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Petrographic and geochemical investigations in the Knappenwand Area, Habach Formation (Tauern Window, Austria)

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With 7 figures and 1 table

Summary

On the course of a research project on the world-famous epidote occurrence of the "Knappenwand" (Untersulzbach valley, Salzburg), detailed studies of the surrounding rock assemblages were carried out. Three profiles through a metamorphosed volcanosedimentary sequence, which is presumably of Paleozoic age, were studied in detail. The petrographic variability ranges from basaltic to andesitic and rhyolitic compositions with intercalated sediments. The profiles indicate a more complex stratigraphy than has been known up to now. This sequence is interpreted as having formed in an island arc environment. In general, a calc-alkaline fractionation trend may be observed throughout the investigated area. Fractionation models with olivine/orthopyroxene – clinopyroxen – plagioclase assemblages and increasing influence of magnetite, amphibole and biotite during melt evolution will best explain the observed element distribution.

Zusammenfassung

Im Rahmen eines Forschungsprojektes über die weltbekannte Epidotfundstelle Knappenwand (Untersulzbachtal, Salzburg) wurden auch umfangreiche Untersuchungen an den umgebenden Gesteinen (Knappenwandmulde) durchgeführt und die ersten Ergebnisse hier dargestellt. Die Bearbeitung von drei Detailprofilen zeigt eine metamorphe, vermutlich paläozoische vulkanosedimentäre Abfolge, die von basaltischen über andesitische zu sauren Zusammensetzungen mit eingeschalteten Sedimenten reicht. Die einzelnen Profile zeigen einen wesentlich komplizierteren Aufbau als bisher bekannt war. Aufgrund der Geochemie wird sie einem Inselbogenmilieu zugeordnet. Kalkalkalifraktionierungstrends sind im Untersuchungsgebiet allgemein ableitbar. Mit Fraktionierungsmodellen, bestehend aus Olivin/Orthopyroxen – Klinopyroxen – Plagioklas Vergesellschaftungen sowie einem zunehmenden Einfluß von Amphibol, Biotit und Magnetit lassen sich die beobachteten Spurenelementgehalte in den differenzierten Schmelzen gut erklären.

1. Introduction and Geological Setting

During the research project "Knappenwand", carried out recently by the Department of Mineralogy and Petrography of the Museum of Natural History in Vienna

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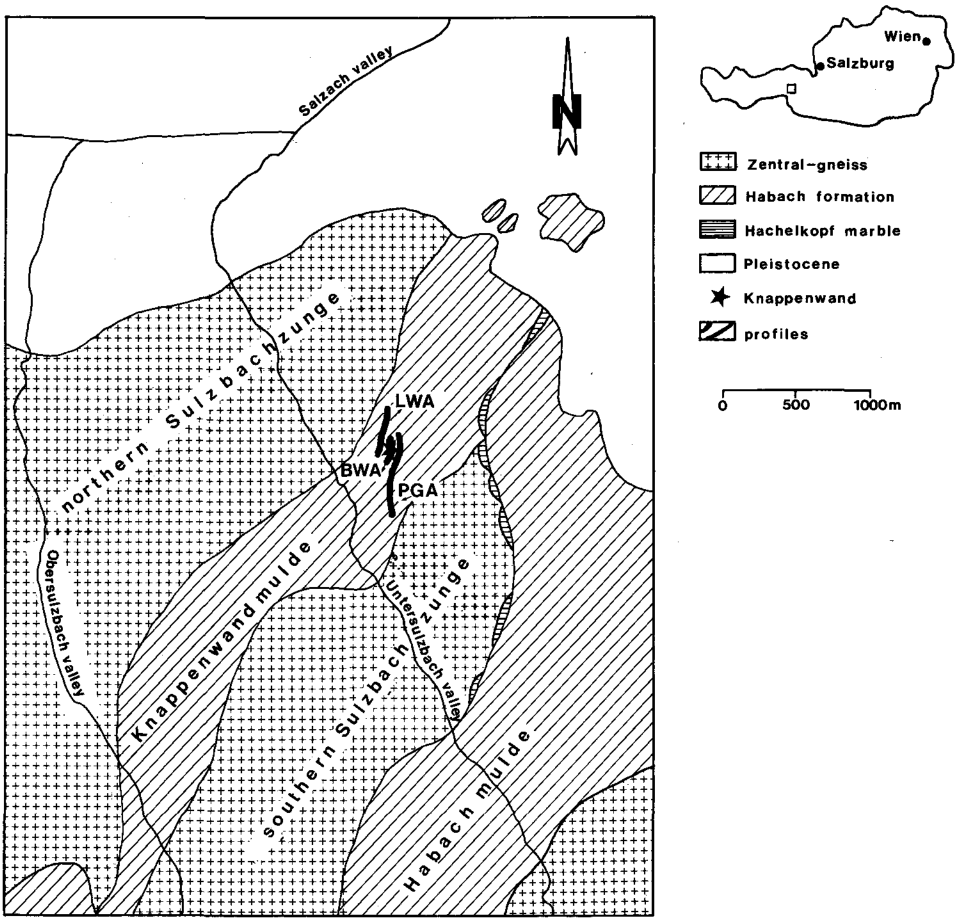

Fig. 1: Schematiced topographic and geological map of the Habach formation in the lower Sulzbach valley according to FRASL (1953), STEYRER (1982), and own results. PGA for Pochergraben, BWA for Blauwandl and LWA for Langwinkel profile; location of the Knappenwand is marked by an asterix.

(SEEMANN, 1987), the epidote mineralisation from the internationally known locality "Knappenwand", Untersulzbach valley (Fig. 1) was reexamined. The neighbouring ore paragenesis in the historical copper mine "Hochfeld", the origin and the metamorphic evolution of the surrounding rock sequences were investigated during this research programme.

The country rocks investigated here are part of the so-called "Knappenwand-mulde" (FRASL, 1953), which is part of the Paleozoic "Habachserie" (FRASL 1958, FRASL and FRANK, 1966), recently renamed to Habach formation bei HÖCK et al. (1982) and is situated at the northern margin of the Tauern window. The whole sequence of the Knappenwandmulde shows a complex alternation of metamorphic equivalents of basic, intermediate to acidic volcanic or volcanoclastic materials

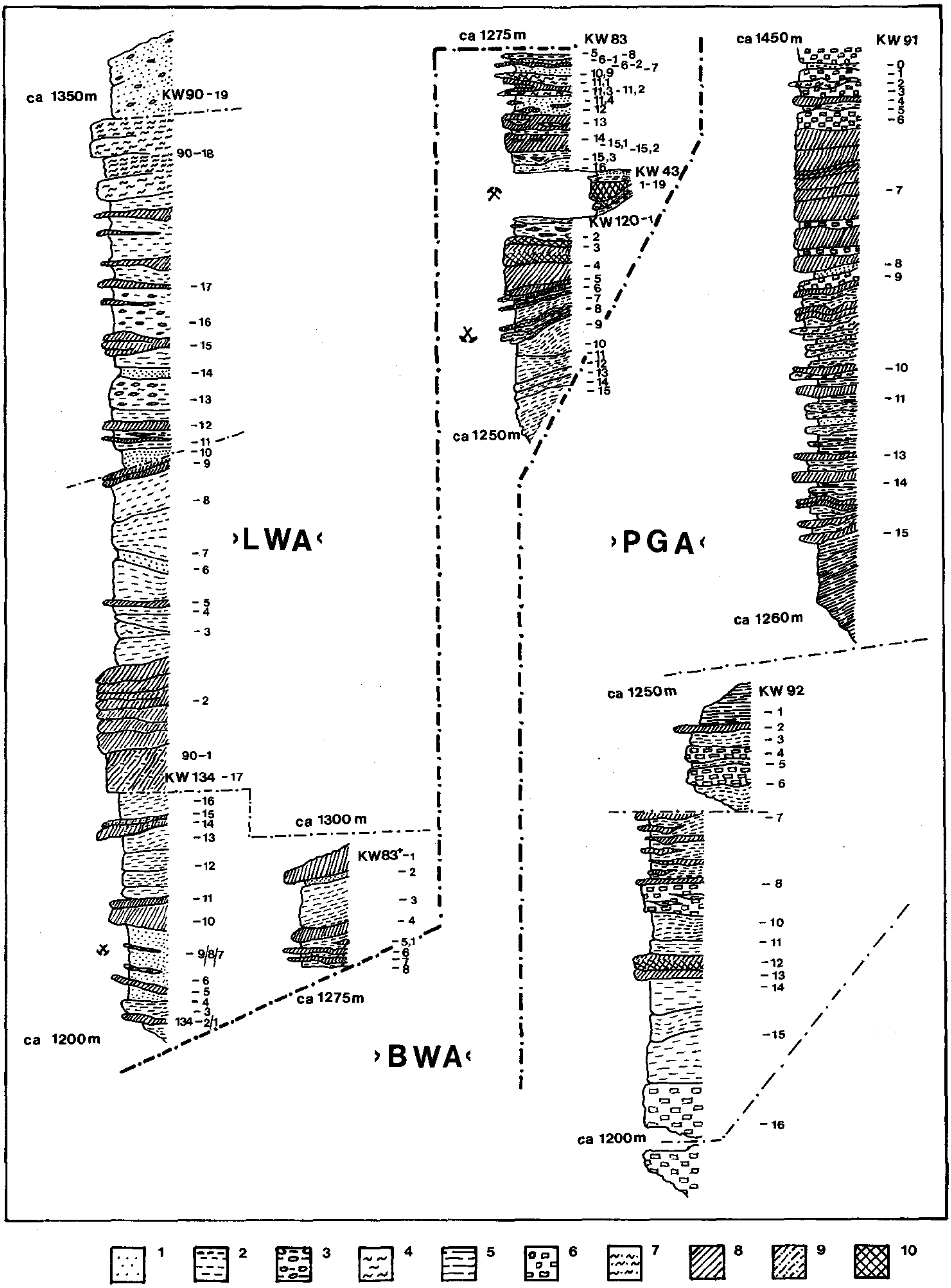

Fig. 2: Detailed profiles in the "Knappenwand" area, Untersulzbach valley, Salzburg (PGA for Pochergraben, BWA for Blauwandl and LWA for Langwinkel profile). Signatures: 1 = quartz rich gneisses, 2 = fine grained albite gneisses, 3 = medium grained "Augen-Flaser"-gneisses, 4 = biotite-rich gneisses to schists, 5 = phengite gneisses ("Weißschiefer"), 6 = "Knappenwand"-gneiss, 7 = biotite chlorite schists, 8 = amphibole schists, 9 = massive amphibolites with form relics, 10 = epidote amphibolites.

interbedded with sediments as well as some intrusive rocks and has a total thickness of approximately 500–700 m (Fig. 2).

The interpretation of the main part of the Habach formation in the investigated area as an early Paleozoic island arc is well established today, based on the geological results by FRASL (1958), FRASL and FRANK (1966), HÖLL (1975), HÖCK et al. (1982), the petrological and geochemical data by STEYRER (1982, 1983), KRAIGER (1987, 1989), FRISCH and RAAB (1987) and the geochronological data by PESTAL (1983) and v. QUADT (1985).

The metamorphic evolution can be subdivided into two different stages. The older one, recognisable only in localities, is due to a possible low grade Variscan event, the younger one is related to the Alpine metamorphism (STEYRER, 1982; KOLLER and RICHTER, 1984; GRUNDMANN, 1989). – The metamorphic conditions for the Alpidic event are typical of the transition from greenschist to amphibolite facies. The primary rocks have been transformed into epidote-amphibolites, greenschists partly with albite-rich layers, albite-rich gneisses, minor quartzites and rare chlorite- and biotite-schists. Locally some lense-like stratiform mobilisations of quartz and epidote occur. The ore deposit (Hochfeld) in chlorite-biotite-schists within the metabasites has been mined in historical time, mainly for copper (SEEMANN and BRANDSTÄTTER, 1987).

The northward movement of the Tauern-Schieferhülle complex during the Alpine orogeny caused strong N–S-compression and intense deformation of the whole sequence. The "Krimmler Gneiswalze" (KÖLBL, 1932; FRASL, 1953) has been formed during this event and the "Knappenwandmulde" was folded into the "Zentralgneis" of the northern and southern "Sulzbachzunge". In the Knappenwand area the Habach formation shows a normal or a slightly overturned dipping to the north, striking NE–SW (Fig. 1).

2. Profile description

At least three rock sequences, divided by tectonic lineaments, with marked lithological differences can be observed in the area of the Knappenwand (Fig. 2). They are called the "Pochergraben"-, "Blauwandl"- and "Langwinkel"-sequence and have been thrust to the north to form an imbricate structure.

a) The Pochergraben sequence (PGA), the southernmost and highest unit, comprises numerous thin amphibole-schists, albite-gneisses, garnet-bearing amphibolites and the thick, massive so-called Knappenwand-gneisses, which are accompanied by thin bedded white-mica gneisses (Weißschiefer). It should be noted that the Knappenwandgneisses form several layers and lenses, some only 50–100 cm thick. Towards the south a thick layer grades without a significant tectonic or lithological boundary into the granitic gneiss of the southern "Sulzbachzunge", as observed by FRASL (1953) and STEYRER (1982, 1983). The sample series KW91 and KW92 are representative of this sequence.

The total thickness is approx. 280 m. 80% of the rocks are of acid and intermediate types (the Knappenwand-gneisses dominate in this sequence), only 20% are basic types.

b) The Blauwandl sequence (BWA) is situated in an intermediate position and is the smallest unit (sample series KW83, KW43 and KW120). It is characterized by a thickly layered to lenticular structured epidote-amphibolite (which contains the famous fissure mineralisation) and thin chlorite-albite-amphibole schists in massive but fine grained albite-gneisses and quartzites. A Cu-sulfide mineralization is observed in extremely thin biotite-chlorite schists. The total thickness is 100 m. The sequence as a whole contains 65% acid and intermediate and 35% basic rocks.

c) The Langwinkel sequence (LWA), the structurally lowest and northernmost unit (sample series KW90, KW134 and KW83*), exhibits a large volume of amphibole-schists on the top and a series of biotite-gneisses and biotite-schists in lower position of the profile. In between, gneisses were found with variable compositions and textures (fine- to medium-grained, some with flaser structures) and changes in amount of minerals such as amphibole, chlorite, biotite, epidote or muscovite and albite. Rhythmic layers of fine-grained amphibole-schists are common, whereas coarse-grained amphibolites are rare. 64% of the rocks in the profile are acidic in geochemistry, 13% are intermediate and 23% are basic. The total thickness is 260 m.

A total of eight detailed profiles were sampled across the three sequences, generally parallel to the slope at various elevations between 1100 and 1700 m (a.s.l.). The most important profiles are summarized in this paper. 140 samples were collected along exactly surveyed profiles. It is difficult to compare the profiles, caused by strong variations in thickness, composition and structure of the individual beds. Faults masked the continuation of the profiles.

3. Petrography

The rock association reconstructed from the detailed study of three profiles (Fig. 2) within the "Knappenwandmulde" consists of metamorphic equivalents of basic, intermediate to acidic volanic or volcanoclastic materials interbedded with sediments as well as some intrusive rocks.

A. Basic parts of the magmatic sequence

The metabasites range from amphibole schists to amphibolites with varying mineral contents. The main constituents are several generations of amphiboles, plagioclase (mainly albite), chlorite and epidote all in varying amounts. The minor components (biotite, quartz, garnet, zoisite and sphene) can also change rapidly in concentrations. The textures of the fine-grained metabasites range from highly schistose to massive granular. Coarse-grained massive types, which may contain amphibole relics, are rare. Three different rock types can be distinguished:

A 1. The fine-grained, finely layered amphibole-schists contain locally deformed microscopically form-relics of an older mafic mineral and of plagioclase. Some lenticular zones are enriched in newly-formed quartz or albite. In tectonized areas the amphibole-schists show a remarkable microfolding. The main constituents, in order of their importance, are amphibole, albite, chlorite, biotite, epidote and quartz. Amphibole occur in this group in several generations and plagioclase forms intensively filled core with a thin clear albite rim. The ore minerals magnetite, ilmenite, pyrite and chalcopyrite may be found locally in enriched zones.

Amphibole-schists with macroscopic form-relics in an inhomogeneous matrix contain large amphibole and plagioclase relics up to 5 mm grain size, which are partly enriched in irregular layers. The inclusion trail in the relics represents an older texture different from the schistosity of the whole rock. This special type occurs locally as thin layers within the fine-grained amphibole-schists and is common in the basal parts of the LWA profile.

A 2. Epidote-amphibolites form thin layers and lenses. They reach a thickness up to 30 m only in the immediate neighborhood of the epidote locality of the Knappenwand. In general these rocks are fine-grained and compact. A weak primary layering is observable. The matrix of the epidote-amphibolites consists of variable amounts of diffuse aggregates of epidote and amphibole. Apart from these minerals, enrichment in albite, rare garnet and quartz in lenses and layers is common. The typical ore minerals are pyrite and magnetite. Discordant young mobilisations of epidote, calcite and quartz are common.

A 3. Massive and coarse grained amphibolites with a granular texture may possibly be derived from massive basalt flows or from gabbros. Their occurrence is restricted to the lower parts of the LWA profile. Amphibole and albite form the main constituents with minor amounts of chlorite, biotite and epidote.

B. Intermediate to acid parts of the magmatic sequence

B 1. The dominant rock type is an albite gneiss. Its texture ranges from an augen- and flaser-structure to a fine-grained gneiss with a well developed schistosity. Apart from the strongly deformed gneisses, all these rock types form massive bodies or lenses with variable thickness. The mineral contents are variable and range from andesitic to almost quartzitic compositions. Apart from some K-feldspar-bearing flaser-gneisses in the LWA profile, the predominance of albite is striking. The augen-structure is produced by form relics of an older plagioclase, now with clinozoisite filled albite. Even some albite rich layers ("albitite") may be found within this rock sequences. Minor components of the albite gneisses are biotite, actinolite, chlorite, epidote, garnet and rare white mica.

B 2. The "Knappenwandgneis" is a greyish porphyritic gneiss, which form usually very compact and massive complexes. In the investigated area the "Knappenwandgneis" is restricted to the PGA profile and is characterised by a greyish groundmass of biotite, muscovite, albite and quartz. Filled form-relics of an older plagioclase with a small rim of clear albite occur together with hypidiomorphic K-feldspars (up to 2 cm). A weak possible primary layering can be observed in massive, undeformed parts. The "Knappenwandgneis" is mineralogically inhomogeneous and varies from rhyolitic to dacitic in chemical composition.

C. Metamorphic sediments

C 1. The light, quartz-rich phengite gneisses with a well developed schistosity are called "Weißschiefer". They occur in the upper part of the PGA profile. Their thickness increases towards the contact with the "Knappenwandgneis". They are characterised by an intensive tectonic fabric formed by parallel oriented phengitic micas and minor sheared older feldspars or quartz.

C 2. Biotite-chlorite-schists can be found as thin, highly deformed layers within the fine-grained albite gneisses of the BWA profile and consists dominantly of a dark green parallel-orientated rhipidolite. Enrichment in biotite and rarely of garnet is locally observed. The garnet is almandine-rich and forms porphyroblasts up to 3 cm in diameter. Minor contents of albite, quartz or epidote are common, but are inhomogenously distributed. Large lenses of flattered mobilised quartz are common.

The garnet-bearing biotite-chlorite-schists contains the Cu-mineralisation "Revier Hochfeld" (Untersulzbachtal), mined in historical times. The common ore minerals are chalcopyrite, pyrite and pyrrhotite, with minor amounts of spalerite, galenite und magnetite. Altaite and glaucodote are rarities worth mentioning (SEEMANN and BRANDSTÄTTER, 1987).

Tab. 1: Selected chemical analyses of metavolcanic rocks from the Knappenwand area, Habach formation. Main and trace elements determined by XRF equipment, total iron calculated as Fe_2O_3, CO_2 and H_2O by gravimetric methods. PGA for Pochergraben-, BWA for Blauwandl- and LWA for Langwinkel sequence; b for basic, i for intermediate and a for acidic bulk geochemistry.

	LWA	LWA	LWA	BWA	BWA	BWA	PGA	PGA	PGA
KW	90–1	90–3	90–7	43–17	43–19	43–18	91–10	91–6	91–8
	b	i	a	b	i	a	b	i	a
SiO_2	48.53	58.36	73.10	45.54	60.29	69.75	48.23	60.75	78.74
TiO_2	1.51	1.72	0.49	1.31	0.91	0.31	1.67	0.88	0.17
Al_2O_3	15.13	12.81	12.64	13.57	15.05	13.73	14.23	17.51	10.88
Fe_2O_3	11.53	10.65	5.12	12.57	7.62	4.26	13.68	4.74	2.78
MnO	0.21	0.24	0.08	0.26	0.09	0.04	0.17	0.10	0.04
MgO	6.92	2.95	0.95	8.29	4.07	1.45	6.78	3.43	0.61
CaO	10.22	8.23	2.05	17.05	4.09	1.92	9.95	4.06	1.58
Na_2O	3.07	2.54	4.98	0.52	6.40	7.84	3.62	5.89	4.35
K_2O	0.18	0.28	0.62	0.14	0.64	0.09	0.30	1.88	0.46
P_2O_5	0.14	0.15	0.12	0.10	0.16	0.03	0.13	0.62	0.03
H_2O	1.17	0.72	0.60	0.64	0.70	0.12	1.07	0.60	0.48
CO_2	0.00	0.00	0.00	0.15	0.16	0.16	0.02	0.00	0.00
Σ	98.61	98.65	100.75	100.14	100.18	99.70	99.85	100.46	100.12
Cr	318	62	<5	211	16	<5	208	85	<5
Ni	64	33	23	87	39	25	69	51	33
Cu	71	7	10	<5	9	22	<5	16	23
Zn	89	67	50	155	44	24	113	106	48
Rb	2	8	26	8	36	12	5	73	26
Sr	169	429	146	440	153	69	223	279	332
Y	35	51	61	35	55	91	38	24	90
Zr	94	211	228	84	180	330	96	320	274
Nb	<2	2	4	5	8	11	<2	24	5
Ba	79	86	91	132	218	<10	119	1113	115

4. Geochemistry

The geochemical results of the metavolcanic suite, based on the detailed sampling along the three profiles in the Knappenwand area (Fig. 2), are presented here. For each profile typical bulk and trace element compositions are listed in Tab. 1.

A. Metabasites

The amphibole schists (group A 1) can be characterized by SiO_2 contents ranging from 45–51 wt. %, combined with variable TiO_2 from 0.8–1.7 and usually high amounts of CaO and MgO. Na_2O contents vary from 1.0 to 3.6 wt. %, K_2O is normally below 0.3 wt. %. A typical sample (KW91–10) is listed in Tab. 1.

Epidote amphibolites (group A 2) are dominant in profile b) (BWA) and only less important in c). As a typical example KW43–17 is listed in tab. 1. The bulk chemistry of the epidote amphibolites shows usually higher SiO_2 contents than the former group. Partly they are grading into andesitic compositions. They also show variable Al_2O_3 and Fe_2O_3 contents, low MgO but high CaO up to a maximal value of 27 wt. %. Na_2O varies in these rocks between 0.2–5.5 wt. %. With increasing CaO the contents of Na_2O decrease. The high CaO is not only buffered by epidote and amphibole, even carbonate contents are common. The epidote amphibolites of profile a) (PGA) are higher in K_2O, up to a maximum value of 5.3 wt. %, than the amphibole schists in the same profile.

The coarse grained massive amphibolites (group A 3) show partly basaltic composition (KW90–1, tab. 1), some others are characterized by low Ti, Zr and Y contents and may be derived from former gabbros.

5. Intermediate to acid rocks of igneous origin

The intermediate samples (KW90–3 and KW43–19, tab. 1) contain around 60 wt. % SiO_2 and show sometimes similar MgO and CaO concentrations close to 4 wt. %. An excess in Na_2O with respect to K_2O is typical. In general there is an increase of K_2O, Rb, Ba and Nb as well as a decrease of TiO_2 in relation to the metabasites.

The SiO_2 concentrations in the acidic rocks, in general albite rich gneisses, show a strong variation from 65 to 78 wt. %. They are usually high in Na_2O, mainly combined with low K_2O. Typical samples are listed in tab. 1 (KW90–70, KW43–18 and KW91–8).

In contrast the Knappenwandgneiss (KW91–6 in tab. 1) is characterized by lower SiO_2, by Na_2O contents between 5.7–6.6 wt. % and by K_2O in the range of 1.8–2.0 wt. %. The K and the Ba concentrations are usually higher than in the above mentioned gneisses and the other trace elements also differ slightly.

The AFM-plot (Fig. 3 a) for profile a) (PGA) shows a wide scatter but represent partly a typical calc-alkaline trend as reported by Brown (1982). It should be noted here, that especially some of the intermediate samples plot below the Cascade/N-Chile trend after Brown (1982). On the other hand in the Zr-Ti-Y-triangle (Pearce and Cann, 1973) only a few metabasites plot in the fields of the CABs (A and B in Fig. 4 a). Some of the amphibolites fall outside the basalt fields as defined by Pearce and Cann (1973). The amphibolites with plot outside have unusually low concentra-

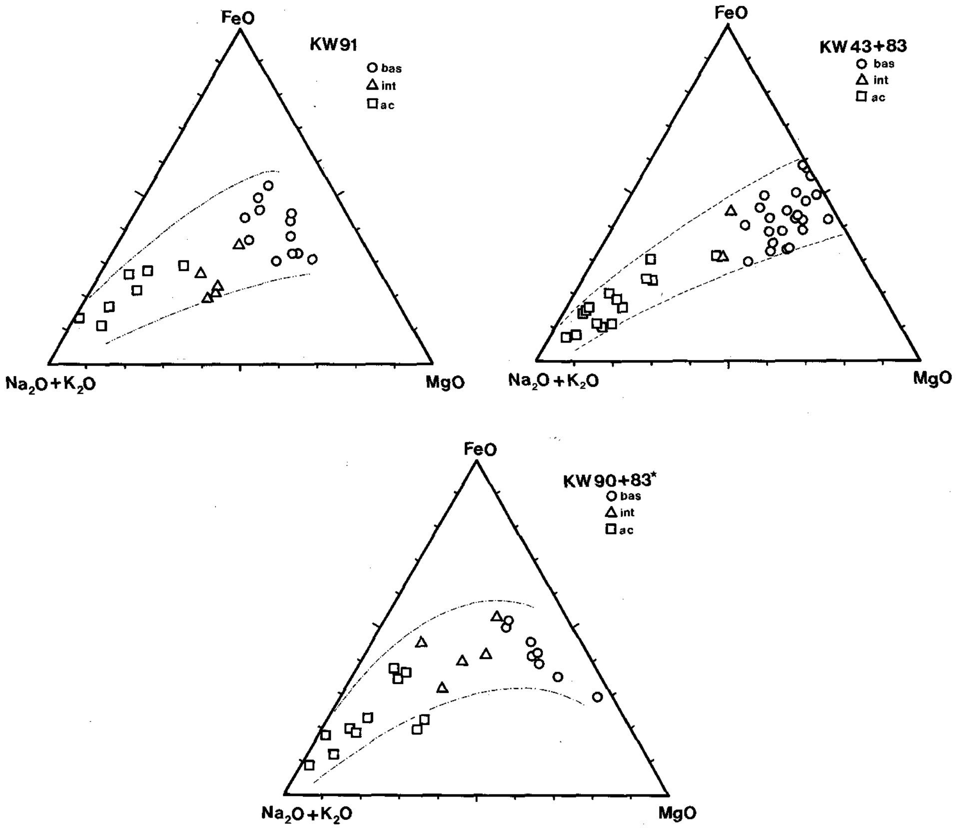

Fig. 3: AFM plot of meta-igneous rocks of the Habach formation in the Knappenwand area. The samples are divided into basic, intermediate and acidic subtypes and grouped for a) profile Pochergraben (PGA), b) profile Blauwandl (BWA) and c) profile Langwinkel (LWA).
Signatures: Open circles for basic, triangles for intermediate and squares for acidic bulk geochemistry.

tion of Ti, Zr and Y. Some of them are coarse-grained with form relics of amphibole and possibly they may be representative of former gabbros. Two samples with higher Y values could derive from tuffitic or pyroclastic material, an interpretation supported by their fine layering with varying mineral contents. The profile b) (BWA) represents a well established calc-alkaline fractionation trend in the AFM diagram (Fig. 3 b). Intermediate compositions are relatively rare. In the basalt discrimination diagram (Fig. 4 b) after PEARCE and CANN (1973) nearly all amphibolites of this profile are in good agreement with a CAB geochemistry (field B). Even the high excess of Na is typical of acid igneous rocks of such a suite.

In profile c) (LWA) the AFM-plot (Fig. 3 c) shows a slight tendency towards relative Fe-enrichment in both the metabasic rocks and the intermediate bulk geochemistry. According to BROWN (1982), such a trend is more typical of island arc

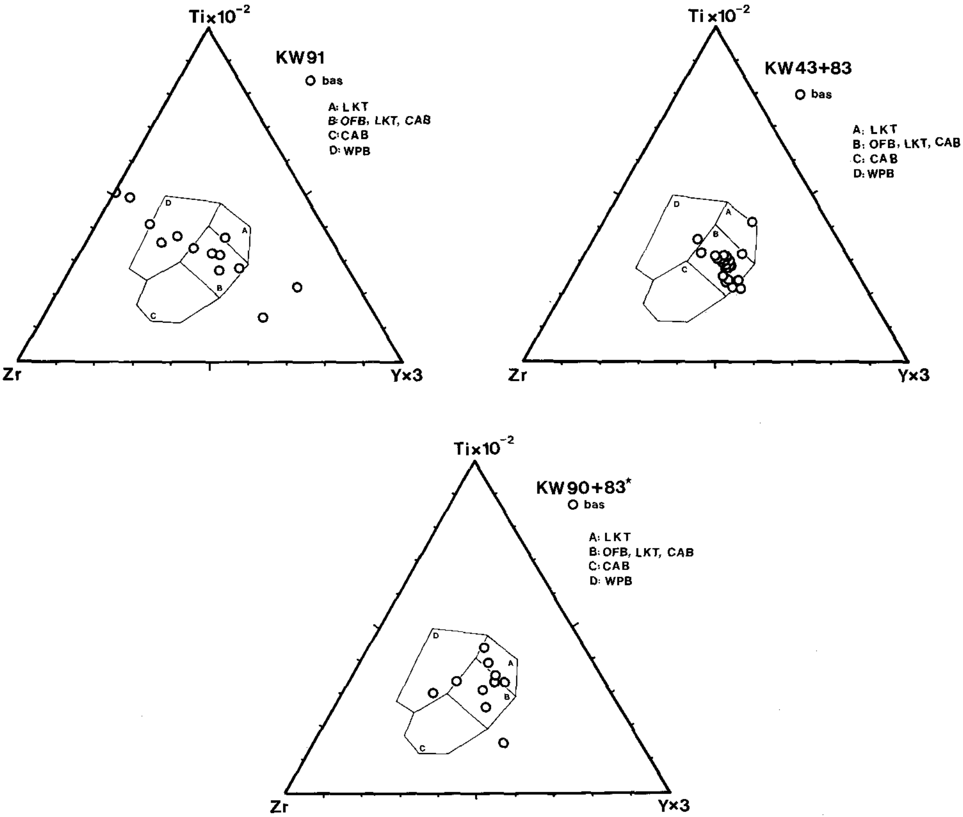

Fig. 4: Ti/100-Zr-3Y diagramm according PEARCE and CANN (1973) for the metabasites of the Knappenwand area, Untersulzbach valley, grouped for a) profile Pochergraben (PGA), b) profile Blauwandl (BWA) and c) profile Langwinkel (LWA). Signatures: Open circles for basic bulk geochemistry.

basalts or low-K tholeiites. The high Mg- and low K-values and the Zr-Ti-Y triangle (Fig. 4 c), where the analyses are partly shifted towards the low K tholeiite field (A), support this assumption.

6. Discussion

The great variation in rock types within a small area is typical for this section of the Habach formation (HÖCK et al., 1982). One of the numerous basic questions here is the relationship between the metabasites, discussed in general by STEYRER and HÖCK (1985), and between basic and intermediate to acidic metavolcanic rocks. One possible answer focusses on fractionation processes, as discussed by PEARCE and NORRY (1979) with immobile elements such as Ti, Zr, Nb and Y. The best results in this respect have been found in profile b) (BWA), as exemplified by the AFM

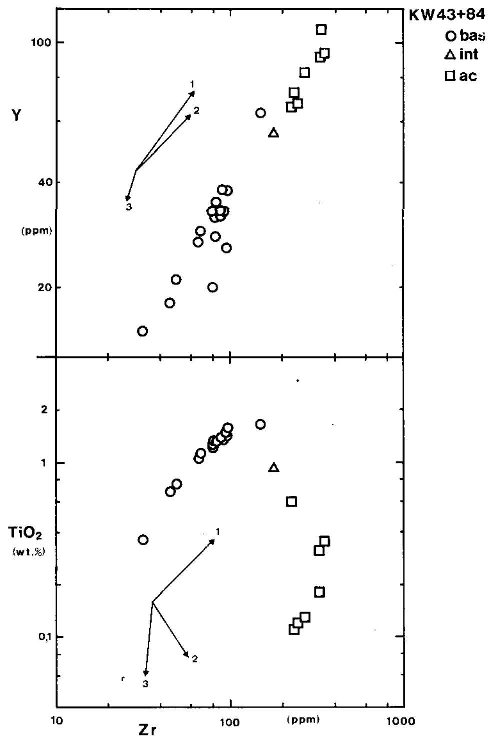

Fig. 5: TiO_2 vs. Zr and Y vs. Zr diagrams for the profile Blauwandl (BWA), the samples are grouped into basic, intermediate and acidic subtypes.
Signatures: Open circles for basic, triangles for intermediate and squares for acidic bulk geochemistry. Modelled fractionation vectors after PEARCE and NORRY (1979) are: 1: $ol_{0.2}cpx_{0.3}plag_{0.5}$, 2: $plag_{0.5}cpx_{0.3}ol_{0.1}mt_{0.05}$ and 3: (ksp, plag) $_{0.6}bi_{0.15}am_{0.2}mt_{0.05}$.

(Fig. 3 b) and the Ti-Zr-Y diagram (Fig. 4 b). A combination of olivine/orthopyroxene + clinopyroxene + plagioclase as crystallising phases in cooling liquids will enrich all elements such as Ti, Zr, Nb, or Y in the melt, as shown by PEARCE and NORRY (1979). Fig. 5 demonstrates a continous enrichment in Zr and Y for all samples with basic and intermediate composition in profile b). Only a large amount of amphibole or apatite as fractionating phases would be able to reduce the Y contents in the melt in a significant way. In the Ti-Zr diagram (Fig. 5) a continous enrichment in both elements in the metabasites can be observed and might be correlated to a theoretical fractionation model of $ol_{0.2}cpx_{0.3}plag_{0.5}$. In the intermediate to acidic rocks an intensive decrease in Ti is followed by a decrease in both elements with more or less constant Zr/Y ratios. Such a fractionation trend is typical of island arc environments, as reported by PEARCE and NORRY (1979) and PEARCE (1982). The decrease in Ti within the intermediate rocks may be related to a fractionation of $plag_{0.5}cpx_{0.3}ol_{0.1}mt_{0.05}$. After PEARCE and NORRY (1979) is in higher fractionated melts amphibole and biotite fractionation in the form of (ksp,

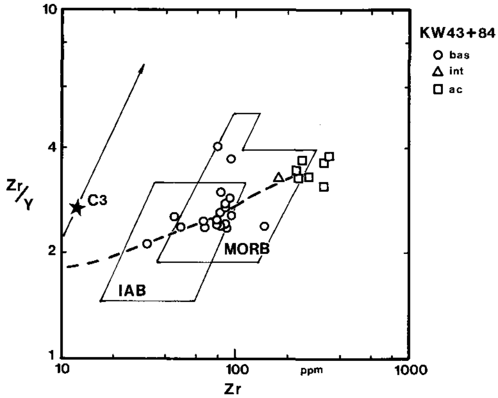

Fig. 6: Zr/Y versus Zr diagram after PEARCE and NORRY (1979) for the profile Blauwandl (BWA), Knappenwand area, the samples are grouped into basic, intermediate and acidic subtypes. Field for island-arc basalts (IAB) and for MORB, C 3 = composition of C_3-chondrite for primitive mantle composition, the mantle variation trend is shown by a vector.
Signatures: Open circles for basic, triangles for intermediate and squares for acidic bulk geochemistry.

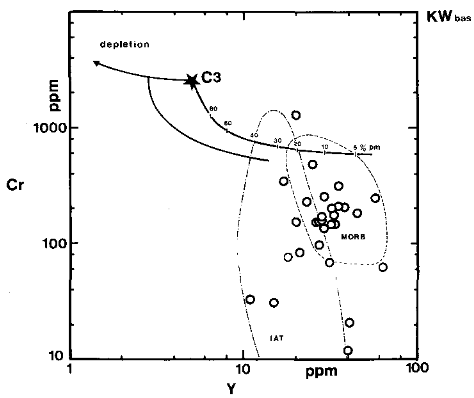

Fig. 7: Cr vs. Y diagram after PEARCE (1980) for all metabasites of the Knappenwand area. C 3 = composition of C_3-chondrite for primitive mantle composition, pm = partial melting line, fields for island-arc theoleiites (IAT) and MORB.
Signatures: Open circles for basic bulk geochemistry.

plag) $_{0.6}$bi$_{0.15}$am$_{0.2}$mt$_{0.05}$ necessary to produce element distributiones, as demonstrated in Fig. 5.

In the Zr/Y versus Zr diagram (Fig. 6) most metabasalts of profile b) plot into the IAB field, which overlaps with the MORB field (PEARCE and NORRY, 1979), and show a moderate increase of Zr/Y ratios from basic to acidic compositions. As shown by the fractionation and partial melting processes (PEARCE and NORRY, 1979) the metabasalts can only be produced from a depleted source relative to a primitive mantle, modelled by a C3-chondritic composition. This is in good agreement with an island-arc environment as geotectonic model.

In the Cr-Y diagram, after PEARCE (1980), all metabasites of the "Knappenwand" area are divided between the IAT and MORB fields (Fig. 7). Similarly to the results of STEYRER and HÖCK (1985), the investigated metabasites can be produced only by different partial melting ratios from a possible depleted mantle source.

Summarizing, the metamorphosed igneous suite found in different profiles of the "Knappenwand" area consists of basic to intermediate and acidic compositions. They are related to an island arc environment, the metabasites in the three profiles vary from more calc-alkaline basalts towards low K-tholeiites. This may be produced by different degrees of arc maturity (BROWN, 1982). A fractionation model with an olivine/orthopyroxene – clinopyroxene – plagioclase ± magnetite assemblage and increasing influence of magnetite, amphibole and biotite during melt evolution will best explain the observed element distribution. Through late fractionation processes the significance of amphibole and biotite as crystallization phases seems to increase. The complexity of the profiles are in good agreement with recent island-arc environments.

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