamorphic event (or events?) after the intrusion no large scale interactions with either isotopic heavier material (sediment etc.) or isotopic lighter material (meteoric water) occured.

If we assume, that most rocks of the Inner Schieferhülle are of sedimentary origin (paleozoic sediments), they should have δ-values between $+15$ and $+20^0/_{00}$ relative to SMOW. Since their whole rock δ-values are lower, we conclude that they have exchanged oxygen isotopes during the different metamorphic cycles after the sedimentation with material of a lower δ-value, for instance magmatic fluids (or meteoric water?). This is obviously not valid for the metamorphosed basic effusiva within the Inner Schieferhülle, which have primary low $^{18}O/^{16}O$-ratios ($+5$–$+7^0/_{00}$).

The rocks of the Peripheral Schieferhülle show the original δ-values of the sediments, between 15 and $20^0/_{00}$ for the rocks of pelitic composition and about 20–$25^0/_{00}$ for the carbonate rich types (see also SCHWARTZ et al., 1970). The rocks with the low δ-values of 8–$10^0/_{00}$ are basic effusiva. This indicates, that during the metamorphic episodes they did not exchange oxygen isotopes on a larger scale. Exchange of oxygen isotopes to equilibrium was observed only in the cm to (maximal) dm-region. This at least gives us some information on the migration of pore-fluids during the alpine metamorphism in the rocks of the Peripheral Schieferhülle.

The large scale oxygen exchange, which is observed in the rocks of the Inner Schieferhülle therefore can not be related to the alpine metamorphic cycle. This probably happened during the same event, which caused the migmatisation in this rock type (Variscan?).

B. Oxygen isotope fractionations between minerals, geologic thermometry

The temperatures for the "formation" of rocks can be derived from oxygen isotope fractionations between minerals, if certain conditions are fulfilled:

1. During the event of the formation of the rocks (in this case the alpine metamorphism), the isotopes have to equilibrate between the cogenetic minerals.
2. After this event, this equilibrium has to be frozen in.

We think, that for most of the rocks we analysed, both assumptions can be made:

Before the alpine metamorphism at least parts of the Zentralgneis were unmetamorphosed magmatic rocks, the bulk of the mesozoic series (Peripheral Schieferhülle) as were unmetamorphosed sediments (or basic intrusives or extrusives) and the rocks of the Inner Schieferhülle were metamorphic rocks of different grade of metamorphism. (Probably low grade metamorphism in the Habach-series and high grade metamorphism and migmatitic stage in the Greiner-series and the Altkristallin).

If all these rock types were to give the same oxygen isotope fractionation for a given mineral pair at the same place – i.e. metamorphosed under the same conditions – it would imply that complete reequilibration had occurred and that no relict minerals were present. This in general is valid for the quartz, magnetite, biotite, hematite, muscovite, garnet and some calcite. Some of the calcite is not in equilibrium and we are uncertain whether it has only partially reequilibrated, or whether it has undergone isotopic exchange after the metamorphic event (fig. 4). We discuss below some interesting exceptions, where oxygen isotope equilibrium has not been attained in the silicate phases.

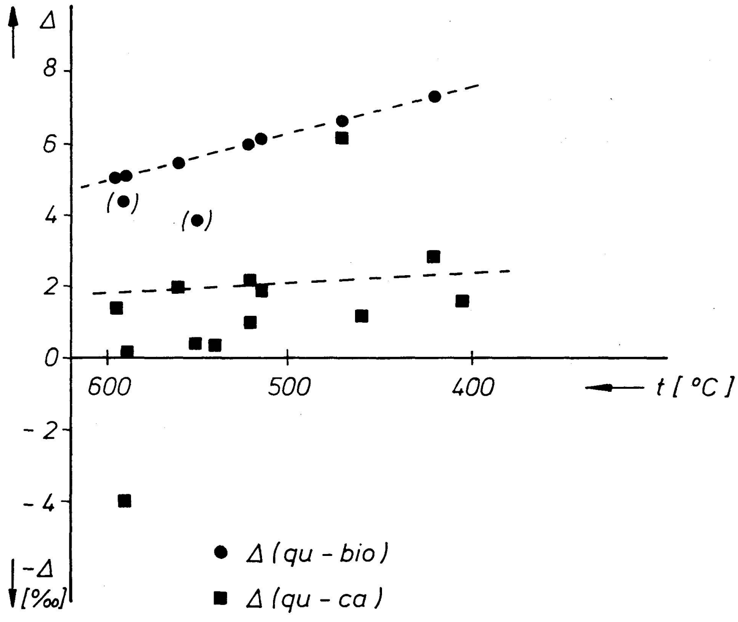

Fig. 4. $^{18}O/^{16}O$ fractionation of coexisting carbonate - silicate phases.

Non equilibrium was mainly observed in calcite-rich rocks between calcite and silicate, and sometimes between those silicate phases, which were not in contact with each other. Another rock type which showed oxygen isotope disequilibrium between quartz and garnet were the eclogites from the Frosnitztal. This might be due to the low water pressure during metamorphism. This may be the reason for further disequilibria (see FRIEDRICHSEN et al., 1973).

Quartz-magnetite, quartz-ilmenite, quartz-biotite, quartz-garnet and feldspar-biotite fractionations within a certain limit of error (± 10 to 25° C, depending on the mineral pairs used) yield the same equilibrium temperatures which must be interpreted as the temperature of formation of these minerals, as is shown below (see mineral reactions).

The temperatures derived are independent on the chemical composition of the rock. Albite/biotite and albite/magnetite fractionations showed the same temperatures in greenstones, meta-pelitic rocks and metagranites as would be predicted from theory.

C. Comparison of the temperatures derived from oxygen-isotope fractionations with those from typical mineral parageneses and mineral reactions

The zone of the lowest metamorphic grade in the Tauern window is characterized by the sporadic occurrence of the parageneses: stilpnomelane + muscovite ± chlorite + quartz. The upper limit for the stability of the paragenesis stilpnomelane + muscovite is 440° C to 460° C at 4 to 7 kb and at the oxygen fugacity of the magnetite/hematite buffer (Nitsch, 1970). From this area only one oxygen-isotope-temperature has been determined (325° C) derived from the calcite-magnetite ^{18}O-fractionation of an ophicalcite of the Tarntaler Berge. Since the temperatures derived from calcite-silicate and calcite-oxide parageneses can be very misleading, this value must be interpreted with care.

The first appearance of biotite has been described by Hoernes (1973) (see fig. 1). The lowest ^{18}O-temperatures for these parageneses are 420–440° C in the metagranites (Friedrichsen et al., 1973) and in the mesozoic series from the Pfitschtal near Sterzing. In one prasinite from Gerlos 405° C has been determined from albite-magnetite ^{18}O-fractionations. The granitic rocks in this area carry chlorite + potassiumfeldspar as a stable paragenesis, which (after Hoschek, 1973) reacts to biotite + muscovite + quartz at 425° C if the chlorite is the Fe end-member, and at 475° C in the case of Mg-chlorite (at 4 kb water pressure). In the rocks of the Schieferhülle, where Hoernes (1973) observed the reaction dolomite + (phengitic) muscovite → biotite + calcite + quartz + CO_2 (I) and the reaction hornblende + muscovite → biotite + plagioclase ± epidote + quartz (II), quartz-biotite isotope fractionations yield temperatures of 550° C. With bomb experiments at 4 kb Hoschek (first unpublished data, personal communication) determined the temperatures for these reactions. For the reaction I he determined temperatures between 500 and 550° C, for the reaction II temperatures near 570° C. For these bomb experiments he used separated minerals of rocks from the Tauernfenster.

Very good internal consistency has been obtained in the metapelites from the Pfitschtal (Steinbruch Grünig). Some of these rocks carry chloritoide + kyanite + staurolite (+ quartz, and magnetite). The quartz-magnetite ^{18}O-

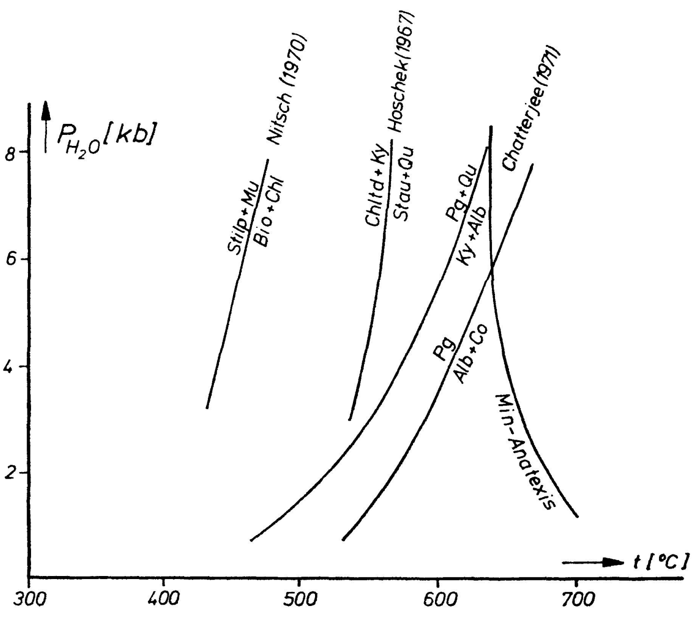

Fig. 5. Stability fields of some mineral parageneses.

fractionations yield temperatures of 565° C, 545° C and 540° C; and the quartz-biotite-fractionations of rocks from the same quarry a temperature of 550° C. Hoschek (1967) investigated the reaction kyanite + chloritoid $\rightleftarrows$ staurolite + quartz. He determined a temperature of 545° C ± 20° C for this reaction, which is more or less independent on the pressure (see fig. 5, reaction curves). In rocks, where higher temperatures were determined for the alpine metamorphism ($\geqq$ 570° C, derived from quartz-biotite ^{18}O-fractionations), the breakdown of paragonite and margarite was observed (Ackermand and Morteani, 1973). In rocks from the high-grade metamorphic zone at the Berliner Hütte (temperatures of metamorphism of ~630° C) no (or only sporadic) paragonite relics could be traced.

The stability fields of these micas have been determined by Chatterjee (1972, 1973), Nitsch and Storre (1972), Storre (1973).

Serpentine (antigorite) seems to be stable at temperatures of 550° C to nearly 600° C. There seems to be an uncertainty on the breakdown temperatures of serpentines. (For literature on this topic see Evans and Ttommsdorff, 1970; Johannes, 1968). The temperatures derived from our data are the highest reported for the stability field of serpentines. Our data are concordant with those of Keusen (1972), who could trace serpentine in the staurolite-zone ($\geqq$ 550° C) in the Penninikum of the Swiss Alps.

The highest temperatures of metamorphism derived from quartz-biotite fractionations are about 650° C, which is the minimum melting temperature for a granite with excess water. So far no granitisation of alpine age has been observed. The migmatisation of the so-called Altkristallin must be related to earlier events.

D. Estimates on pressure

The only aluminum-silicate observed in this region is kyanite. The first occurrence of kyanite was observed near the 500° C isotherm, and it seems to be stable even in the high-temperature region (~630° C). This observation puts some limits on the pressure during the alpine metamorphism in the Tauernfenster. The pressure must have been higher than 4 kb in the temperature region of 500° C and higher than 6 kb in the temperature region of 630° C if we accept the experimental results of RICHARDSON (1969) and HOLDAWAY (1971) and the pressure must have been higher than 5,5 kb and 9 kb, if we accept the results of ALTHAUS (1967). On the other hand the reaction zoisite + muscovite + quartz → plagioclase (An 20) + K-feldspar (+ water) and possibly the reaction muscovite + calcite + quartz → plagioclase (An 20) + K-feldspar + volatiles) have been observed in the so-called "gefüllte" plagioclase (filled plagioclase) of the metagranites and metatonalites (ACKERMAND and KARL (1972).

HEWITT (1973) investigated the reaction muscovite + calcite + quartz ⇄ k-feldspar + anorthite + $CO_2 + H_2O$. The temperature of this reaction depends on: total pressure, X_{CO_2}, X_{H_2O} and the An-content of the plagioclases. ACKERMAND and KARL (1972) (fig. 6) (see also JOHANNES and ORVILLE (1972) investigated the reaction zoisite + muscovite + quartz ⇄ anorthite + k-feldspar + H_2O. The isograde of the plagioclase-forming reaction (see ANGENHEISTER, BÖGEL and MORTEANI, 1973; HÖRMANN and RAITH, 1973) agrees with our 550° C (± 25° C) isotherm. If we apply the experimental results to an estimate of the pressure, we must assume, that the pressure in this temperature region was less than 5.5 kb.

CONCLUSION

The gradients of the metamorphic temperature are relatively high in the marginal zones from 400 to 550° C and flatter in the central part to 600° C with a small region higher than 600° C.

In the Swiss Central Alps (Tessin) two models for the alpine metamorphism are discussed:

1. Increased heat supply during the metamorphic event by a (not exposed) magma body (WENK, 1970, 1962).
2. Deep burial of the region by the tectonic overriding of alpine nappes (JÄGER et al., 1967; NIGGLI, 1970).

These models have been discussed by CLIFF et al. (1971) for the eastern part of the Hohe Tauern. They favoured the model of Wenk and accepted that there must have been an additional source of heat responsible for the heat supply.

The estimates of the pressures were derived by Cliff et al. (1971) from the thickness of the overlying sediments. Their estimates agree with our estimates of the temperatures of metamorphism in conjunction with typical mineral occurrences and mineral parageneses.

They determined a pressure of 6 kb for the deepest part of the Zentralgneis which is exposed today, 5 kb for the bottom of the peripheral Schieferhülle and 3 kb for the top of the peripheral Schieferhülle.

From these data, in combination with the temperatures of metamorphism, we can derive a temperature/pressure curve (fig. 6).

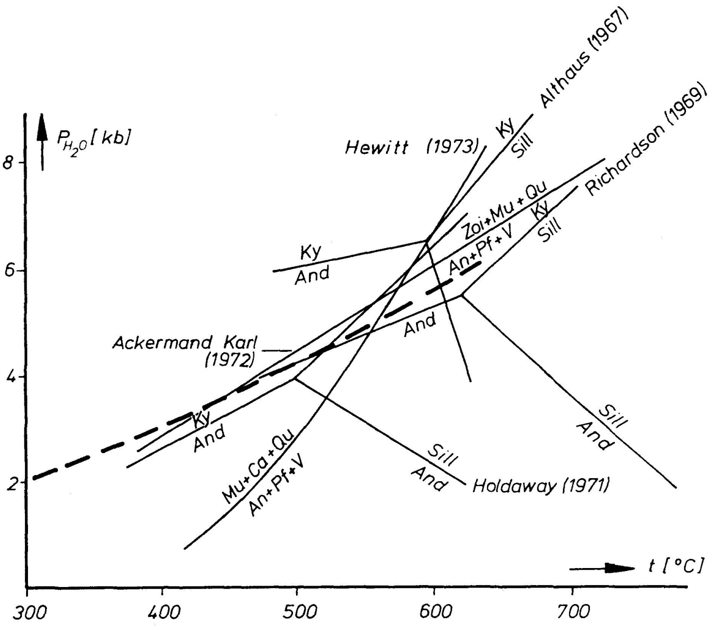

Fig. 6. Estimate on pressure with the stability fields of the aluminium silikates and some other pressure-dependent reactions. Dashed line represents the gradient of metamorphism.

The termal gradient is higher in the peripheral Schieferhülle at shallower depths and lower in the Inner Schieferhülle and metagranites. The estimated gradient would match with a heat flow of 2 HFU (2 μcal sec^{-1} cm^{-2}) on the surface region. (Richardson, 1970). Clark (1961) and Jäger (1969) have determined 2 HFU for the heat flow in the railway Tauern-Tunnel, which indicates that we have even now a higher heat flow than normal in this area.

Acknowledgments

We acknowledge the generous supply of rock-samples and mineral-fractions from Prof. G. Morteani and Dr. M. Raith. We thank Dr. G. Hoschek and Dr. E. R. Oxburgh for reading this manuscript.

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APPENDIX

Oxygen isotope analyses of rocks of the Zentralgneis (for modal analyses see Karl (1959), Friedrichsen et al. (1973), Cliff et al. (1971))

Legend:

qu: quartz, plag: plagioclase, hbl: hornblende, bio: biotite, mu: muscovite, chl: chlorite, cld: chloritoide, gar: garnet, stau: staurolite, ky: kyanite, epi: epidote, klzoi: klinozoisite, klpx: klinopyroxene, sph: sphene, opq: opaques, mag: magnetite, ilm: ilmenite, cc: calcite, dol: dolomite, alb: albite, alkfsp: alkali feldspar, serp: serpentine.
* possibly not in equilibrium.

	Description and location of samples			δ 18_0 [$^0/_{00}$]	
71.94	Metagranite from upper Schlegeistal			whole rock	8,5
				quartz	9,4
				biotite	4,9
		Δ (qu-bio)	4,5	T 650°C	
72.115	Augengneiss from the Pfundererertal near Eisbruggsee			whole rock	12
				quartz	13,5
				biotite	6,9
		Δ (qu-bio)	6,6	T 470°C	
71.138	Metagranite from Weissenbachtal, Ahrntal			whole rock	8,5
				quartz	10,1
				biotite	4,4
		Δ (qu-bio)	5,7	T 550°C	
71.152	Metagranite from the Frankbachtal, Ahrntal			whole rock	8
				quartz	10,1
				biotite	4,1
		Δ (qu-bio)	6,0	T 515°C	
T 23	Metagranite from the Krimmler Tauernhütte, Ahrntal			whole rock	8,5
				quartz	10,1
				biotite	4,0
		Δ (qu-bio)	6,1	T 510°C	
T 24	Metagranite from the Krimmler Tauernhütte, Ahrntal			whole rock	9
				quartz	10,5
				biotite	4,8
		Δ (qu-bio)	5,7	T 550°C	
T 132	Augengneiss from the Neves-Stausee, Lappachtal, Ahrntal			whole rock	8,5
				quartz	10,3
				biotite	4,1
		Δ (qu-bio)	6,2	T 505°C	
R 22	Metagranite north of St. Peter, Ahrntal			whole rock	8
				quartz	10,1
				biotite	4,6
		Δ (qu-bio)	5,5	T 560°C	
S 17	Metagranite northwest of Kasern, Ahrntal			whole rock	9
				quartz	10,6
				biotite	4,6
		Δ (qu-bio)	6,0	T 520°C	
360	Metagranite from Kleiner Löffler, Floitengrund, Zillertal			whole rock	7
				quartz	7,9
				biotite	3,3
		Δ (qu-bio)	4,6	T 640°C	

	Description and location of samples			δ 18$_0$ [$^0/_{00}$]	
396	Metagranite from the Grünewand, Stilluppgrund, Zillertal			whole rock	8,5
				quartz	9,8
				biotite	4,5
		$\varDelta$ (qu-bio)	5,3	T 575°C	
A 20	Metagranite from the Grünewand, Stilluppgrund, Zillertal			whole rock	8,5
				quartz	9,4
				biotite	4,4
		$\varDelta$ (qu-bio)	5,0	T 600°C	
A 07	Metagranite from Ginzling, Zillertal			whole rock	8,5
				quartz	10,3
				biotite	3,7
		$\varDelta$ (qu-bio)	6,6	T 470°C	
A 11	Metagranite near Plauener Hütte, Zillergrund			whole rock	8
				quartz	9,5
				biotite	4,5
		$\varDelta$ (qu-bio)	5,0	T 600°C	
A 17	Metagranite from the Zillergrund near Häusling, Zillertal			whole rock	8,5
				quartz	10,2
				biotite	4,7
		$\varDelta$ (qu-bio)	5,5	T 560°C	
A 26	Augengneiss from the Stilluppgrund, Zillertal			whole rock	9
				plagioklase	9,4
				biotite	5,8
		$\varDelta$ (plag-bio)	3,6	T 580°C	

Oxygen isotope analyses of rocks of the Inner Schieferhülle

G 8	Amphibolite near Berliner Hütte, plag an 28, qu, hbl, bio, chl, ap, opq			whole rock	7
				plagioclase	9,5
				biotite	6,0
		$\varDelta$ (plag-bio)	3,5	T 610°C	
G 11	Metapelite near Berliner Hütte, qu, plag an 20, bio, mu, gar, chl, klzoi			quartz	9,8
				biotite	5,0
				garnet	5,1
		$\varDelta$ (qu-bio)	4,8	T 620°C	
G 10	Metapelite near Berliner Hütte qu, plag, bio, mu, gar, ky, chl, cc, pyrr			whole rock	9
				quartz	10,6
				biotite	6,0
		$\varDelta$ (qu-bio)	4,6	T 640°C	
T 295	Metapelite from Schlegeistal qu, plag, bio, gar, hbl, chl, cc, opq			whole rock	9
				quartz	10,9
				biotite	6,5
		$\varDelta$ (qu-bio)	4,4	T 650°C	
T 446	Dolomite-mica schist from Pfitscherjoch, Pfitschtal dol, cc, bio, mu, plag, epi, chl			whole rock	15
				quartz	18,7
				biotite	13,3
		$\varDelta$ (qu-bio)	5,4	T 565°C	
T 302 *	Calcite-dolomite marble from the Schlegeistal dol, cc, qu, bio, mu, plag, opq			whole rock	18
				biotite	16,1
				calcite	18,8
		$\varDelta$ (cc-bio)	2,7		

	Description and location of samples			δ 18$_0$ [$^0/_{00}$]	
T 375	Migmatitic gneiss from the Floitengrund, Zillertal			whole rock	6
	qu, plag, bio, gar, klzoi, hbl, sph			quartz	8,8
				biotite	3,5
		Δ (qu-bio)	5,3	T 575°C	
T 404	Amphibolite from the Obersulzbachtal, near Berndl Alm			whole rock	6
	plag, qu, hbl, bio, chl, gar, opq			quartz	10,4
				biotite	4,9
		Δ (qu-bio)	5,5	T 560°C	
T 283	Augengneiss from the Wildlahner, Schmirntal			whole rock	8
	qu, alb, alkfsp, mu, bio, chl, cc, opq			quartz	9,6
				biotite	3,7
		Δ (qu-bio)	5,9	T 525°C	
T 286	Biotite-schist from the Wildlahner, Schmirntal			whole rock	9
	qu, alb, bio, mu, cc			quartz	10,2
				biotite	4,1
				calcite	8,3
		Δ (qu-bio)	6,1	T 515°C	
T 365	Amphibolite from the Floitengrund, Zillertal			whole rock	5
*	plag, qu, hbl, bio, mu, chl, gar, klzoi			plagioclase	6,3
				biotite	3,4
				muscovite	5,8
		Δ (plag-bio)	2,9	T 670°C	
		Δ (plag-mu)	0,5		
T 371	Migmatitic gneiss from the Floitengrund, Zillertal			whole rock	6
*	qu, plag, bio, mu, gar, epi, cc, sph			plagioclase	6,4
		Δ (plag-mu)	1,0	muscovite	5,4
		Δ (plag-gar)	2,2	calcite	9,5
				garnet	4,2
T 215	Biotite-schist, Venntal near Brenner			whole rock	12
*	qu, plag an 20, bio, dol, cc, epi, opq			quartz	11,2
				biotite	6,8
				calcite	15,2
		Δ (qu-bio)	4,4		
G 7	Metapelite near Berliner Hütte			whole rock	8
	alb, qu, bio, mu, chl, gar, ilm			quartz	9,4
				ilmenite	1,8
		Δ (qu-ilm)	7,6	T 620°C	
H 4	Biotite-plagioclase gneiss from the Hollersbachtal,			whole rock	6
	near Rossgrubalm, qu, plag, bio, hbl, cc			quartz	7,3
				biotite	1,3
				calcite	5,1
		Δ (qu-bio)	6,0	T 520°C	
H 5	Amphibolite from the Hollersbachtal, near Scharreralm			whole rock	5
*	qu, plag, bio, hbl, chl, cc			quartz	7,1
				biotite	2,4
		Δ (qu-bio)	4,7	T 635°C	
H 7	Prasinite from the Hollersbachtal (Habachserie)			whole rock	7
	qu, plag, bio, hbl, epi			quartz	8,5
				biotite	2,7
		Δ (qu-bio)	5,8	T 530°C	
H 9	Prasinite from the Hollersbachtal (Habachserie)			whole rock	5
	qu, plag, bio, hbl, epi			quartz	10,4
				biotite	2,8
		Δ (qu-bio)	7,6	T 400°C	

	Description and location of samples			δ 18$_0$ [$^0/_{00}$]	
H 15	Micaschist from the Hollersbachtal			whole rock	8
	qu, mu, bio, epi			quartz	9,7
				biotite	4,0
		Δ (qu-bio)	5,7	T 550° C	
Fe 5	Micaschist from the Felbertal, near Hintersee			whole rock	7
	qu, plag, mu, bio, chl, opq			quartz	11,4
				biotite	6,4
		Δ (qu-bio)	5,0	T 600° C	
Fe 9	Prasinite from the Felbertal, near Hintersee			whole rock	5
	plag, qu, bio, hbl, epi, cc			quartz	7,3
				biotite	2,2
				calcite	7,2
		Δ (qu-bio)	5,1	T 590° C	
V 22 B	Hornblendegneiss from the Tauerntal, near Matreier Tauernhaus			whole rock	8
	qu, plag, bio, hbl, epi, sph, opq			quartz	10,6
				biotite	5,3
		Δ (qu-bio)	5,3	T 575° C	
F 4	Micaschist from the Frosnitztal, near Badener Hütte			whole rock	10
	qu, alb, bio, mu, chl, cc, gar			quartz	11,1
		Δ (qu-chl)	6,7	biotite	5,4
				chlorite	4,4
		Δ (qu-bio)	5,7	T 550° C	
F 10	Metapelite from the Frosnitztal, near Badener Hütte			whole rock	10
	qu, mu, cld, ky, gar			quartz	11,8
		Δ (qu-mu)	2,6	muscovite	9,2
D 3	Metapelite from the Dorfertal, near glacier			whole rock	8
	qu, alb, mu, bio, chl, gar, cc, ilm			quartz	10,3
				biotite	4,9
		Δ (qu-chl)	6,3	chlorite	4,3
		Δ (qu-bio)	5,7	T 550° C	
D 13	Metapelite from the Dorfertal, near glacier			whole rock	11
	qu, alb, mu, gar, chl, cc, opq			quartz	11,2
		Δ (qu-mu)	3,1	muscovite	8,1
D 16	Migmatitic gneiss from the Dorfertal, near Johannishütte			whole rock	8
	qu, plag, bio, hbl, chl, gar, epi			quartz	9,8
				biotite	3,9
		Δ (qu-chl)	6,0	chlorite	3,8
		Δ (qu-bio)	5,9	T 525° C	

Mesozoic rocks from the Inner- and Periferal Schieferhülle

T 166	Metapelite from the Pfitschtal, quarry east of Stein			whole rock	14
	qu, mu, chl, cld, stau, mag			quartz	17,6
				magnetite	7,6
		Δ (qu-mag)	10,0	T 540° C	
T 165	Metapelite from the Pfitschtal, quarry east of Stein			whole rock	14
	qu, mu, chl, cld, stau, ky, mag			quartz	16,4
				magnetite	7,6
		Δ (qu-mag)	9,2	T 565° C	
T 73	Metapelite from the Pfitschtal, quarry east of Stein			whole rock	14
	qu, bio, mu, chl, epi, turm, opq			quartz	16,7
				biotite	11,0
		Δ (qu-bio)	5,7	T 550° C	

	Description and location of samples			$\delta\ 18_0$ [$^0/_{00}$]	
T 72	Metapelite from the Pfitschtal, quarry near Stein			whole rock	14
	qu, mu, chl, cld, stau, mag			quartz	16,4
				magnetite	6,5
		Δ (qu-mag)	9,9	T 545°C	
T 126	Metapelite from the Lappachtal			whole rock	17
	qu, mu, chl, bio, gar, ilm			quartz	19,6
				ilmenite	11,4
		Δ (qu-ilm)	8,2	T 570°C	
T 47	Metapelite from the Pfitschtal			whole rock	15
	qu, plag, bio, mu, chl, epi, ilm, cc			plagioclase	15,8
				ilmenite	8,7
				calcite	16,9
		Δ (plag-ilm)	7,1	T 540°C	
T 334	Carbonateschist near Brenner			whole rock	17
	dol, cc, qu, bio, mu			quartz	18,3
				biotite	12,8
				calcite	16,3
		Δ (qu-bio)	5,5	T 560°C	
T 325	Biotiteschist from the Pfitschtal, near Kematen			whole rock	15
	qu, plag, bio, epi, gar, opq			quartz	17,9
				biotite	12,7
		Δ (qu-bio)	5,2	T 580°C	
T 80	Prasinite from the Pfitschtal			whole rock	16
*	epi, cc, bio, hbl, qu, plag, chl, opq			quartz	16,1
				biotite	12,3
		Δ (qu-bio)	3,9	calcite	15,7
T 95	Metapelite from the Pfunderertal			whole rock	16
	qu, plag, mu, chl, ilm, gar			quartz	18,4
		Δ (qu-mu)	3,5	muscovite	14,9
F 8	Eklogite from the Frosnitztal			whole rock	10
*	gar, klpx, hbl, mu, ky, epi, qu			quartz (rock)	11,2
	segregation: qu, ky			quartz (seg)	14,0
				garnet	10,3
F 24	Eklogite from the Frosnitztal			whole rock	9
*	gar, klpx, zoi, mu, ky, qu, alb			quartz	8,8
				garnet	10,1
T 218	Marble from the Venntal, near Brenner			whole rock	24
	qu, plag, cc, mu, bio			quartz	25,5
				biotite	20,4
				muscovite	22,1
		Δ (qu-mu)	3,4	calcite	23,9
		Δ (qu-bio)	5,1	T 590°C	
F 30	Metapelite from the Frosnitztal, near Gruben			whole rock	17
	qu, mu, chl, cld, gar, ilm, turm, cc			quartz	18,2
				muscovite	14,8
		Δ (qu-mu)	3,4	calcite	17,0
T 259	Serpentine-karbonate schist (Ophicalcite) from the Navistal			whole rock	16
	near Reckner, cc, mag, serp			magnetite	3,1
				calcite	17,9
		Δ (mag-cc)	14,8	T 325°C	

	Description and location of samples			δ 18$_0$ [$^0/_{00}$]	
T 331	Carbonate-micaschist (Bündnerschiefer), from the Riederbergalm, near Sterzing, qu, alb, mu, chl, bio, cc, dol			whole rock	19
				quartz	20,9
				biotite	14,3
				calcite	14,8
		Δ (qu-bio)	6,6	T 470°C	
T 76	Prasinite from the Pfitschtal epi, qu, hbl, cc, plag, bio, ilm			whole rock	13
				quartz	16,7
				ilmenite	7,3
				calcite	14,7
		Δ (qu-ilm)	9,4	T 520°C	
T 310	Prasinite from the Gerlos-area, near lake qu, alb, chl, epi, hbl, cc, mag			whole rock	11
				quartz	17,9
				magnetite	4,8
		Δ (qu-mag)	13,1	T 405°C	
T 36	Carbonate-micaschist (Bündnerschiefer), near Sterzing qu, plag, dol, cc, mu, bio, chl, opq			whole rock	20
				quartz	21,7
				biotite	14,4
				calcite	18,9
		Δ (qu-bio)	7,3	T 420°C	
T 349	Metapelite from the Tuxertal near Spannagelhaus (Wustkogelserie), qu, plag, alkfsp, bio, mu			whole rock	15
				quartz	16,4
				biotite	10,3
		Δ (qu-bio)	6,1	T 515°C	
V 1	Metapelite from the Virgental, south Virgen qu, alb, chl, mu, epi, ilm			whole rock	16
				quartz	17,4
				ilmenite	7,0
		Δ (qu-ilm)	10,4	T 460°C	
T 459	Metapelite from the Pfitschtal, near Kematen (Wustkogelserie), qu, plag, alkfsp, bio, mu			whole rock	15
				quartz	16,3
				biotite	10,9
		Δ (qu-bio)	5,4	T 570°C	
17	Prasinite east of the Johannis Hütte, Dorfertal			quartz	13,1
				magnetite	3,5
				calcite	13,0
		Δ (qu-mag)	9,6	T 560°C	
		Δ (cc-mag)	9,5	T 500°C	
44	Prasinite near Gumbachkreuz, Dorfertal			albite	13,7
				magnetite	4,4
		Δ (alb-mag)	9,3	T 530°C	
39	Prasinite near Gumbachkreuz, Dorfertal			albite	15,2
				calcite	14,0
				magnetite	5,8
		Δ (alb-mag)	9,4	T 520°C	
		Δ (cc-mag)	8,2	T 550°C	
50	Prasinite from the Dorfertal, north Hinterbichl			albite	15,2
				magnetite	5,5
		Δ (alb-mag)	9,7	T 510°C	
54	Prasinite from the Dorfertal, near Hinterbichl			albite	15,0
				hematite	3,0
		Δ (alb-hem)	12,0	T 415°C	

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