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Autor: Giese, Uwe

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Lower Paleozoic volcanic evolution at the northwestern border of the Gurktal nappe, Upper Austroalpine, Eastern Alps

by Uwe Giese[1]

Abstract

From the Middle / Upper Ordovician to the Lower Devonian four different volcanic stages can be distinguished at the NW border of the Upper Austroalpine Gurktal nappe.

Calc-alkaline volcanics (Nock sequence) with basic to intermediate effusives and pyroclastics are of Middle / Upper Ordovician age. They are similar in their composition to high-K calc-alkaline volcanic rocks. The stratigraphic position of the Kaser series in unknown. These volcanics are massive intrusive sills and pillow-basalts in composition and represent a transitional basalt-hawaiite sequence that mediates between typical within-plate tholeiites and within-plate alkalibasalts. The Silurian Eisenhutschiefer series is dominated by pyroclastics. The series can be interpreted as products of volcanic islands composed of typical alkalibasalt-hawaiite-mugearite-trachyte suites. A locally occuring rhyolite tuff marks the Silurian / Devonian boundary. Chemical analyses show similarities with the composition of orogenic rhyolites of continental regions.

The Lower Paleozoic volcanic evolution is marked by a transition from calc-alkaline to alkaline compositions. Different models of the geodynamic evolution are discussed.

Keywords: Volcanic evolution, geodynamic models, Lower Paleozoic, Upper Austroalpine, Gurktal nappe.

Introduction

Paleozoic volcanic rocks, basic and acid in composition, are widespread in the Upper Austroalpine regions. However, only little is known about their occurence, stratigraphy and geochemistry. Detailed geological and geochemical investigations have concentrated on the basic and acid volcanism of the Greywacke zone (COLINS et al., 1980, HEINISCH, 1981, SCHLAEGEL, 1987) and of regions in the Southern Saualpe (HURLER, 1972), the Magdalensberg (RIEHL-HERWIRSCH, 1970, LOESCHKE, in press) and the area of Eisenkappel (LOESCHKE, 1970, 1973, 1975, LOESCHKE and SCHNEPF, 1987).

Although, the geochemical investigations of volcanic rocks, in particular of basalts, can be used for geotectonic interpretations (PEARCE and CANN, 1973), no concept of the Paleozoic evolution of the Upper Austroalpine has as yet been generally accepted (HÖLL and MAUCHER, 1976, LOESCHKE, 1977, FRISCH et al., 1984, POHL, 1984).

At the northwestern border of the Gurktal nappe (Fig. 1) volcanic rocks, which are called Eisenhutschiefer series, have been known for over one hundred years (PETERS, 1855, SCHWINNER, 1931, 1938) and have always been regarded as Paleozoic in age. Only HÖLL (1970) could date this series for the first time by conodonts as Lower Silurian to Lower Devonian. In contrast, NEUBAUER and PISTOTNIK (1984) found Upper Ordovician conodonts in dolomites at the Nockalm road. Both, Ordovician and Silurian conodonts have been found in dolomites which are in direct contact to volcanic rocks. This suggests, that different volcanic stages of different ages exist in this region. The paper which is presented here, shows that at least four different Lower Paleozoic volcanic

[1] Geologisches Institut RWTH-Aachen, Wüllnerstr. 2, D-5100 Aachen.

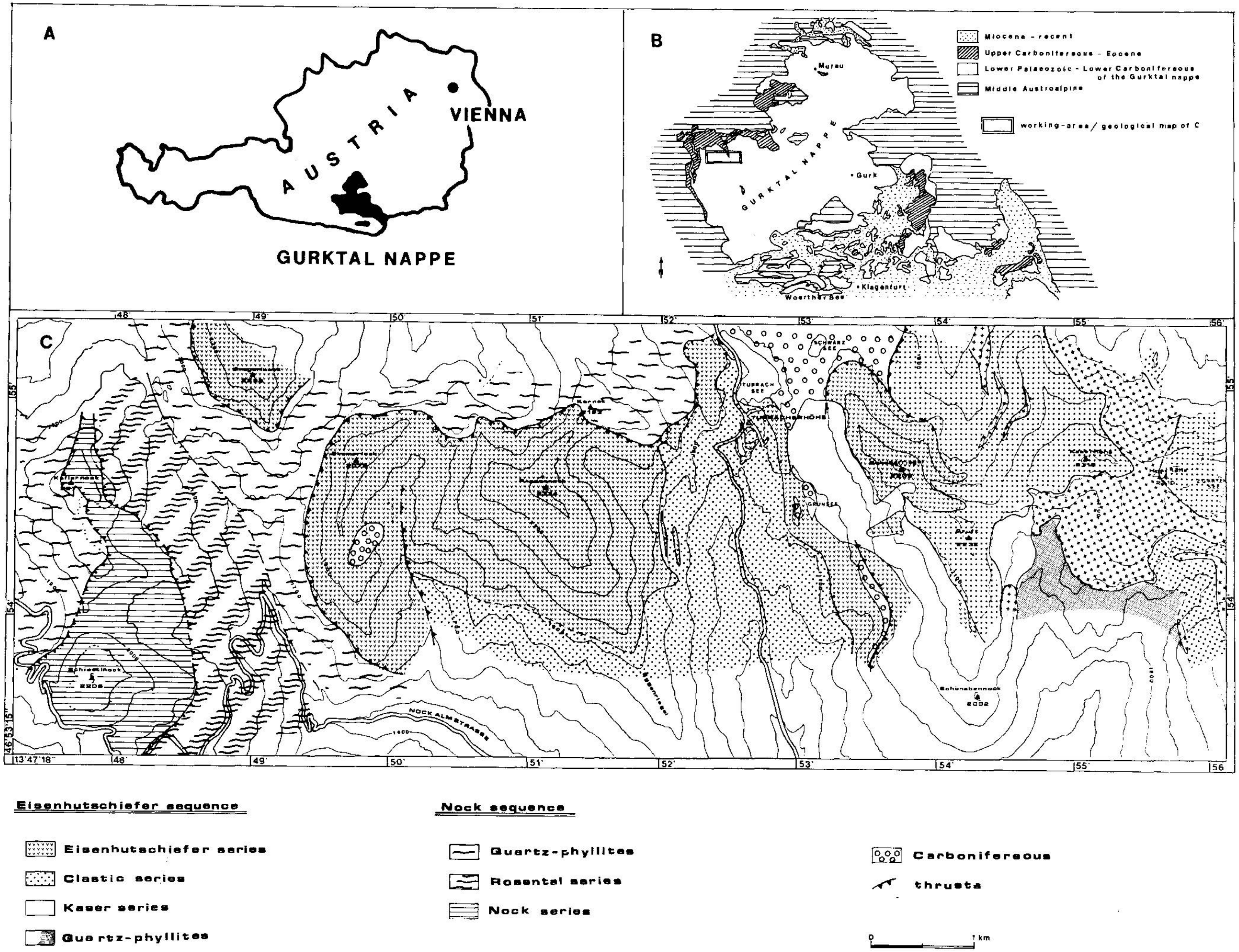


Fig. 1 Geological position of studied area A) location of Gurktal nappe, B) location of the geological map of Fig. 1C, C) geological map of studied area.

series can be distinguished by geological, petrological and geochemical means.

Geological setting

The mapped area lies in the Nock region and comprises a section - from west to east - between the Nockalm road, the Turracherhöhe and the Lattersteig. The geological map is shown in Fig. 1.

Two structural units can be distinguished: the lower unit is called *Nock sequence* which is overlain by an upper structural unit called *Eisenhut sequence*. The Nock sequence is composed of greenschists, phyllites and carbonates which are intensively deformed and sheared. At least four deformations can be recognized (MULFINGER, 1986). The metamorphism reaches the middle greenschist facies. The Nock sequence crops out only along the northwestern border of the Gurktal nappe in a sickle-shaped form and disappears rapidly to the NE and SW. The whole structure is interpreted as an anticlinal stack of tectonic slices with the oldest rocks (Nock series) in the center and the youngest rocks (quartz phyllites) on both sides (Fig. 1).

A schematic stratigraphic section is given in Fig. 2. The lack of specific stratigraphic horizons makes it difficult to present a detailed vertical column. The base is formed by greenschists which dominate over phyllites and quartz-feldspat-schists. This rock assemblage is called *Nock series* and is overlain by a series of phyllites with minor intercalations of quartzites, greenschists and carbonates which is called *Rosental series*. In general the contact between the two series is tectonic, but petrographical and geochemical similarities of the metavolcanics strongly support a direct relationship of these series. Towards the top the Rosental series grades into quartz phyllites which solely include some massive iron-dolomites and magnesites.

Up to now, only three iron-dolomites could be dated by conodonts as Upper Ordovician (NEUBAUER and PISTOTNIK, 1984). All these iron-dolomites are found nearly in the same stratigraphic position in direct contact to greenschists of the upper part of the Rosental series (Fig. 2). Therefore, the volcanism of the Nock series and Rosental series is regarded to be at least of Upper Ordovician age. Quartz phyllites associated with massive carbonates are younger and probably represent Silurian and Devonian strata.

A more detailed stratigraphic section can be given for the *Eisenhut sequence*. This unit is less metamorphosed and less deformed. Metamorphism only reaches the upper anchizone. Two main deformations are responsible for small to large scale structures which result in normal and overturned lying rock sequences. The stratigraphic section starts with black phyllites which are overlain by a first volcanic stage, the *Kaser series*. The series is composed of pillow basalts and intrusives. The maximum thickness of 300 m decreases rapidly to the sides and the volcanics interfere with fine clastic, distal turbidites. The *clastic series* comprises phyllites, greywackes and minor intercalations of sandstones, black cherts, dolomites and tuffites. The top of the sequence is intruded by sills which announce a second stage of volcanism which is called *Eisenhutschiefer series*. This volcanism is dominated by pyroclastic rocks. Pillow basalts and intrusives become of secondary importance.

The hanging wall is represented by a shale sequence with interstratified massive Upper Silurian to Lower Devonian iron-dolomites. A locally occuring rhyolite tuff is closely associated with the iron-dolomites. The stratigraphic position is considered to be the Silurian / Devonian boundary.

From this the age of the Eisenhutschiefer series can be deduced as Lower to Middle Silurian. One black dolomite which yielded conodonts of Llandovery / Wenlock age (NEUBAUER and PISTOTNIK, 1984) is found close to an intrusive sill in the subjacent beds of the Eisenhutschiefer series.

The stratigraphic position of the clastic series and the Kaser series is unknown.

Massive, SW-NE striking calc-alkaline dikes which are up to 20 m thick, cut through all Lower Paleozoic units. These dikes are nearly undeformed. Chemical similarities to other dikes of the Western and Eastern Alps suggest a Tertiary age. They will not be described in this paper.

In order to examine the Lower Paleozoic volcanic evolution, the geology, petrography, mineral chemistry and geochemistry of the four different volcanic series are described and compared with each other in the following section.

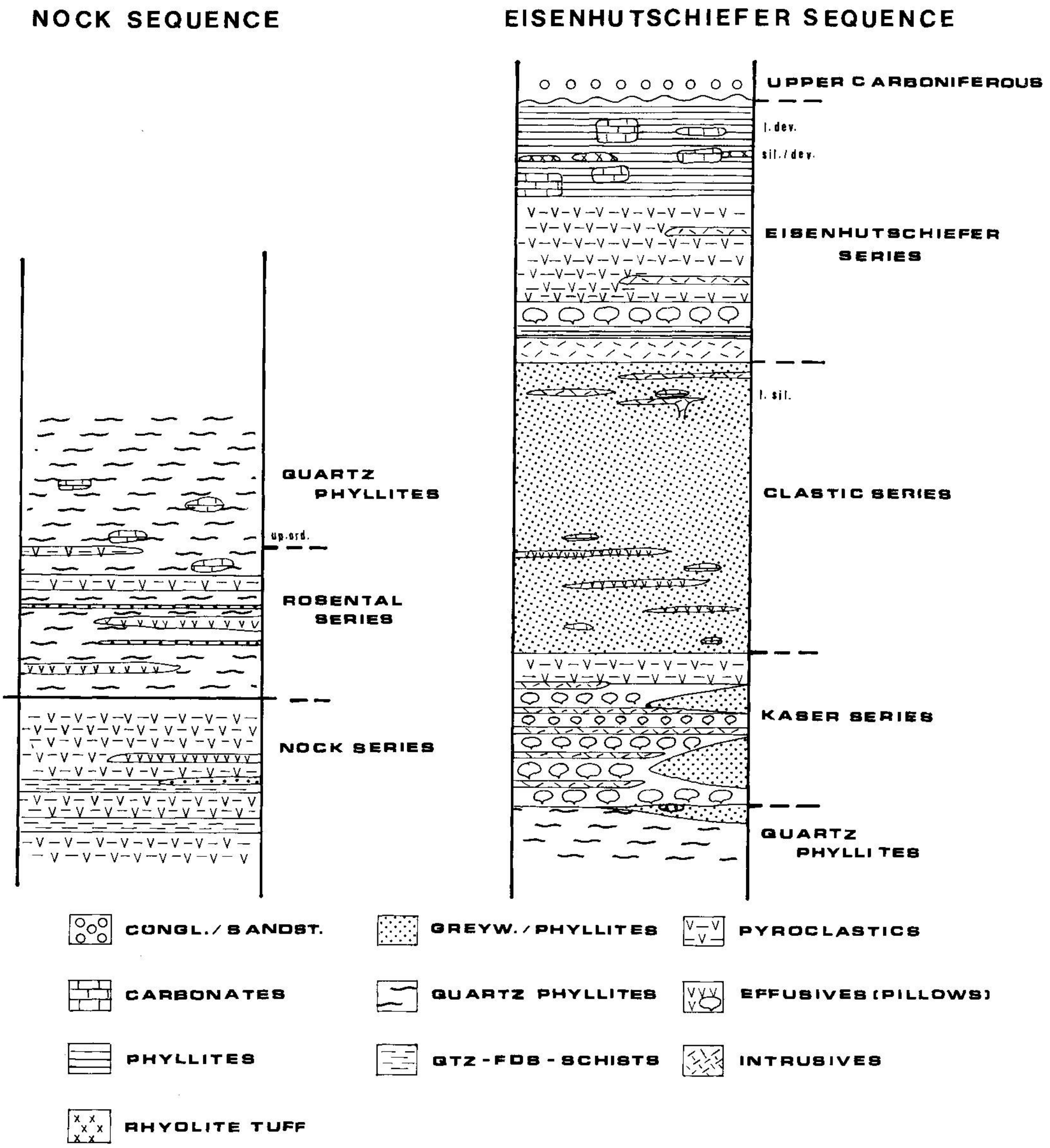


Fig. 2 Simplified stratigraphic sections of the Nock sequence and the Eisenhutschiefer sequence (no scale).

All the volcanic rocks have undergone secondary alterations which have changed their primary chemical composition. Therefore, the interpretation is based on elements which have remained nearly immobile. A general check of the mobility of elements of each volcanic series has been done by GIESE (1988), and is not reported here.

About 200 mineral analyses were performed with an ARL electron microprobe. 110 chemical analyses of major and trace elements have been carried out by X-ray fluorescene analyses. Detection limits and analytical errors of the most important trace elements are (in ppm): Sr (8/4), Rb (9/5), Ba (48/24), Nb (7/4), Zr (29/15), V (9/4), Y (10/3), Cr (48/25) and Ni (36/19). Numerical results do not appear in this paper, but are available upon request. Average compositions are given in Tables 1, 2 and 3.

Nock sequence

GEOLOGY-PETROGRAPHY

The Nock series is composed predominantly of greenschists, quartz-feldspar-schists and phyllites. Quartzites, white marbles and dolomites are sometimes intercalated.

The Rosental series is dominated by phyllites with minor intercalations of greenschists, various carbonates and two quartzite horizons (Fig. 2).

Greenschists are often laminated. The layers are mm to 1 cm thick and have compositions of chlorite-epidote, chlorite-actinolite-epidote and quartz-albite-epidote. In these layers phenocrysts of plagioclase and amphibole occur. The lamination is regarded as a primary texture and refers to different tuff or tuffite layers. Massive, partly porphyritic rocks which represent effusives are rare. Therefore, most of the greenschists of the Nock series are pyroclastic in origin. Sometimes the amount of plagioclase phenocrysts exceeds 50%, so that these rocks are crystal tuffs. Greenschists of the Rosental series are dominated by fine-grained ash-tuffs.

Leucocratic rocks rich in feldspar are associated with the greenschists and phyllites. They are mainly composed of quartz, albite and white mica. They always possess a distinct amount of plagioclase (oligoclase-andesine). It is possible that these rocks represent intermediate volcanics in part, but on the whole petrographic features (mica-, heavy-mineral content) favour a sedimentary origin.

Relics of primary constituents are plagioclase and amphibole. Albitised plagioclases reach sizes up to 4 mm. The crystals show complex twinning and zoning. They are strongly altered and deformed, but not recrystallised. Relics of amphibole phenocrysts are extremely rare. Greenish-brown hornblendes are rimmed by actinolite. No relics of pyroxene have been found.

MINERAL CHEMISTRY

Primary amphiboles have been studied in one sample. Average compositions are given in Tab. 1.

The chemical composition corresponds to an edenitic hornblende (Fig. 3, DEER et al., 1963, LEAKE, 1978), although the Fe_2O_3 content has not been determined. The hornblende is calcic in compositions (Ca › 1.50) and shows high contents of Al^4 (1.5.-1.7), alkalies (Na+K = 0.6) and SiO_2 (Si = 6.3-6.7).

After JAKES and WHITE (1972) and GILL (1981) amphiboles from andesites of active continental margins differ from andesites of island arcs. In comparison with these investigations the amphibole of the Nock series corresponds to amphiboles of high-K calc-alkaline suites of continental margins.

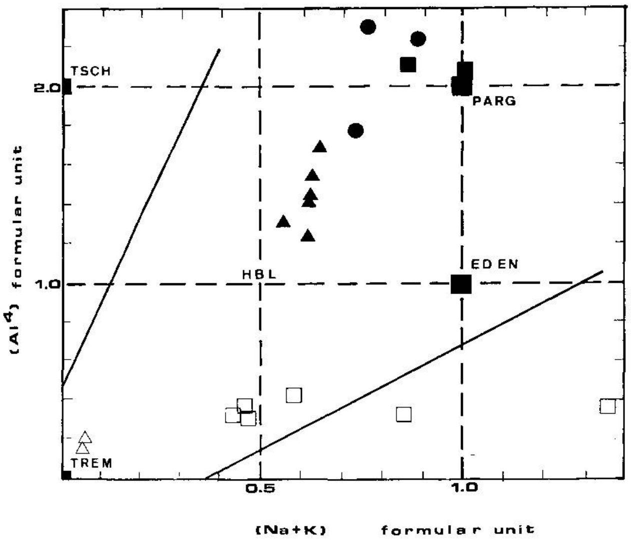


Fig. 3 Al^4-Na+K-diagram (after DEER et al., 1963) for the classification of calcium-rich amphiboles.

▲ - hornblende of the Nock series
△ - actinolite of the Nock series
● - kaersutite of the Kaser series
■ - titanium-rich pargasitic hornblende of the Eisenhutschiefer series
□ - edenetic hornblende of the Eisenhutschiefer series

GEOCHEMISTRY

33 samples of the Nock sequence (28 samples of greenschists and 5 samples of quartz-feldspar-schists) have been analysed. Average compositions are given in Tab. 2.

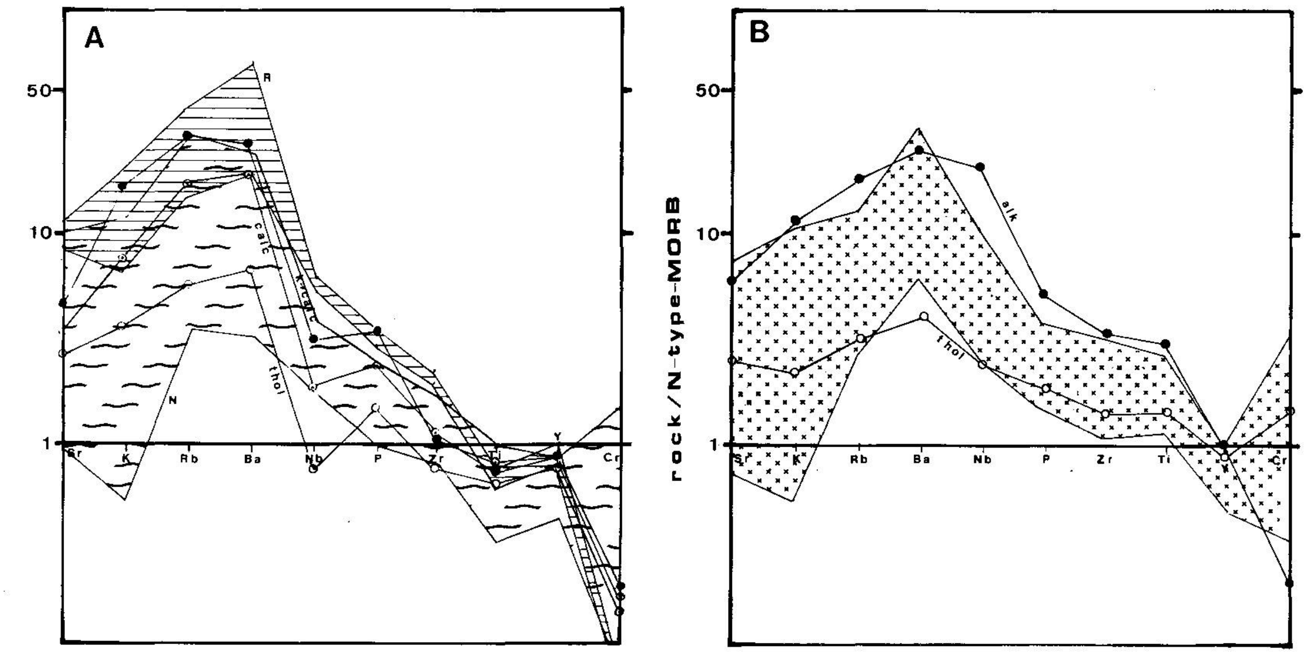
The whole rock chemistry has suffered severe alterations and no chemical trends of major elements can be observed. Ratios of various immobile trace elements show consistent variations and might represent primary values (GIESE, 1988).

In general the SiO_2 content ranges between 46% and 57%. The average amounts to 54%.

According to most systems of classification they could be refered to as basalts, basaltic andesites and andesites. This is in agreement with trace element classifications (WINCHESTER and FLOYD, 1976). The major element chemistry is characterised by relative high $Al_2 O_3$ contents (14%-18%) and low TiO_2 (< 1.36%) and $P_2 O_5$ (< 0.43) contents. The FeO_{tot}/MgO ratio averages up to 2 and shows constant values with increasing SiO_2 and Zr contents. Therefore, no iron enrichment trend can be observed in the AFM-diagram.

While major element chemistry clearly indicates a calc-alkaline affinity, trace elements show a more complex pattern. In general the volcanics can be classified as non-alkalic (Fig. 7). The Nb/Y ratio varies between 0.3 and 1 which shows a tendency to transitional compositions. The Ti/V ratio ranges between 10 and 30. After SHERVAIS (1982) calc-alkaline basalts can be distinguished from other basalts by their low Ti/V ration (10–20).

MORB-normalised distribution patterns of the basic rocks of the Nock sequence are shown in Fig. 4. Two groups can be distinguished. The first group which corresponds to the average greenschist of the Nock series shows depletion in Zr, Ti and Y and enrichment of the LIL ele-



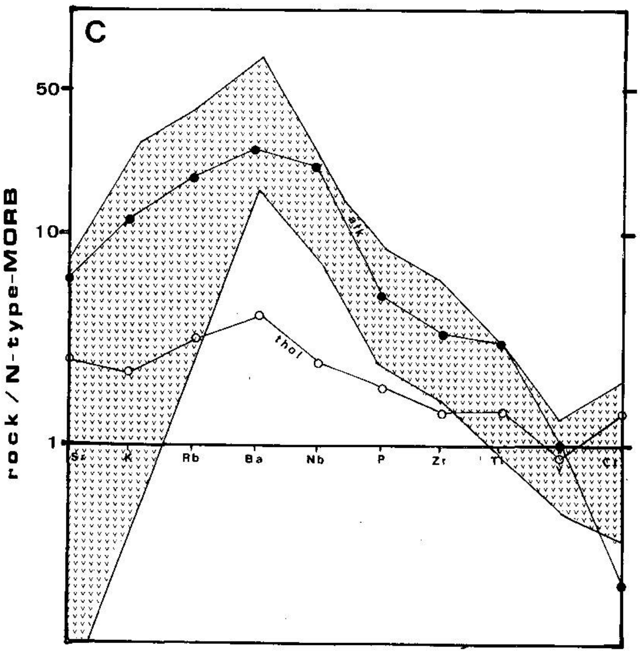


Fig. 4 MORB-normalised element distribution patterns after PEARCE (1983).

A. Basalts of the Nock series and the Rosental series in comparision with average compositions of tholeiitic, calc-alkaline and high-K calc-alkaline basalts from Java and Bali (WHITFORD et al., 1979).

B. Basalts of the Kaser series in comparison with a tholeiite and an alkalibasalt from Hawaii (PEARCE, 1983).

C. Basalts of the Eisenhutschiefer series in comparison with a tholeiite and an alkalibasalt from Hawaii (PEARCE, 1983).

ments, Nb and P. Therefore, these rocks show a subduction related component as well as a within-plate component (PEARCE, 1983). The second group which dominates in the Rosental series shows enrichment of all trace elements with the exception of Ti and Y. In comparison with published calc-alkaline basalts the volcanics of the Nock sequence are similar to high-K calc-alkaline series of continental margins or continental island arcs. The greenschists of the Rosental series show a transition to more enriched, alkalic compositions.

The geotectonic position can be determined by various discrimination diagrams. In all conventional diagrams the Nock volcanics plot in the volcanic arc field (Fig. 8) Very often this is the result of the low Ti content. According to PEARCE (1983) the Zr/Y–Zr diagram (PEARCE and NORRY, 1979) can be used to distinguish between oceanic and continental volcanic arcs. In this diagram the position of the greenschists of the Nock sequence can be compared with continental island arcs like those of New Guinea or Indonesia (PEARCE, 1983).

In conclusion, the volcanics of the Nock series represent basalts, basaltic andesites and andesites of calc-alkaline composition. Trace element abundances show enrichment of LIL elements and Nb excluding an oceanic environment. The data are compatible with a continental volcanic arc. The ash-tuffs of the Rosental series show higher trace element abundances and marks a transition to alkalic compositions.

Kaser series

GEOLOGY - PETROGRAPHY

The volcanics of the Kaser series consist mainly of pillow basalts and intrusive sills. In massive horizons of metabasalts pillow structures (up to 1 m in size) are still recognizable. The intrusives form up to 10 m thick sills, while discordant dikes are rare. Towards the top of the volcanic pile the content of pyroclastics increases. Here, more evolved rocks of intermediate composition are locally found. Sometimes small lenses of dolomite are randomly interstratified in the volcanics.

Pillow basalts and intrusives show the same mineralogy. They are intensely spilitised, so that the constituents of the primary composition have only survived as relics of pyroxene, plagioclase and amphibole. In the basic rocks of the Kaser series pyroxenes are always present. Two types of pyroxenes can be distinguished under the microscope. The first is a rounded, colourless to brownish clinopyroxene which reaches sizes of up to 2 cm. Twinning is frequent, but no zoning has been observed. Corroded cores are found in which amphibole has sometimes grown. Inclusions are round serpentine- and tremolite pseudomorphs after olivine and reddish, titanium-rich amphiboles. In contrast, the second type is a pink to brown-coloured clinopyroxene with euhedral, strongly zoned crystals. These pyroxenes are only found in thin intrusive veins.

MINERAL CHEMISTRY

Pyroxenes and amphiboles have been studied in four samples. In each sample 1 to 10 crystals and up to 6 spots in cross-sections of single pyroxenes have been analysed. Average compositions are given in Tab. 1 and 3.

The typical pyroxene is a Cr-rich augite which is characterised by low TiO_2- (<1%), Na_2O- (<0.3%) and Al_2O_3- (<3%) contents and high Cr_2O_3- (>0.6%) and SiO_2- (>52%) contents. In the MgO - CaO - FeO+MnO diagram (POLDERVAART and HESS, 1951) the analyses plot mainly in the augite field close to the boundary line of the endiopside field (Fig. 5). The pyroxenes are very homogeneous. Even single crystals show little variations from core to the rim. In contrast, the euhedral zoned pyroxenes can be classified as Ti-diopsides. They show high contents of TiO_2 (>1.5%), Al_2O_3 (>6%) and Na_2O (>0.3%). In the diagram (Fig. 5) they differ clearly from the Cr-augites and plot in the fields of diopsides and salites. Zoned crystals show a very complex chemistry which can not be easily explained (normal and reversed zoning). They probably derived from a new pulse of primitive magma which rose rapidly from the mantle and crystallised in several stages on their way up to the surface (GIESE, 1988).

The pyroxenes of the Kaser series show both, tholeiitic and alkalic affinities which can be best explained by a transitional primary magma which can yield very different pyroxene compositions by small variations during the differentiation and crystallisation process (BARBERI et al., 1971).

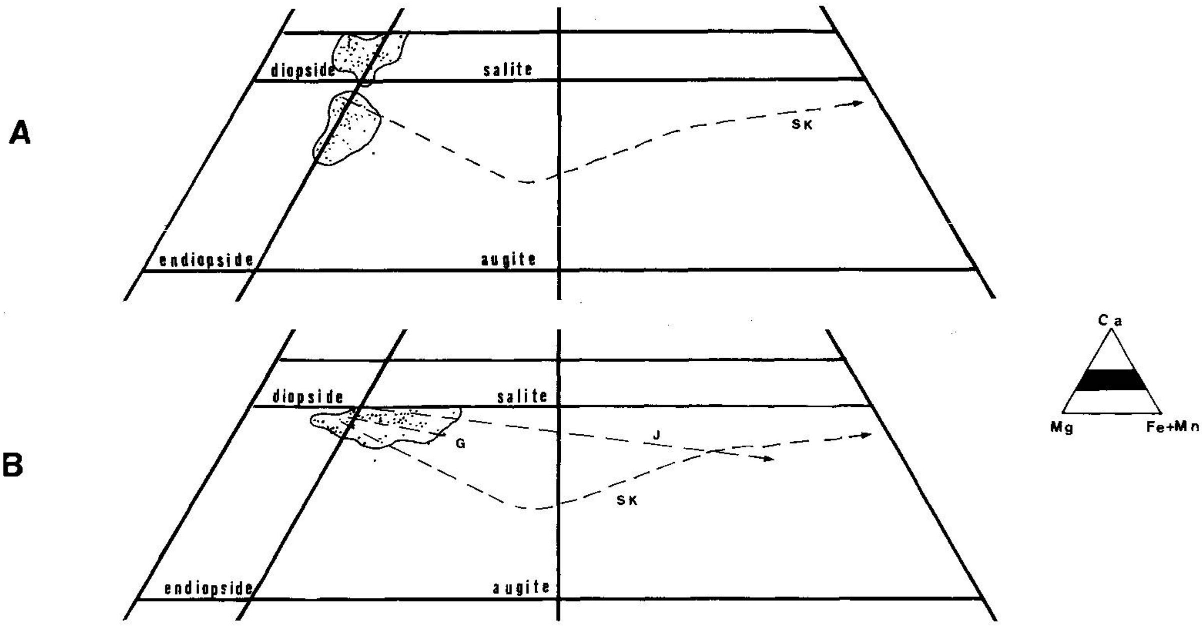


Fig. 5 Mg-Ca-Fe+Mn-diagram (after POLDERVAART and HESS, 1951) for the classification of pyroxenes. A. Kaser series B. Eisenhutschiefer series
The compositions are compared with crystallisation trends of the tholeiitic Skaergaard intrusion (Sk), the alkaline series of Gough Island (G) and the alkalibasalt-trachyte series of Japan (J), (after BARBERI et al., 1971).

Tab. 1 Amphibol Compositions

	A (n=6)	B (n=2)	C (n=3)	D (n=6)	E (n=2)
SiO_2 (wt.%)	44.53	53.47	40.50	50.20	41.41
TiO_2	1.72	0.02	5.36	0.90	3.54
Al_2O_3	10.87	1.17	13.76	2.10	15.06
FeO*	14.59	14.83	12.98	7.64	6.97
MnO	0.27	0.25	0.12	0.33	0.10
MgO	13.97	16.37	12.53	20.74	16.35
CaO	10.87	11.92	11.49	13.66	12.36
Na_2O	1.96	0.17	2.38	2.11	2.91
K_2O	0.33	0.08	0.48	0.46	0.79
Sum	99.11	98.28	99.60	98.14	99.50
cation concentration on the basis of 23 oxygens					
Si	6.55	7.73	5.90	7.50	5.91
Al^4	1.45	.20	2.10	.37	2.09
Al^6	.29	-	.26	-	.44
Ti	.19	-	.59	.10	.39
Fe^{2+}	1.80	1.79	1.58	2.59	.82
Mg	3.06	3.53	2.72	3.04	3.40
Mn	.03	.02	.02	.04	.03
Ca	1.71	1.85	1.79	1.22	1.77
Na	.56	.05	.67	.61	.84
K	.06	.02	.09	.09	.16

n = number of analyses, FeO* = total iron as Fe^{2+}

A - hornblende of the Nock series
B - actinolite of the Nock series
C - kaersutite of the Kaser series
D - edenitic hornblende of the Eisenhutschiefer series
E - titanium-rich pargasitic hornblende of the Eisenhutschiefer series

Tab. 2 Average compositions of basic volcanic rocks of the different volcanic stages

wt.%	A n=19	B n=5	C n=13	D n=15	E n=17	F n=4
SiO_2	53.71	54.12	51.51	47.16	49.52	78.31
TiO_2	0.93	0.90	2.84	3.18	2.80	0.17
Al_2O_3	16.24	18.82	14.97	15.13	14.72	12.88
Fe_2O_3	5.95	4.79	2.62	3.74	2.99	0.34
FeO	5.06	4.56	8.51	7.96	7.73	0.82
MnO	0.18	0.17	0.16	0.16	0.16	0.03
MgO	5.18	4.00	7.80	6.10	5.87	0.68
CaO	8.02	6.98	7.26	5.20	4.87	0.83
Na_2O	4.15	3.62	3.48	3.58	4.06	2.63
K_2O	0.35	1.67	0.65	1.06	1.85	2.68
P_2O_5	0.24	0.38	0.36	0.62	0.63	0.04
Cr ppm	138	-	273	144	134	-
Ni	49	-	143	70	92	-
V	269	88	221	180	196	17
Rb	22	48	12	14	34	85
Sr	444	957	447	260	466	32
Ba	203	646	295	378	432	372
Y	19	23	23	25	28	29
Nb	10	18	21	48	50	18
Zr	109	179	209	292	348	85
Zr/TiO_2	0.009-0.03		0.006-0.009	0.006-0.08		
Ti/Y	150-350		600-800	350-1100		
Nb/Y	0.3-1.0		0.6-1.0	1.0-2.5		
Zr/Nb	8-15		8.5-12	4-9		
Zr/Y	4-11.5		7.0-10	8.5-16		

n = number of analyses, analyses are recalculated to 100%

A - average composition of basic volcanics (basalts and basaltic andesites) of the Nock series.
B - average composition of basic ash-tuffs and basalts of the Rosental series
C - average composition of basic volcanics (tholeiites, alkalibasalts and hawaiites) of the Kaser series
Element ratios are for A + B, C and D + E.
D - average composition of basic effusives (alkalibasalts and hawaiites) of the Eisenhutschiefer series
E - average composition of basic intrusives (hawaiites and mugearites) of the Eisenhutschiefer series
F - average composition of the rhyolite-tuff

GEOCHEMISTRY

16 samples of volcanics and intrusives have been analysed. Average compositions are given in Tab. 2.

The analyses can be best compared with enriched tholeiites, alkalibasalts and hawaiites. High MgO- (>8%), Cr and Ni contents indicate compositions which are close to primitive magmas (WASS, 1980, PEARCE, 1983). Evolved hawaiites reach total iron contents of over 14% and refer to a more pronounced tholeiitic iron enrichment trend. These rocks are very similar to ferrobasalts of the Gregory rift in Kenya (BAKER et al., 1977).

The distinction in tholeiitic and alkalic basalts always fails. In applying the different discrimination criteria (MACDONALD and KATSURA, 1964, IRVING and BARRAGAR, 1971, FLOYD and WINCHESTER, 1975, PEARCE, 1983) the rocks of the Kaser series always plot in between and indicate a transitional volcanic

Tab. 3 Clinopyroxene Compositions

	A (n=49)	B (n=37)	C (n=18)	D (n=56)
SiO_2 (wt%)	52.39	49.03	52.78	50.58
TiO_2	0.87	1.88	0.97	1.59
Al_2O3	2.61	6.69	2.89	3.15
FeO*	6.40	5.12	5.54	8.06
MnO	0.11	0.08	0.10	0.14
MgO	16.55	14.11	16.36	14.25
CaO	19.01	21.60	20.35	20.50
Na_2O	0.29	0.39	0.26	0.42
K_2O	0.03	0.05	0.04	0.04
Cr_2O_3	0.88	0.33	0.62	0.16
Sum	99.09	99.26	99.91	98.89
cation concentration on the basis of 6 oxygens				
Si	1.94	1.81	1.93	1.87
Al^4	.06	.19	.07	.13
Al^6	.06	.10	.06	.01
Ti	.02	.05	.03	.04
Cr	.03	.01	.02	.01
Fe^{2+}	.20	.16	.18	.26
Mg	.91	.78	.89	.80
Mn	.00	.00	.00	.01
Ca	.75	.86	.80	.79
Na	.02	.03	.02	.03
K	.00	.00	.00	.00
SUM	3.99	3.99	4.00	3.95

n = number of analyses, FeO* = total iron as Fe^{2+}

A - Cr-augite of intrusive sills of the Kaser series
B - Ti-diopside of intrusive dikes of the Kaser series
C - augite of basic effusives of the Eisenhutschiefer series
D - Ti-augite of basic intrusives of the Eisenhutschiefer series

series. Trace elements are shown in MORB-normalized distribution patterns (Fig. 4) and demonstrate an intermediate position between a tholeiitic and an alkalic basalt from Hawaii.

In conclusion, geochemistry and mineral chemistry show that the submarine volcanics of the Kaser series present a transitional basalt-hawaiite suite which is intermediate between the composition of intraplate tholeiites and intraplate alkalibasalts. Transitional series have been predominantly described from extensional areas and rift systems (BARBERI et al., 1975, FITTON and HUGHES, 1977, BAKER et al., 1977, etc.).

Eisenhutschiefer series

GEOLOGY - PETROGRAPHY

The volcanics of the Eisenhutschiefer series consists predominantly of pyroclastic rocks which usually make up more than 50% of the whole volcanic sequence. Vesicular pillow basalts and intrusives generally form the basal part of the sequence, while the pyroclastics dominate towards the top. Small dikes and stocks of intermediate composition cut across the volcanics. The volcanism was explosive and erupted under shallow marine conditions.

A detailed description will be given by GIESE (in prep.). Only a brief summary is presented here.

In fresh, unaltered samples primary textures and primary mineral constituents have been preserved. Pillow basalts have aphyric, vesicular and porphyritic textures with phenocrysts of plagioclase and pyroxene. Intrusives show intersertal and intergranular textures and consist of pyroxene, plagioclase, amphibole and red- to brown-colored biotite.

Intrusives comprise brown- to pink-coloured, zoned Ti-augites. Inclusions of titanomagnetite and compositional zoning including sector-zoning are generally restricted to the rim. In contrast, pillow basalts contain colourless, anhedral and slightly zoned pyroxenes. Under the microscope two different amphiboles can be recognized in the intrusive rocks. A brown-colored, titanium-rich amphibole is found as inclusions in completely altered phenocrysts (olivine? pyroxene?). Small, olive-green amphiboles are restricted to the groundmass.

MINERAL CHEMISTRY

Pyroxenes and amphiboles have been studied in 6 samples (1 to 8 crystals per sample). Chemical cross-sections of single crystals consist of up to 18 spots. Average compositions are presented in Tab. 1 and 3.

The pyroxenes can be classified as endiopsides and augites. Crystals of intrusives and extrusives differ only by their degree of differentiation. Therefore, pyroxenes of pillowbasalts possess higher contents of MgO and Cr_2O_5, while intrusives show higher contents of TiO_2 and FeO (titanium-rich augites). In Fig. 5 the analyses are shown in the MgO – CaO – FeO+MnO diagram. Their CaO content ranges between 43% and 45%. They plot close to the salite field and constitute a parallel trend to the boundary line. Zoned crystals show the same trend. This trend has been observed in other mildly alkaline volcanic suites of oceanic islands or back arc regions (Japan) (BARBERI et al., 1971, GIBB, 1973).

The brown-coloured amphibole shows high contents of TiO_2 and Al_2O_3 and is classified after DEER et al. (1963) and LEAKE (1978) as a titanium-rich pargasite (Tab. 1, Fig. 3). The olive-green amphibole contains high contents of alkalies and plots between hornblende and tremolite in Fig. 3. After LEAKE (1978) it is a ferro-actinolitic hornblende and ferro-edenite.

Titanium- and alkali-rich amphiboles and biotites are typical for water-rich, alkalic magmas.

GEOCHEMISTRY

55 samples of the Eisenhutschiefer series have been analysed. Their chemical compositions are very consistent and clearly reveal an alkalic character. Pillow basalts classify mainly as alkalibasalts and hawaiites. Intrusives are more evolved and have compositions of hawaiites and mugearites. Intermediate rocks show strong enrichment of incompatible elements and are phonolitic trachytes. Average compositions of the basic rocks are given in Tab. 2. MORB-normalized distribution patterns of the Eisenhutschiefer series are in excellent accordance with an alkalibasalt from Hawaii (Fig. 4).

In conclusion, the Eisenhutschiefer series presents an alkalibasalt-hawaiite-mugearite-trachyte suite of within-plate character.

Rhyolite tuff

The rhyolite tuff is only locally found. Its maximum thickness reaches 20 m, but it is often less than 2 m thick. The tuff was probably reworked after deposition. Therefore, its significance is not quite clear, and it is only described here for reasons of completeness.

Quartz phenocrysts and rock-fragments are visible in the leucocratic rock. Under the microscope the volcanic origin is clearly shown by corroded quartz phenocrysts, and phenocrysts of plagioclase and chessboard albite. Zircon is partly magmatic and partly clastic in origin, while rock-fragments of phyllites, cherts and dolomites clearly prove a pyroclastic origin.

4 samples have been analysed and the average composition is given in Tab. 2.

Although, the samples have suffered from secondary alterations, the major element chemistry still shows their rhyolitic composition. Low contents of immobile and incompatible elements like Nb (16–19 ppm), Y (23–35 ppm) and Zr (76–99 ppm) rules out a peralkaline origin which would be typical of extensional areas. Instead, the contents of these elements can be compared with calcalkaline rhyolites of continental volcanic arcs (EWART, 1979, LOESCHKE, 1985, LEAT et al., 1986).

Discussion

Between the Middle/Upper Ordovician and the end of the Silurian the volcanic evolution at the NW-border of the Gurktal nappe is marked by a transition from calcalkaline to alkaline volcanism.

The Nock series shows both, subduction-related as well as within-plate geochemical patterns. The Kaser series and the Eisenhutschiefer series solely possess enriched within-plate patterns. The change is clearly demonstrated by their mineral- and whole-rock chemistry. Although, the major element chemistry has suffered severe alterations, even norm calculations (CIPW) still show a succession from qtz-normative volcanics (Nock series) over di-hy-normative volcanics (Kaser series) to di-hy-ol-normative volcanics (Eisenhutschiefer series, Fig. 6). This is associated with a general enrichment in incompatible elements (Fig. 4), a change from tholeiitic to alkalic (Fig. 7) and a decrease in the degree of partial melting (GIESE, 1988). The geotectonic position which can be deduced from conventional discrimination diagrams (PEARCE and CANN, 1973, MULLEN, 1983, PEARCE, 1983) shows a change from a continental volcanic arc to a marine, but not necessaryly oceanic within-plate setting (Fig. 8).

The lack of a detailed stratigraphy and a reliable paleogeography poses severe limitations on the interpretation of the volcanic succession. The paleogeographic relationship between the two stratigraphic sections, which are presented in this paper, is unclear. However, due to comparisons with other regions of the Gurktal nappe NEUBAUER and PISTOTNIK (1984), VON GOSEN et al. (1985) and NEUBAUER (pers. communications) put both sections into the Stolzalpen nappe, a partial unit of the Gurktal nappe.

Furthermore, the real space of time between the Nock series and the Eisenhutschiefer series is unknown. Instead of the assumed short period around the Ordovician/Silurian boundary, a much longer period of time is possible and could imply, that each volcanic stage could

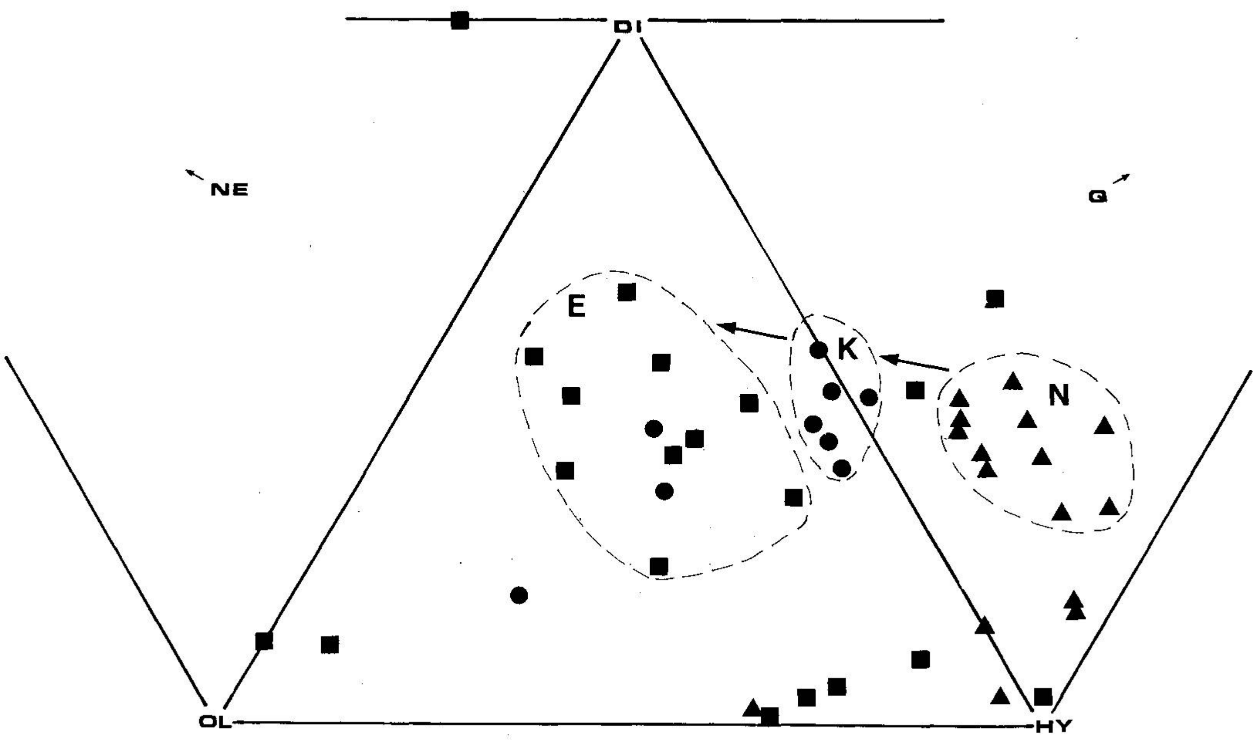


Fig. 6 Ne-Di-Qz-Ol-Hy-diagram. Presentation of CIPW norm calculations of basic volcanics. Samples with corundum content are not listed. Fe^{3+}/Fe^{2+} ratio is calculated after HUGHES (1976).
N - Nock sequence, K - Kaser series, E - Eisenhutschiefer series

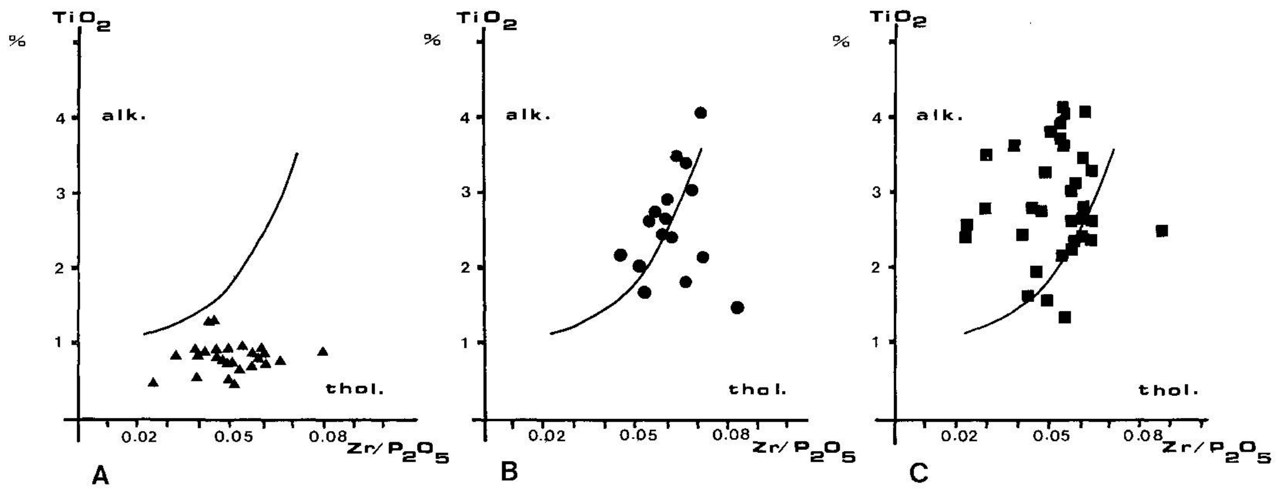


Fig. 7 TiO_2-Zr/P_2O_5-diagram after FLOYD and WINCHESTER (1975)
A - Nock sequence, B - Kaser series, C - Eisenhutschiefer series

have erupted in a very different geotectonic setting, so that they may not be related to one another. On the other hand, the described volcanic succession strongly suggests a connection. Anyway, these objections should be kept in mind.

Transitions between volcanic arc and within-plate basalts occur in well defined settings, notably in continental, extensional areas of back-arc regions above a subduction zone (PEARCE, 1983) or in regions marked by subduction cessation (GILL, 1981, 1982).

Back-arc regions of active continental margins are extensional areas which are characterized by block-faulting and subsiding basins. Basic volcanism shows a transition from high-K-calcalkaline or shoshonitic to alkaline compositions (NAKAMURA et al., 1985). Intermediate volcanics step back towards a more bimodal volcanism with subalkaline or sometimes peralkaline rhyolites (CHRISTIANSEN and LIPMAN, 1972, EWART, 1979, LEAT et al., 1986).

These features are readily compared with the volcanic evolution of the Gurktal nappe. In

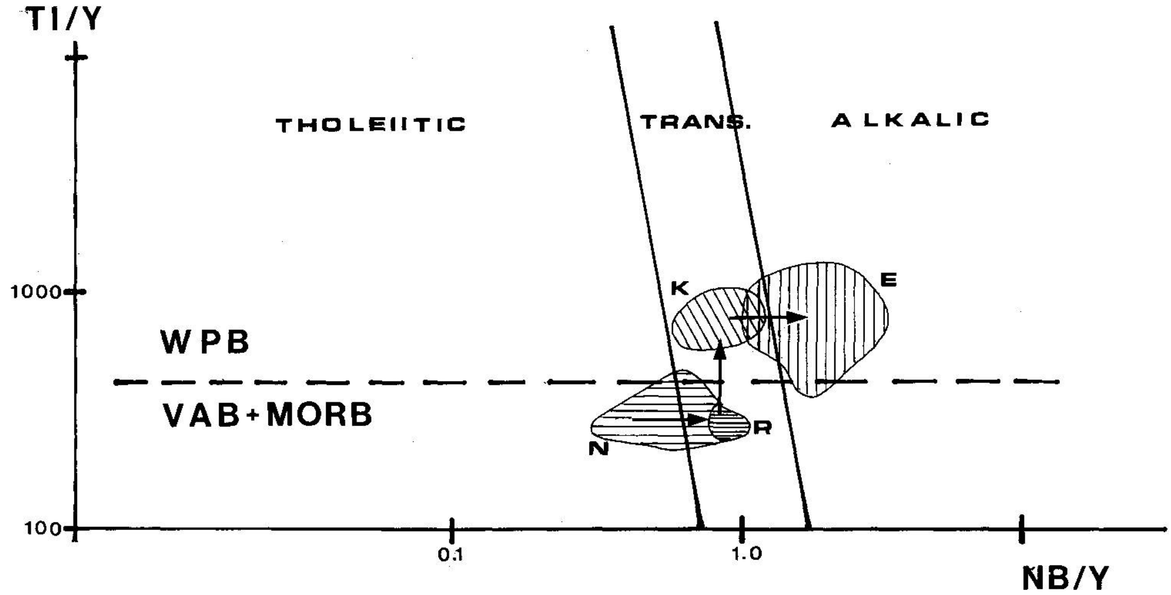


Fig. 8 Ti/Y-Nb/Y-diagram after PEARCE (1983)
N - Nock series, R - Rosental series, K - Kaser series, E - Eisenhutschiefer series

this model the Nock series and the rhyolite tuff represent the influence of a continous subduction process, while the Kaser series and the Eisenhutschiefer series represent the within-plate component. In comparison with other regions of the Upper Austroalpine, however, only a bimodal volcanism with voluminous rhyolitic ignimbrites (HEINISCH, 1981) and transitional or alkaline basalts (LOESCHKE, 1977, KOLMER, 1978, SCHLAEGEL, 1987) can be found during the Ordovician and the Silurian. Subduction-related volcanics have not been described at all. This makes the model of a back-arc region uncertain. Another point of controversy are the associated sediments. Back-arc basins are strongly influenced by volcanic debris. However, the clastic sedimentation of the Upper Austroalpine indicates a continental, cratonic provenance (HEINISCH et al., 1987, LOESCHKE and SCHNEPF, 1987). Modal and chemical analyses of greywackes of the clastic series in the investigated area are also comparable with a passive continental margin (GIESE, 1988). At least, this would place the position towards the continental side of a back-arc region.

If subduction related volcanism has occured in the Upper Austroalpine during the Lower Paleozoic, then it seems to be restricted to the Upper Ordovician (ignimbrites of the Greywacke zone, Nock series of the Gurktal nappe, granitoid intrusions). This could mean that subduction had ceased or the Upper Austroalpine was separated from a subduction zone since the beginning of the Silurian.

Subduction termination can be caused by several different plate tectonic processes. One possibility is a collision as discussed here. FRISCH et al. (1984) and NEUBAUER and FRISCH (1987) have proposed a Caledonian orogeny during the Middle Ordovician. They interprete the orogeny as an arc–continent or continent-continent collision.

Calc-alkaline volcanism can outlast collision before changing to alkaline compositions (GILL, 1981, 1982). Regional uplift and extensional tectonics are associated with the post-collisional stage. The volcanism which accompanies the collision is dominated by high-K andesites, dacites and rhyolites before it is succeeded by transitional or alkaline basalts. Subduction cessation is connected with an increase in incompatible element concentrations and a decrease in the degree of partial melting (GILL, 1981, CHRISTIANSEN and LIPMAN, 1972). This model could also explain the volcanic evolution at the NW-border of the Gurktal nappe.

Up to now stratigraphic and paleogeographic knowledge is to incomplete to offer more than a working hypothesis. A back-arc extensional area is favoured by the volcanic succession of the Nock series, the Kaser series and the Eisenhutschiefer series. From the investigated area it is not possible to decide whether the volcanism is situated above a subduction or belongs to a post-collisional stage.

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