Geologische Rundschau 79/1 | 85–97 | Stuttgart 1990

Mid-Cretaceous, primitive alkaline magmatism in the Northern Calcareous Alps: Significance for Austroalpine Geodynamics

By V. TROMMSDORFF, V. DIETRICH, Zürich, M. FLISCH, Bern, P. STILLE, Strasbourg and P. ULMER, Zürich*)

With 8 figures and 3 tables

Zusammenfassung

Basanitische Ganggesteine (Lokalbezeichnung Ehrwaldite) treten in einer schmalen, über fünfzig Kilometer langen, Ost-West verlaufenden Zone der Lechtal-Decke in den Nördlichen Kalkalpen auf. Die Ganggesteine durchschlagen mesozoische Sedimente bis zur Unterkreide, welche in unmittelbarer Umgebung der Gänge kontakt-metamorphisiert wurden. Die basanitischen Gesteine enthalten neben zum Teil noch frischem Olivin (fo 91–87) wechselnde Anteile von Titanaugit, Kaersutit, Titanbiotit und Zeolithen. Nebengemengteile sind Titanomagnetit, Picotit, Apatit, Ilmenit, Karbonat und Sulfide. Mantelxenolithe und Mantelxenokristalle können bis zu fünf Prozent des Gesteins ausmachen. Die Gesamtgesteinschemie der Ehrwaldite belegt deren Charakter als primitive Mantelschmelzen und ist typisch für Nephelinbasanite (ne = 11–17 Gew.%, mg-Zahl = 74–78). Alle Spurenelementgehalte der Ehrwaldite stimmen ausgezeichnet mit denjenigen von Basaniten und Olivinnepheliniten tertiärer und quartärer Vulkanprovinzen in Europa überein. Dasselbe gilt für die Isotopencharakteristik der Gänge (mittleres ϵ_{Nd} von + 4.7, mittleres ϵ_{Sr} von −8.2). Die Daten belegen ähnliche Mantelausgangsgesteine und Schmelzcharakteristika wie für andere europäische Alkaligesteine und damit Ähnlichkeiten des europäischen subkontinentalen Mantels an verschiedenen Orten für den Zeitraum der letzten 100 Millionen Jahre. Die Isotopendaten stehen im eindeutigen Gegensatz zur Isotopencharakteristik des penninischen subozeanischen Mantels. Geochemische Daten und laufende Piston Cylinder Experimente ergeben eine Ursprungstiefe der Ehrwaldite als Mantelteilschmelzen von > 80 km bei Temperaturen von mindestens 1250 °C. K-Ar Gesamtgesteinsalter der Ehrwaldite an petrographisch verschiedenen Proben aus verschiedenen Aufschlüssen ergeben sehr konsistente Alter von ca. 100 Millionen Jahren (oberes Alb). Nach ihrer Platznahme erlitten die Ehrwaldite Bedingungen der »Diagenesezone« mit Temperaturen um 120 °C, wobei die primär gebildeten Zeolithe überlebten.

Für die Entwicklung des Ostalpins westlich von Innsbruck bedeutet dies, daß zur Zeit des Magmenaufstiegs keine Subduktionszone unter den Nördlichen Kalkalpen bestand. Dieser Magmenaufstieg erfolgte in einem Gebiet mit Extension, als die Nördlichen Kalkalpen noch keinen Deckenbau aufwiesen und auf einem kontinentalen Sockel lagen, weit entfernt von einer penninischen Subduktionszone. Der Aufstieg der basanitischen Ehrwalditschmelzen könnte in einem Horst-Graben System erfolgt sein, welches möglicherweise Beziehungen zu transpressiver Tektonik aufwies.

Abstract

Basanitic dykes (local name: Ehrwaldite) occur over a distance of at least fifty kilometres in a narrow, east-west trending zone within the Lechtal nappe of the Northern Calcareous Alps. The dykes crosscut Mesozoic sedimentary strata up to the Lower Cretaceous. The sedimentary rocks show contact-metamorphism in the immediate vicinity of the dykes. The Ehrwaldites vary in mineral content from olivine (fo 91–87) — titanian augite basanites to basanites containing also kaersutite, titanian biotite and zeolites. Minor phases are titanian magnetite, picotite, ilmenite, carbonate and sulfides. Mantle derived xenoliths and xenocrysts form up to five percent of the rock. Bulk chemical analyses show the typical characteristics of nepheline basanites (ne = 11–17 wt%; mg-number = 74–78) and demonstrate that the Ehrwaldites are primitive mantle-derived melts. Trace element contents of the dykes are in excellent agreement with those for basanites and olivine-nephelinites from Tertiary and Quaternary European Provinces. The same is true for the isotope characteristics of the dykes with average initial ϵ_{Sr} and ϵ_{Nd} values of −8.2 and +4.7, respectively. These data demonstrate similarities in the mantle source rocks and in the melting characteristics with European alkaline rocks and thus similarities in the European subcontinental mantle at different localities for the last 100 Ma. These data are in clear contrast with the value for the penninic suboceanic mantle. Geochemical constraints and piston cylinder experiments indicate a depth of origin of > 80 kilometres at temperatures of at least 1250 °C for the Ehrwaldites. Potassium-argon bulk rock data of petrographically different samples of the dykes from different localities yield consistent ages around 100 Ma (Upper Albian). After emplacement, the Ehrwaldites underwent conditions of the »zone of diagenesis« with temperatures around 120 °C which the late magmatic zeolites survived.

*) Authors' addresses: V. TROMMSDORFF, V. DIETRICH, Swiss Federal Institute of Technology Zürich, Institute for Mineralogy and Petrography, CH-8092 Zürich, M. FLISCH, University Bern, Abt. Isotopengeologie, Erlachstrasse 9a, CH-3012 Bern, P. STILLE, C.N.R.S. (Sédimentologie et Géochimie) F-67084 Strasbourg and P. ULMER, Swiss Federal Institute of Technology Zürich, Institute for Mineralogy and Petrography, CH-8092 Zürich.

For the evolution of the Northern Calcareous Alps west of Innsbruck this means that there was no subduction zone beneath the Northern Calcareous Alps at the time of magma ascent. The dykes intruded in an extensional regime when the Northern Calcareous Alps had not yet suffered thrust faulting. The Northern Calcareous Alps were still part of a continental basement far away from a possible Penninic subduction zone. To account for the ascent of the basanitic Ehrwaldite melts, a horst-graben system is proposed, possibly related to transpressive tectonics.

Résumé

Des filons basanitiques (ehrwaldites) sont présent dans la nappe du Lechtal (Nördliche Kalkalpen) le long d'une étroite zone qui s'étend d'est en ouest sur plus de 50 Km. Ces filons traversent, jusqu'au Crétacé inférieur, les sédiments mésozoïques, qui sont légèrement métamorphisés à leur contact. Ces roches basanitiques contiennent, outre de l'olivine relativement fraîche (fo 91–87), de l'augite, de la biotite titanifère, de la kaersutite et des zéolites en quantités variables. Les minéraux accessoires identifiés sont la titano-magnétite, la picotite, l'apatite, l'ilménite, des carbonates et des sulfures. Des xénolithes et des xénocristaux provenant du manteau peuvent représenter jusqu'à 5% de la roche. La composition chimique des ehrwaldites, caractéristique de basanites à néphéline, montre qu'elles représentent un liquide primitif de fusion mantellique. Les teneurs en éléments en trace de ces roches correspondent parfaitement à ceux de basanites et de néphélinites à olivine que l'on trouve dans différentes provinces volcaniques européennes tertiaires et quaternaires. De telles analogies ont également été mises en évidence en ce qui concerne les caractéristiques isotopiques des filons qui montrent des valeurs initiales moyennes de $\varepsilon_{Sr} = -8.2$ et $\varepsilon_{Nd} = +4.7$. Ces données démontrent qu'entre les roches ici en question et les roches alcalines de diverses régions d'Europe, il existe une similitude quant aux roches parentales mantelliques et au processus de fusion et qu'il existe donc une similitude dans la nature du manteau subcontinental européen pendant les 100 derniers Ma. Ces données se distinguent nettement de celles qui caractérisent le manteau subocéanique du domaine pennique. Des données géochimiques complémentaires et des expérimentations de type cylindre/piston actuellement en cours indiquent pour les ehrwaldites une profondeur d'origine supérieure à 80 Km et des températures d'au moins 1250 °C. Les analyses géochronologiques K-Ar réalisées sur des échantillons provenant de différentes localités et de compositions pétrographiques diverses donnent des âges très comparables de 100 Ma. Après leur mise en place, les ehrwaldites ont subi des conditions typiques de la zone de diagenèse (T ~ 120 °C), dans lesquelles les zéolites primaires ont été préservées.

On peut déduire de ces résultats diverses conséquences sur le développement du domaine austroalpin à l'ouest d'Innsbruck: il n'existait pas de zône de subduction sous des Nördliche Kalkalpen pendant l'ascension des magmas; cette ascension a eu lieu au cours d'une phase d'extension, durant laquelle les Nördliche Kalkalpen n'avaient pas encore fait l'objet de phénomènes de charriage et participaient à un socle continental très éloigné de la zone de subduction pennique. L'ascension de ces ehrwaldites a pu avoir lieu le long d'un système en horst et graben, en relation avec une tectonique transformante.

Краткое содержание

Базанитские дайки – местное название их «эрвальдиты» (Ehrwaldite) найдены в узкой зоне покрова Лехталь северных известковых Альп длиной более 50 км и простирающиеся с востока на запад. Дайки пронизывают мезозойские седименты до нижнего мела, породы которого вокруг этих дайков претерпели контактный метаморфизм. Базанитские дайки содержат частично еще неизмененный оливин (fo 91–87) и различные количества титанавгита, каэрсутита, титанбиотита и цеолита. Второстепенными минералами здесь являются титаномагнетит, пикотит, апатит, ильменит, карбонаты и сульфиды. Ксенолиты и ксенокристаллы мантии могут составлять до 5% пород. Общий химизм эрвальдитов указывает на примитивный расплав мантии и является типичным для нефелинбазанитов (ne – 11–17 вес.-%, mg-zahl – 74–78 б). Содержание микроэлементов в эрвальдитах соответствует таковому базанитов и оливиннефелитов вулканических провинций Европы третичного и четвертичного периодов. То же можно сказать и о данных изотопного анализа пород этих дайков: Средний E_{Nd} +4,7 и средний E_{Sr} −8,2. Подобные данные, а также характеристики расплавов получили и для исходных пород мантии и для других европейских щелочных пород, и т.о. подтвердилось сходство европейской субконтинентальной мантии в различных регионах ее для отрезка времени в последние 100 миллионов лет. Важно, что эти данные не совпадают с изотопными характеристиками пеннинской субокеанической мантии. Геохимические данные и исследования с помощью поршневой грунтовой трубки указывают на исходную глубину эрвальдитов, как расплавленной части мантии, в более чем 80 км при температуре, по-крайней мере, в 1250°C. Общий возраст эрвальдитов, определенный с помощью калий-аргонового метода, на пробах различного петрологического состава, дает постоянную цифру в примерно 100 миллионов лет, т.е. верхний альб. После их интрузии эрвальдиты претерпели влияние диагенетических процессов с температурой в 120°C, причем первичные цеолиты остались неизмененными.

При образовании восточных Альп западней Иннсбрука это означает, что во время подъема магмы зоны субдукции под северными известковыми Альпами не существовало. Поднятие магмы имело место в регионе расширения, когда северные известковые Альпы еще не имели покрова и залегали на материковом цоколе далеко от пеннинской зоны субдукции. Поднятие базанитского расплава эрвальдитов могло иметь место в системе горст-грабен, которая, была связана с transpressiver Tektonik.

Introduction

Dykes of basanitic composition occur over a distance of at least 50 km in the Lechtal thrust sheet of the Upper Austroalpine sedimentary cover (Fig. 1). The great majority of the dykes occur in a narrow, east-

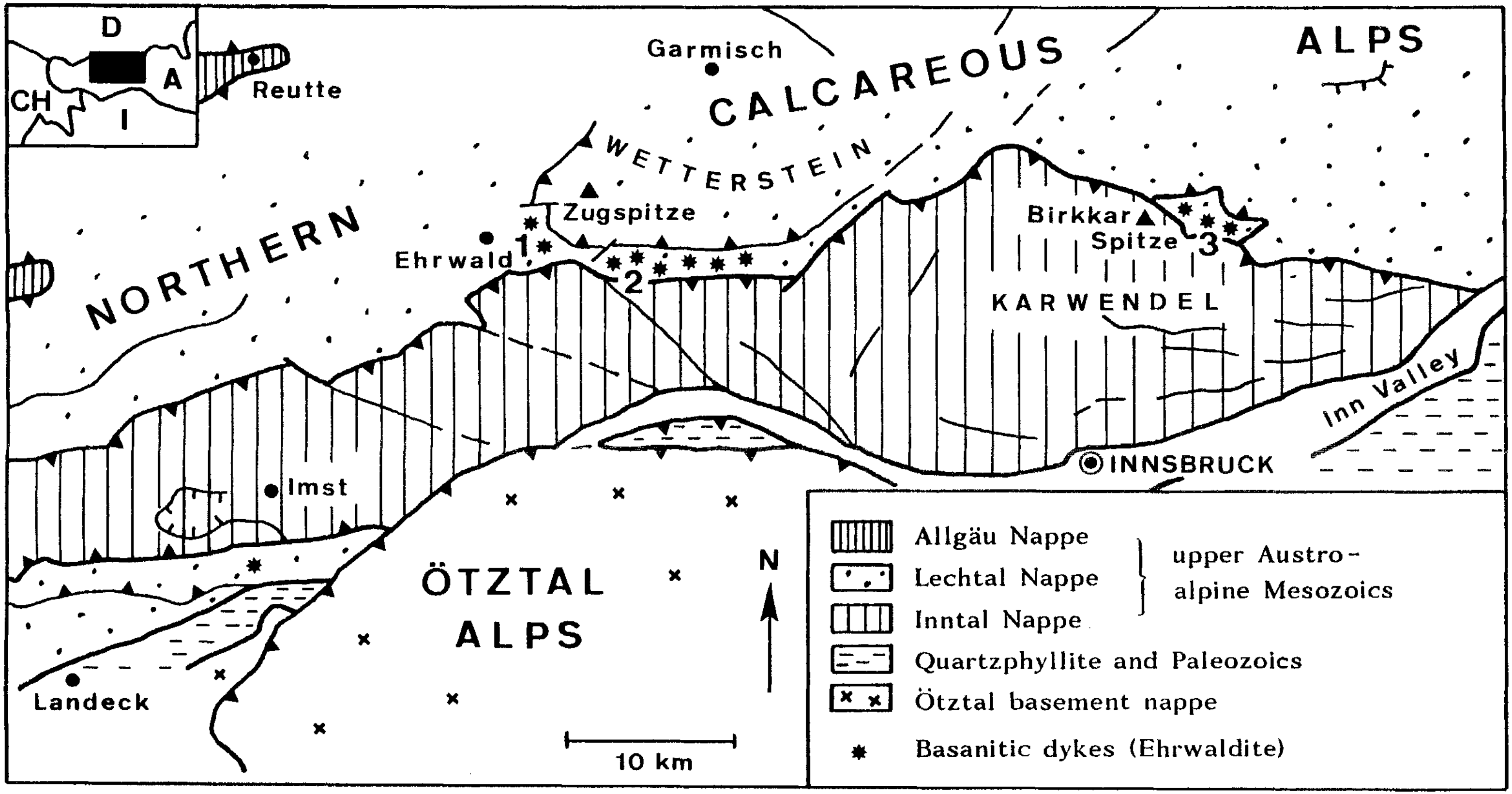

Fig. 1. Distribution of basanitic dykes (Ehrwaldites) in the Northern Calcareous Alps (Tectonics after BRANDNER, 1985 & EISBACHER, pers. comm.).

west tending zone within the Wetterstein- and Karwendel mountains (TROMMSDORFF, 1962). The dykes were first described in 1866 by ADOLF PICHLER from outcrops southwest of Zugspitze and named 1875 by the same author after the nearby village Ehrwald (see also TRÖGER, 1969).

Near Ehrwald the dyke widths are usually one to two meters. They are mainly concordant with but also discordant to the bedding of Upper Jurassic limestones and cherts. Narrow zones of contact metamorphism, mostly no more than a few centimeters but locally up to one meter wide are associated with the dykes.

Numerous additional occurrences of Ehrwaldite have been found since the times of Pichler. To date the westernmost occurrence has been reported by AMPFERER (1930) from Jurassic rocks near Imst in the southernmost Lechtal nappe. In the occurrences from the Karwendel mountains (Fig. 1), Ehrwaldite crosscuts Lower Triassic to Jurassic rocks. In the southern Wetterstein mountains, the dykes have contact-metamorphosed marls and siltstones of Early Cretaceous (Neocomian) age (TROMMSDORFF, 1962). From field relations, the maximum age of the dykes is therefore Mid-to Early Cretaceous.

In our investigations, we exclusively used samples from the Wetterstein since this is the freshest material found. In this area, the best exposures of Ehrwaldites occur and it is clear that the dykes underwent locally brittle deformation indicated by fractures and slickensides. The Ehrwaldites are, however, essentially unmetamorphosed. Illite crystallinities and coal rank in the surrounding sediments have values corresponding to the zone of diagenesis (KRALIK et al. 1987; KRUMM et al., 1988). As typical for many alkaline rocks, the amygdul bearing varieties of Ehrwaldites contain analcite, natrolite and heulandite. These minerals survived the diagenetic event as did apophyllite in the contact-zones. For mafic bulk compositions this would correspond to temperatures below laumontite stability (KISCH, 1987). From this, we estimate that after their emplacement, the dykes were not subjected to temperatures in excess of 130 °C. A comprehensive description of Ehrwaldite occurrences, their mineralogy, chemistry and contact phenomena may be found in TROMMSDORFF (1962). For the geology of the Wetterstein area we refer to MILLER (1962).

It is the purpose of this paper to present new data on the bulk and trace element chemistry of the dykes and of their isotopic composition and radiometric age. We then will discuss the origin of the Ehrwaldites on the basis of these data and in the light of modern geodynamic models for the evolution of the Austroalpine thrust sheets.

Petrography

The Ehrwaldite dykes are characterized by the presence of up to 30% fine grained, devitrified matrix which results in the usual difficulties applying a purely petrographic nomenclature to them. As shown by TROMMSDORFF (1962), the chemical composition of Ehrwaldites is nepheline normative and closely matches that of nepheline-basanites. The normative nepheline content however, does not appear in the mode. To avoid complications arising from a »pheno«-nomenclature we thus keep the name Ehrwaldite.

The most primitive rocks of the Ehrwaldite suite come from the Lehnbachgraben (locality 1, Fig. 1). They are relatively rich in xenocrysts and xenoliths with about 5–10% of phenocrysts. The hemicrystalline groundmass is dominated by augite prisms, olivine fo 91 (core) to 85 (rim) which is commonly serpentinized, but sometimes well preserved (Fig. 2), varying amounts of kaersutite and biotite which are not always present. Minor constituents that are always present are apatite and titanian magnetite. The devitrified part of the groundmass consists of micro- to crypto-crystalline radiating chlorite, interstitial analcime and less commonly natrolite. Phenocrysts are: titanian augite, sometimes radiating (Fig. 3), olivine, mostly serpentinized, and rarely kaersutite. Biotite forms local microphenocrysts. Xenoliths and xenocrysts are composed of clinopyroxene, olivine pseudomorphs and aluminous spinel and will be discussed in detail in a subsequent article. Other, more differentiated types of Ehrwaldite rocks come from the southern margin of the Wetterstein mountains (locality 1 in Fig. 1). They contain fewer pheno- and xenocrysts and are dominated by kaersutite, biotite or both.

Amygdul bearing varieties of Ehrwaldite occur quite commonly at locality 2 and less commonly at locality 1. The amygdules are filled with zeolites (natrolite, analcime, heulandite), calcite and chlorite. For a detailed discussion see TROMMSDORFF (1962).

Geochemistry

Bulk chemical data of Ehrwaldite from Lehnbachgraben (locality 1 on Fig. 1) are, with the exception of sample EJ 10, fairly uniform (Table 1, see also TROMMSDORFF, 1962, p. 317, No. 1 and 2). Samples were used for the analyses which macroscopically do show neither alteration nor veins and microscopically still contain fresh olivine. Contents of clinopyroxene xenocrysts in the analyzed rocks are less than 5%. Sample EJ 10 is an amygdul bearing variety, whereas all the other rocks from table

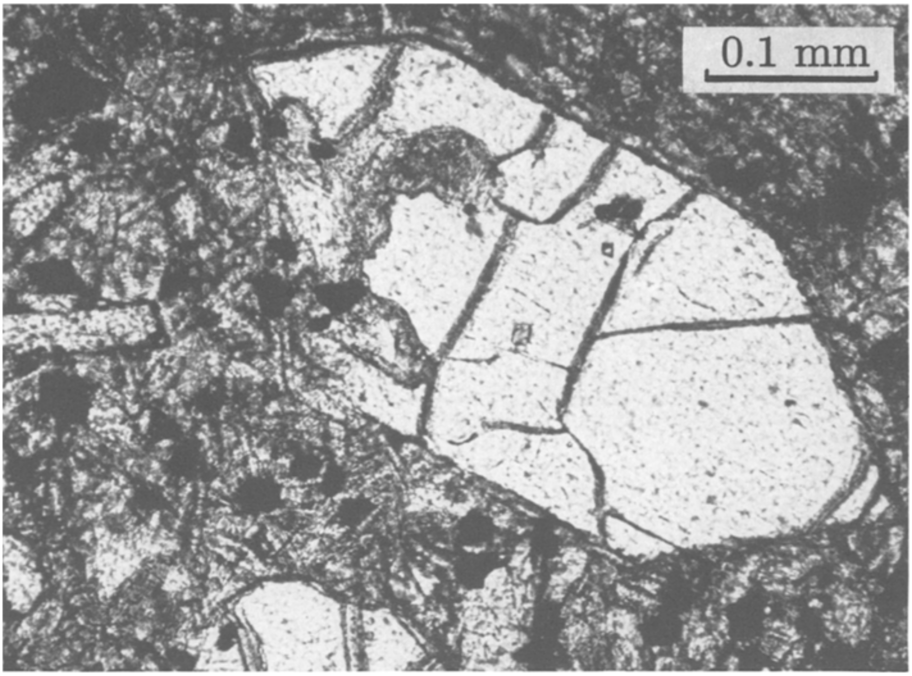

Fig. 2. Idiomorphic olivine phenocryst (fo 91–87) in a fine grained matrix of clinopyroxene and magnetite (dyke No. 88–32, Lehnbachgraben). Plane polarized light.

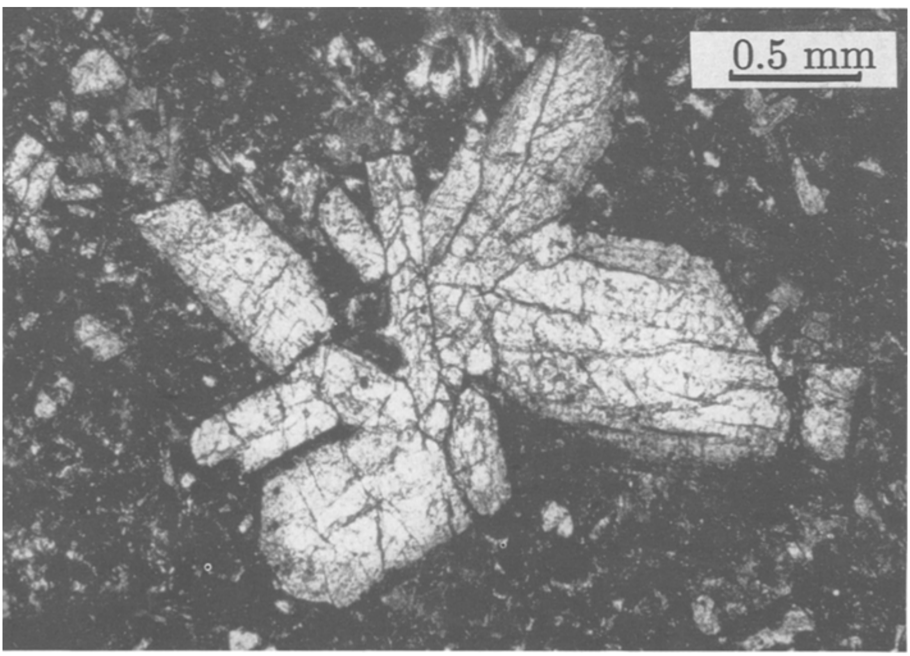

Fig. 3. Clinopyroxene phenocrysts, radiating in a matrix of clinopyroxene, magnetite, alkalifeldspar, biotite, zeolite and clorite (dyke No. 145, Wetterstein S-rim). Plane polarized light.

Sample no	EJ 6	EJ 3	EJ 7	EJ 5	2/31	EJ 14	EJ X	EJ 10
Major elements [Wt.-%]								
SiO2	38.20	39.25	38.51	39.64	39.52	39.82	39.29	40.75
TiO2	3.19	3.20	3.09	3.07	2.93	3.07	3.13	3.58
Al2O3	11.14	11.90	11.84	12.27	11.62	12.14	12.13	13.90
Fe2O3	5.07	3.49	5.09	5.38	4.49	5.33	5.28	5.80
FeO	6.25	7.77	6.00	5.67	6.25	5.72	6.06	5.71
MnO	0.20	0.19	0.20	0.19	0.18	0.19	0.19	0.17
MgO	12.64	12.44	12.15	11.92	11.72	11.88	11.46	8.17
CaO	12.99	12.75	12.70	12.60	12.42	12.63	12.43	10.76
Na2O	1.70	2.30	2.20	2.70	2.35	2.40	2.70	3.80
K2O	0.98	0.93	0.89	0.85	0.81	0.98	0.84	1.32
P2O5	0.86	0.77	0.78	0.73	0.73	0.72	0.83	0.88
H2O+ calc.	5.59	4.29	5.28	4.01	5.19	4.46	4.68	4.03
CO2	0.33	0.27	0.25	0.20	0.26	0.27	0.19	0.16
Total	99.14	99.55	98.98	99.23	98.47	99.61	99.21	99.03
Trace elements [ppm]								
F	1351	1044	1145	853	852	1006	1038	1406
Ba	614	650	629	621	597	662	743	725
Rb	20	23	20	18	15	20	21	26
Sr	757	997	1041	849	890	775	900	871
Nb	79	89	81	88	76	86	91	105
La	60	64	57	57	51	59	64	86
Ce	111	123	117	122	111	112	128	136
Nd	59	52	51	52	50	53	62	66
Y	18	23	16	19	17	20	19	21
Zr	306	318	293	298	279	295	326	326
V	326	337	317	336	286	340	312	319
Cr	446	434	404	443	461	450	443	119
Ni	295	325	290	293	343	301	320	123
Co	82	95	82	75	88	78	81	68
Cu	67	56	45	52	45	47	55	36
Zn	104	102	86	91	86	90	90	104
Ga	17	17	15	16	14	16	16	17
Sc	16	19	15	17	14	19	14	13
S	1593	1429	1338	1692	900	877	778	882
La		70.7				66.5		79.1
Ce		118.				113.		137.
Sm		11.4				10.7		12.6
Eu		3.08				2.97		3.55
Tb		1.01				0.91		1.12
Yb		1.39				1.34		1.47
Lu		0.18				0.19		0.18
Hf		6.54				6.18		6.99
Th		6.72				6.93		8.52
U		2.7				4.3		3.5

Tab. 1. Major and trace element abundances form basanitic dikes (Lehnbachgraben). Analytical procedures and errors (X-ray fluorescence technique, and for rare earth elements, Hf, Th, U with instrumental neutron activation analysis) described in DIETRICH et al. (1984). FeO contents were determined colorimetrically; CO_2, based on coulometric alkalimetric titration (SIXTA, 1977), with a Coulomat CS701.

1 are amygdul-free. Their general characteristics are (wt%) SiO_2 = 38–40; MgO = 11.5–12.7; CaO = 12.5–13; Na_2O = 1.7–2.7; TiO_2 = 3.1; P_2O_5 = 0.8. H_2O and CO_2 contents are around 4–5 and 0.2–0.35 wt% respectively. All the samples are nepheline-normative, with ne = 11–17 wt% and Na_2O/K_2O (wt%) varying from 1.7 to 3.2. Normative olivine ranges from 13 to 17 wt% and the mg-number varies from 74 to 78. All these characteristics are typical for nepheline basanites (see EDGAR, 1987, p. 36). Sample EJ 10, although still a nepheline basanite, shows slightly higher SiO_2, higher TiO_2 and Na_2O values and distinctly lower MgO, CaO, NiO and Cr_2O_3 which may be explained by differentiation, see below.

All the trace element contents of the Ehrwaldites, including rare earth elements (REE), coincide well with the range displayed by basanites and olivine-nephelinites from Tertiary and Quaternary European provinces, as well as from other localities worldwide. Characteristic features of the Ehrwaldite dykes are:

their high Cr (400–450 ppm) and Ni (290–325 ppm) contents indicating their primitive character; high contents in volatile components or with respect to mantle mineralogy incompatible elements such as F (1000–1400 ppm), Ba (600–650 ppm), Sr (760–1050 ppm) and LREE; also high contents of Nb (79–88 ppm), V (312–340 ppm) and Zr (295–325 ppm). On the other hand, contents in elements compatible with mantle mineralogy are relatively low: Y (16–23 ppm) and HREE.

A general enrichment in all incompatible elements from Sr to Yb is evident in Fig. 4 (spider diagrams) which is normalized against the values for primitive mantle. An inversion of this pattern occurs at Sc which exactly matches the mantle value, whereas Cr already lies at .2 and for the more differentiated sample EJ 10 even at 0.04 for the mantle value. Positive anomalies of Nd, Sm and Ti are evident as in other basanite and olivine-nephelinite melts from Europe (WEDEPOHL, 1985; MERTES & SCHMINCKE, 1985) and can be explained by melting of minor phases in the mantle lherzolite such as perovskite and phlogopite.

The fact that the K/Rb ratio of 340 to 400 matches the values for other alkaline rocks (CHAUVEL & JAHN, 1984; MERTES & SCHMINCKE, 1985) shows that these rocks have retained their original ratios independant of possible later alteration. Abundances in rare earth elements fall in the range between 5 to 200 times that of chondrites. The overall pattern (Fig. 5) is straight from La to Yb with a strong negative slope and an apparent flattening from Yb to Lu. These data are in excellent agreement with those of other European basanites and olivine-nephelinites (WEDEPOHL, 1985; MERTES & SCHMINCKE, 1985). In addition, olivine nephelinites and melilitites from SE-Australia (FREY, GREEN & ROY, 1978) show REE patterns very similar to those for Ehrwaldites. The latter coincide with the narrow range displayed by Hawaiian nephelinites and melilitites (KAY & GAST, 1973).

FREY et al. (1978) have calculated the characteristics of their mantle sources for Australian nephelinites and basanites on the basis of their REE abundances. They conclude that a single source lherzolite (pyrolite) model composition can yield the observed REE contents by 4–7% melting provided that the source region was already relatively enriched in LREE (LREE 7–9x chondrites; HREE 2–5x chondrites) prior to the partial melting event. Despite the assumptions and uncertainties involved in these calculations, the striking coincidence of the REE patterns and in the mineralogical and chemical characteristics of basanitic to olivine nephelinitic rocks worldwide argues in favour of similar mantle sources and of similar melting characteristics for these alkaline lavas.

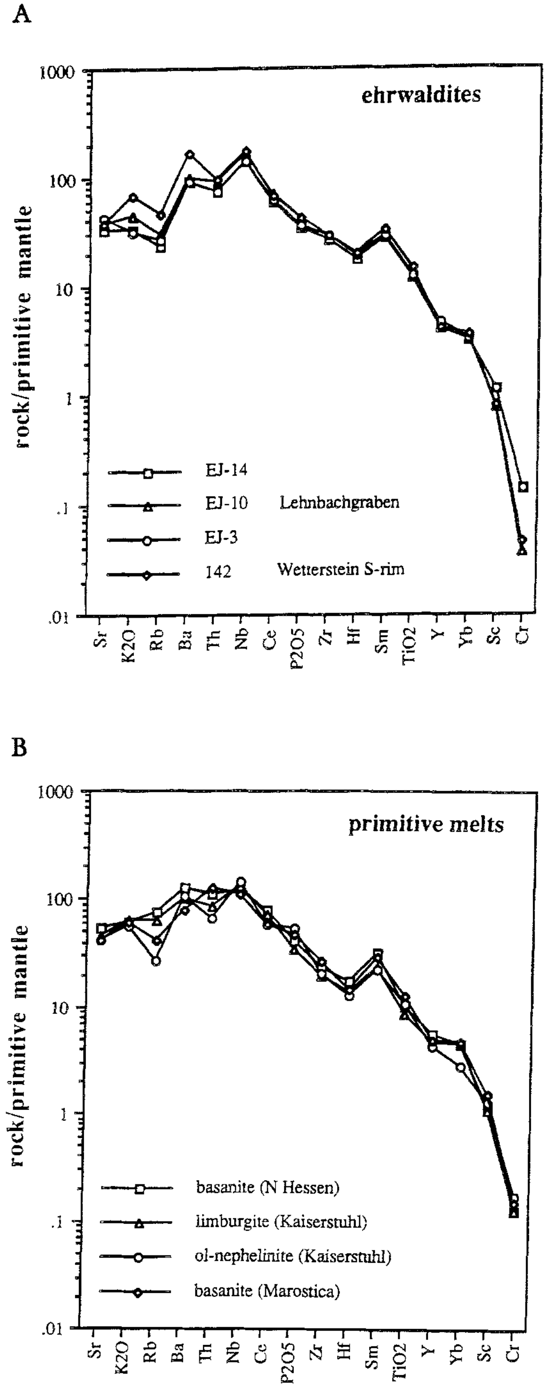

Fig. 4 A and B. Primordial mantle normalized plots of selected Ehrwaldite dykes (Fig. 4 A) and selected primitive melts (Fig. 4 B).
The normalizing values are taken from WOOD et al. (1979). Data for primitive melts: Kaiserstuhl (KELLER, 1984a & b); N-Hessen (WEDEPOHL, 1985); Marostica (DIETRICH, unpublished data).

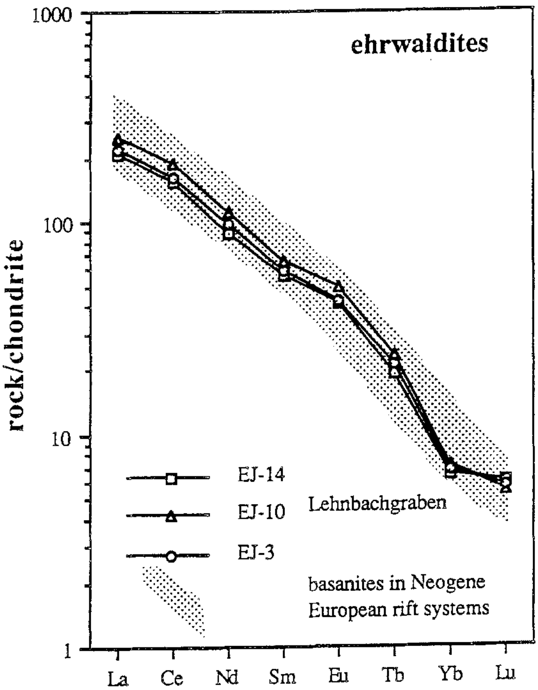

Fig. 5. Rare earth element patterns of selected Ehrwaldite dykes normalized to chondrites (SUN & NESBITT, 1977). Basanites in Neogene European rift systems (e.g., CHAUVEL & JAHN, 1984; WEDEPOHL, 1985).

Analysis EJ 10 shows a trend relative to the other samples towards a slight enrichment in SiO_2, enrichment in TiO_2 and Na_2O and decrease in MgO, CaO, Cr_2O_3 and NiO. Whereas the behaviour of all the other elements is readily explained by olivine, clinopyroxene and spinel fractionation, the behaviour of SiO_2 is not readily understood. More evolved rocks are extremely rare at Lehnbachgraben, there are more of them along the south rim of the Wetterstein (area No. 2 in Fig. 1) and Karwendel (area No. 3 in Fig. 1). The differentiation of Ehrwaldites however, is beyond the aim of the present article and will be discussed elsewhere.

Sr – Nd isotope geochemistry

The Sr and Nd isotope data of the Ehrwaldite samples (in Table 2) show initial ϵ_{Sr} and ϵ_{Nd} values ranging from −3.3 to −12.4 and +3.9 to +5.2, respectively. Decarbonatisation is lowering considerably the Sr isotopic composition. Thus, in carbonate bearing samples, the total rock $^{87}Sr/^{86}Sr$ ratios have been significantly increased, possibly by interaction with the sedimentary environment. In how far the Rb/Sr ratios and the Sm-Nd system have been affected in such samples is unclear.

As shown in Fig. 6 the initial Sr and Nd isotopic compositions of the dykes are close to average values of other European basanitic rocks from the Massif Central (CHAUVEL & JAHN, 1984; DOWNES, 1984) of basanites from the Siebengebirge (WÖRNER et al., 1986) and the Kaiserstuhl (SCHLEICHER, 1986) and melilitites from the Hegau (ALIBERT et al., 1983). The basanites from the E-Eifel show a somewhat lower average ϵ_{Nd} value of +1.1 and ϵ_{Sr} value of 0 (WÖRNER et al., 1986). The subcontinental mantle south and north of the Penninic realm at 100 Ma and at Tertiary to recent times, respectively, therefore shows striking similarities in their geochemical and isotopic characteristics. The initial ϵ_{Nd} values of primitive alkaline rocks plotted in Fig. 6 range in between +1 and +6, the average ϵ_{Sr} values in between 0 and −15. Thus, like the chemial also the isotopic characteristics may indicate that these alkaline rocks originated from similar subcontinental mantle segments (STILLE et al., 1989a) whose isotopic signatures have to be explained by at least two stages of evolution — an older period of mantle depletion followed by later mantle enrichment processes (STILLE, 1987).

The isotope data of the dykes are in contrast to those of Alpine ophiolites which are regarded as relics of Penninic oceanic crust and which show Pb, Sr and Nd isotopic signatures typical for a depleted suboceanic mantle (RICHARD & ALLEGRE, 1980; POLVE, 1983; PERETTI & KÖPPEL, 1986; CURTI, 1987; RÖSLI, 1988; STILLE et al., 1989b).

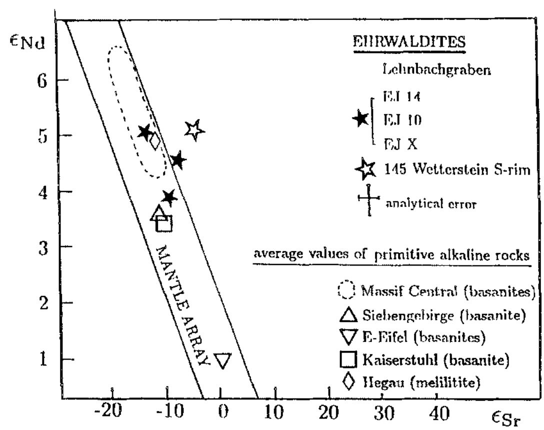

Fig. 6. ϵ_{Sr} vs. ϵ_{Nd} diagram for selected Ehrwaldite dykes and primitive alkaline rocks from Neogene European volcanic provinces. Data for basanites: Kaiserstuhl (SCHLEICHER, 1986); Siebengebirge and E-Eifel (WÖRNER et al., 1985, 1986); Massif Central (CHAUVEL & JAHN, 1984; DOWNES, 1984); Data for melilites from Hegau (ALIBERT et al. 1983).

Rb/Sr ANALYTICAL DATA BEFORE DECARBONATISATION

sample no	Sr (ppm)	Rb (ppm)	87Sr/86Sr (±2 sigma)	87Rb/86Sr	Epsilon Sr (0 Ma /100 Ma)
EJ 10	931.4	31.65	.703677±.000018	0.09826	-11.7 / -12.0
EJ 14	817.4	26.50	.703892±.000007	0.09377	-8.63 / -8.87
EJ X	944.1	25.61	.704173±.000010	0.07847	-4.64 / -4.58
145	982.3	31.45	.704285±.000011	0.09261	- 3.05 / -3.28
121	845.5	36.03	.703693±.000008	0.12667	-11.5 / -12.4

Sr ANALYTICAL DATA AFTER DECARBONATISATION

sample no	87Sr/86Sr (±2 sigma)	Epsilon Sr (0 Ma)
EJ 10	.703313±.000007	-16.8
EJ 14	.703400±.000008	-15.6
EJ X	.703543±.000007	-13.6
145	.703368±.000006	-16.1
121	.703422±.000007	-15.3

Sm/Nd ANALYTICAL DATA BEFORE DECARBONATISATION

sample no	Nd (ppm)	Sm (ppm)	143Nd/144Nd (±2 sigma)	147Sm/144Nd	Epsilon Nd (100 Ma)
EJ 10	63.581	11.414	.512841±.000018	0.1085	5.04
EJ 14	55.358	10.129	.512783±.000010	0.1106	3.89
EJ X	57.813	10.196	.512812±.000015	0.1066	4.51
145	66.037	11.761	.512847±.000004	0.1077	5.18

Tab. 2. Rb-Sr and Sm-Nd isotope data for Ehrwaldite samples. Analytical methods and standard measurements in JÄGER (1979) & STILLE et al. (1989 b).

Radiometric age determinations

Four samples of Ehrwaldite from Lehnbachgraben as well as from the southern margin of the Wetterstein mountains were selected to determine total rock ages using the potassium-argon method. The samples chosen are compact, contain partly fresh olivine and do not show any fracturing or post-magmatic alteration. Samples were prepared and analyzed according to standard techniques (FLISCH, 1986, 1987) as described by HUNZIKER (1974). Fractions of 60–80 mesh were used for the dating. The results are shown in Table 3.

The total rock ages for the Ehrwaldites are very consistent and yield 99.4 Ma with a 1 σ error limit of ± 2 Ma (Table 3). The data plot nicely along an isochron in a $^{40}Ar/^{36}Ar$ vs $^{40}K/^{36}Ar$ diagram (Fig. 7). The slope of the isochron of y = 289.69 + 5.887 e − 3x corresponds to an age of 102 ± 2 Ma. Inspection of these analytical data in ^{40}Ar(rad) vs ^{40}K plot (Harper diagram) shows no significant loss of radiogenic argon.

Postmagmatic conditions for the Ehrwaldites did not exceed 130 °C and 3.5 km tectonic overburden (KRUMM et al., 1988); biotite and amphibole as the main potassium phases remained absolutely unaltered. A postintrusive change in the potassium-argon system therefore is excluded. This is also evident from the fact

K/Ar ANALYTICAL DATA FOR THE SIZE FRACTION 0.175-0.25mm

sample no	40Ar rad. nl/g	%K	%40Ar rad.	40Ar/36Ar	40K/36Ar	age Ma (±2 sigma)
EJ X	2.801	0.705	60	734.23	73914	99.4±2
2/31	2.861	0.725	74	1137.24	142680	98.8±2
106	3.079	0.775	69	951.55	110478	99.4±2
EJ 7	3.102	0.775	78	1319.96	171231	100.1±2

Tab. 3. K-Ar analytical data for selected Ehrwaldite dykes. Analytical techniques in FLISCH (1982, 1986).

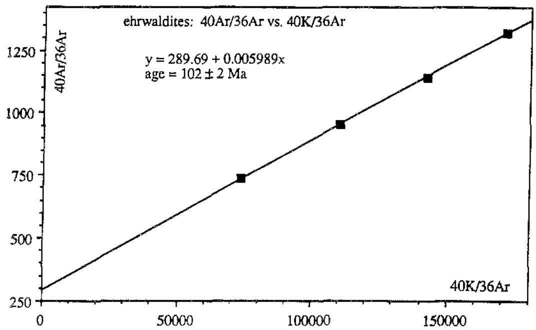

Fig. 7. $^{40}Ar/^{36}Ar$ vs $^{40}K/^{36}Ar$ diagram for the Ehrwaldite samples. The isochrone intercept of 289.69 corresponds well with the $^{40}Ar/^{36}Ar$ air ratio of 295.5.

the data are very consistent for the four samples that come from localities several kilometres apart and that the samples include a variety of rocks including one rich in amygdules. In addition, geochemical data of the almost calcite free samples used for the radiometric determinations (see Table 1) demonstrate the primary character of the mantle-derived melts and show that there was little postmagmatic alteration.

We therefore conclude, that the age of 100 Ma represents the intrusion age of the Ehrwaldite dykes which is consistent with the limits given by stratigraphic relationships.

Discussion and Conclusions

Experiments using basanitic rocks (Mg number ≈ 70; ne ≈ 10.5% H_2O = 2–7%; GREEN, 1973) result in quite a narrow pressure-temperature range at which liquids of this composition are saturated with olivine, orthopyroxene, clinopyroxene and garnet i.e. garnet-lherzolite mantle. This range is 25–30 kb, 1200–1300 °C. Experiments using Ehrwaldite powders and thermobarometric data on mantle xenocrysts in the Ehrwaldite (ULMER et al., [1989]) indicate a similar P-T range as above for the generation of Ehrwaldite melts. For the purpose of discussion of regional tectonic consequences of Ehrwaldite occurrences, we therefore propose an origin of these melts at ~ 80 km depth and at temperatures ~ 1250 °C. According to the K-Ar isotope data presented in this paper these melts must have intruded the Lechtal unit 100 Ma ago, which corresponds to a Late Albian age according to the 1983 Geological Time Scale of the Geological Society of America. Sr and Nd isotope data of the Ehrwaldites agree perfectly with those of other alkaline rock suites of subcontinental origin. These suites occur in extensional tectonic settings with no subduction zone crossing the channelways of the rising magmas. At the time of Ehrwaldite ascent, 100 Ma ago, we must therefore assume an extensional, non-subduction, supra-continental regime for the rocks in which the dykes occur. Such a setting would contradict a convergent situation in the Austroalpine thrust sheets west of Innsbruck as still proposed by TOLLMANN (1987) in his evolution-scheme of the Eastern Alps. For 100 Ma ago, Tollmann's model requires that the Northern Calcareous Alps are the tectonic cover of the Penninic domain of the Hohe Tauern in a compressive, supra-subduction regime. Similarly all models that involve a continuously compressive regime for the Lechtal and Allgäu thrust sheets during Abtian/Albian times (for example, WINKLER, 1988) cannot satisfy our data.

On the other hand, an evolution scheme as recently proposed by FRANK (1987) needs little adjustment to satisfy our data. For the time span from 100 to 90 Ma ago, Frank assumes that the Northern Calcareous Alps were still in contact with their underlying crystalline basement. Beginning compression led to folding of the sedimentary cover, local thrusting and to considerable thickening of basement and sedimentary cover. This scenario is in agreement with our data if the onset of Frank's 10 Ma compressive regime (100–90 Ma) is placed after the ascent of the Ehrwaldite dykes. Basanites and melts of relatively low viscosity generally do rise along channelways that are subvertical. As the Ehrwaldites with their extremely low viscosity (see TROMMSDORFF, 1962, Abb. 13) frequently are parallel to bedding in Jurassic to Cretaceous strata these sedimentary rocks may have attained their subvertical orientation prior to the emplacement of the dykes. Such a situation could have prevailed during an extensional décollement (LAUBSCHER, 1988) of the Northern Calcareous Alps from their basement or shortly thereafter. From the fact that the Ehrwaldites are only found in one nappe unit, i.e. the Lechtal nappe, we conclude that no major nappe systems of the present stack existed at the time of dyke emplacement.

An extensional setting would be satisfied by transverse fault systems. It is possible that such transverse faults occurred in continuation of transform systems in the Penninic ocean causing a horst-graben situation in the adjacent Austroalpine continent (Fig. 8). The linear occurrence of Ehrwaldite dykes (Fig. 1) suggests such a possibility. Such a setting could also have initiated vertical tectonic displacements, such as the uplift events that have been reported for this time in the Silvretta crystalline basement (HURFORD et al., 1989). Our model satisfies the observation of a top to the west directed imbrication of the Austroalpine and Penninic units between 110 and 50 Ma (RING et al., 1988). However, it has do be kept in mind that the

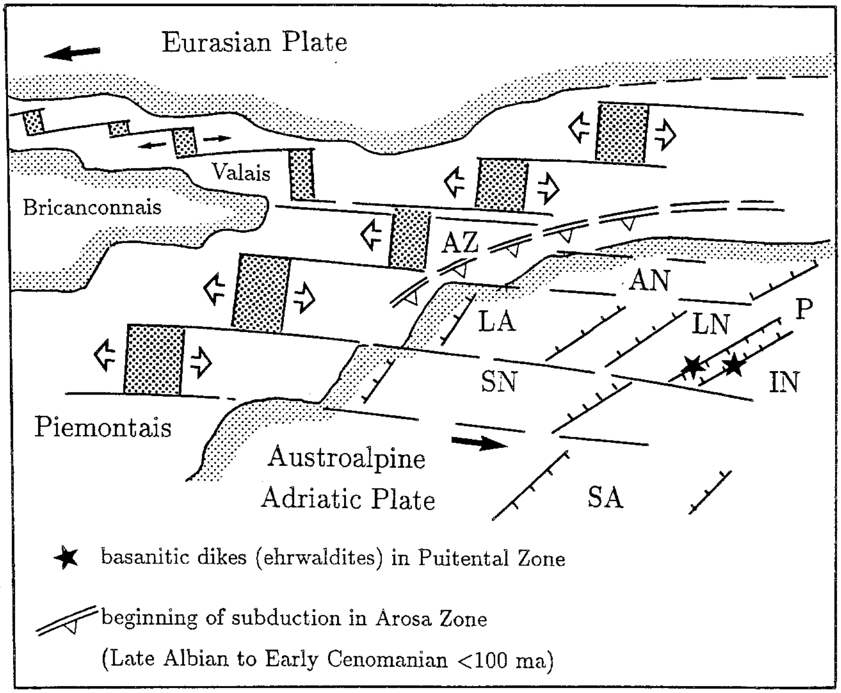

Fig. 8. Paleotectonic Sketch (not to scale) of the Penninic oceanic belts and the Austroalpine horst-graben systems during Lower Cretaceous time (approx. 120 to 100 Ma) prior to subduction (modified after DIETRICH, 1976 and WEISSERT & BERNOULLI, 1985). Abbrevations: AN = Allgäu nappe, AZ = Arosa nappe (pre-flysch, flysch and mélange), IN = Inntal nappe, LA = Lower Austroalpine nappes, LN = Lechtal nappe, P = Puitental Zone, SN = Silvretta nappe, SA = Southern Alps.

Ehrwaldite dykes originated in a subcontinental mantle and not in a depleted suboceanic mantle.

By 100 Ma subduction may have already occurred far away from the Lechtal unit in the Penninic zone to the north. Paleogeographic reconstructions based on sedimentological evidence for the Allgäu area by GAUPP (1982) indicate an onset of deformation in frontal parts of the Lechtal thrust sheet during latest Albian time which would be in agreement with our data. Subsequent tectonic stacking of thrust sheets in the Northern Calcareous Alps led to »non-metamorphic« conditions in the Lechtal unit around the Ehrwaldite dykes. Vitrinite reflectances (~ 0.7 R_{max}%; KRUMM et al., 1988) and illite crystallinities (KRALIK et al., 1987) correspond to the zone of diagenesis as defined in FREY (1987). Analcime and heulandite as occurring in amygdules of the Ehrwaldite dykes are stable in the zone of diagenesis (KISCH, 1987). It is likely that they formed, as in many other basanitic rocks, during magmatic cooling and survived subsequent conditions of diagenesis.

Acknowledgements

We thank A. Wyttenbach (Paul Scherrer Institute, Würenlingen) for the REE data, R. Brandner (Innsbruck), G. Eisbacher (Karlsruhe), W. Frank (Vienna), H. P. Laubscher (Basel) and D. Bernoulli (Zürich) for their constructive reviews, B. Bühlmann for drafting figures and C. Büchel for patiently typing the paper.

References

ALIBERT, C., MICHARD, A. & ALBAREDE, F. (1983): The transition from alkali basalts to kimberlites: Isotope and trace element evidence from melilites. – Contrib. Mineral. Petrol, **82**, 176–186.

AMPFERER, O. (1930): Über den Südrand der Lechtaler Alpen zwischen Arlberg und Ötztal. – Jb. d. geol. Bundesanstalt Wien, **80**, 438.

BRANDNER, R. (1985): Geologische und tektonische Übersichtskarte von Tirol, 1:600000. – In: Tiroler Heimat. Jahrb. Geschichte und Volkskunde, 48/49, 1–12.

CHAUVEL, C. & JAHN, B. M. (1984): Nd-Sr isotope and REE geochemistry of alkali basalts from the Massif Central, France. – Geochim. Cosmochim. Acta, **48,** 93–110.

CURTI, E. (1987): Lead and Oxygen isotope evidence for the origin of the Monte Rosa Gold Lode deposits (Western Alps, Italy): A comparison with Archean Lode deposits. – Economic Geol., **82,** 2115–2140.

DIETRICH, V. J. (1976): Plattentektonik in den Ostalpen, eine Arbeitshypothese. – Geotekt. Forsch., **50,** 1–84.

—, CARMAN, M. F., WYTTENBACH, A. & MCKEE, E. H. (1984): Geochemistry of basalts from Holes 519A, 520, 522B and 524, DSDP Leg 73 (South Atlantic). – Initial Rep. Deep Sea Drilling Project, **73,** 579–601, U.S. Government Printing Office.

DOWNES, H. (1984): Sr and Nd isotope geochemistry of coexisting alkaline magma series, Cantal, Massif Central, France. – Earth and Planet. Sci. Lett., **69,** 321–334.

— (1987): Tertiary and Quaternary volcanism in the Massif Central, France. – In: Alkaline Igneous Rocks, Fitton, J. G. & Upton, B. G. J. (eds.), Geol. Soc. Spec. Publ. No. **30,** 517–530.

EDGAR, A. D. (1987): The genesis of alkaline magmas with emphasis on their source regions: interferences from experimental studies. – In: Alkaline Igneous Rocks, Fitton, J. G. & Upton, B. G. J. (eds.), Geol. Soc. Spec. Publ. No. **30,** 29–52.

FLISCH, M. (1982): Potassium-Argon Analysis. – In: Odin, G. S. (ed.): Numerical Dating in Stratigraphy. John Wiley, Chichester, 151–158.

— (1986): K-Ar Dating of Quaternary Samples. – In: Hurford, A. J., Jäger, E. & Ten Cate, J. A. M. (eds.): Dating Young Sediments: Proceedings of the Workshop, Beijing, China, September 1985. CCOP-UNESCO Technical Publication 16, 299–323.

— (1987): Geologische, petrographische und isotopengeologische Untersuchungen an Gesteinen des Silvretta Kristallins. – Unpublished Ph. D. Thesis, Univ. Bern.

FRANK, W. (1987): Evolution of Austroalpine Elements in the Cretaceous. – In: Flügel, H. & Faupl, W. (ed.): Geodynamics of the Eastern Alps, 379–406, Deutike.

FREY, F. A., GREEN, D. H. & ROY, S. D. (1978): Integrated models of basalt petrogenesis: A study of quartz tholeiites to olivine melilites from south eastern Australia utilizing geochemical and experimental petrological data. – J. Petrol., **19,** 3, 463–513.

FREY, M. (1987): Low temperature metamorphism. Blackie London, 351 pp.

GAUPP, R. (1982): Sedimentationsgeschichte und Paläotektonik der kalkalpinen Mittelkreide (Allgäu, Tirol, Vorarlberg). – Zitteliana, **8,** 33–72.

GREEN, D. H. (1973): Conditions of melting of basanite magma from garnet peridotite. – Earth and Planet. Sci. Lett., **17,** 456–465.

HUNZIKER, J. C. (1974): Rb-Sr and K-Ar determination and the alpine tectonic history of the Western Alps. – Mem. Ist. Geol. Mineral. Univ. Padova, **31,** 54 p.

HURFORD, A. J., FLISCH, M. & JÄGER, E. (1989): Unravelling the thermo-tectonic evolution of the Alps: A contribution from fission track analysis and mica dating. – In: Coward, M. P., Dietrich, D. & Park, R. G. (eds.): Alpine Tectonics. Geol. Soc. of London Spec. Publ.: **15,** 369–398.

JÄGER, E. (1979): The Rb-Sr Method. – In: Jäger, E. & Hunziker, J. C. (eds.): Lectures in Isotope Geology, Springer-Verlag Berlin, Heidelberg, New York, 13–26.

KAY, R. W. & GAST, P. W. (1973): The rare earth content and origin of alkali rich basalts. – J. Geol., **81,** 653–682.

KELLER, J. (1984a): Geochemie und Magmenentwicklung im Kaiserstuhl. – Fortschr. Mineral., **62,** Bh. 1, 116–118.

— (1984b): Der jungtertiäre Vulkanismus Südwestdeutschlands: Exkursionen im Kaiserstuhl und Hegau. – Fortschr. Mineral., **62,** Bh. 2, 2ff.

KISCH, H. J. (1987): Correlation between indicators of very low grade metamorphism. – In: Frey, M. (ed.): Low temperature metamorphism, 227–300, Blackie, London.

KRALIK, M., KRUMM, H. & SCHRAMM (1987): Low grade and very low grade metamorphism in the Northern Calcareous Alps and in the Greywacke zone: Illite-crystallinity data and isotopic ages. – In: Flügel, H. & Faupl, W. (ed.): Geodynamics of the Eastern Alps, 164–178, Wien, Deutike.

KRUMM, H., PETSCHIK, R. & WOLF, M. (1988): From diagenesis to anchimetamorphism, upper Austroalpine sedimentary cover in Bavaria and Tyrol. Geodis. Acta, **2,** 1, 33–47.

LAUBSCHER, H. P. (1988): Décollement in the Alpine system: an overview. – Geol. Rdsch., **77**/1, 1–9.

MERTES, M. & SCHMINCKE, H.-U. (1985): Mafic potassic lavas of the Quaternary West Eifel volcanic field. – Mineral. Petrol., **89,** 4, 330–345.

MILLER, H. (1962): Der Bau des westlichen Wettersteingebirges. – 2. deutsch. geol. Ges. Jg., 1961, 113, 2, 3, 409–425.

PERETTI, A. & KÖPPEL, V. (1986): Geochemical and lead isotope evidence for a mid-ocean ridge type mineralization with a polymetamorphic ophiolite complex (Monte del Forno, North Italy/Switzerland) – Earth and Planet. Sci. Lett., **80,** 252–264.

PICHLER, A. (1866): Beiträge zur Geognosie Tirols. – Jb. d. K. K. Reichsanstalt Wien, **16,** 4, 501–504.

— (1875): Beiträge zur Geognosie Tirols. – Neues Jb. Mineral. Geol. Palaeont. Jg. 926–936.

POLVE, M. (1983): Les isotopes du Nd et du Sr dans les lherzolites orogéniques: contribution à la détermination de la structure et de la dynamique du manteau supérieur. – Thèse de doctorat d'état. Université Paris VII.

RICHARD, P. & ALLEGRE, C. J. (1980): Neodymium and strontium isotope study of ophiolite and orogenic herzolite petrogenesis. – Earth and Planet. Sci. Lett., **47,** 65–74.

RING, U., RATSCHBACHER, L. & FRISCH, W. (1988): Plate boundary kinematics in the Alps: Motion in the Arosa suture zone. – Geology, **16,** 696–698.

RÖSLI, U. (1988): Geochemische und mineralogische Untersuchungen an Metarodingiten. – Ph. D. Thesis ETH Zürich, No. 8589.

SCHLEICHER, H. (1986): Isotopenchemie der Alkalivulkanite des Kaiserstuhls (Ein Beitrag zu ihrer Genese mit Hilfe radiogener Isotope). – Habilitationsschrift Universität Freiburg i. Br., pp. 200.

SIXTA, V. (1977): Coulometric determinations of carbonates in rock samples. – Ztschr. Anal. Chem., **285**, 369–372.

STILLE, P. (1987): Geochemische Aspekte der Krustenevolution im zentral- und südalpinen Raum. – Habilitationsschrift, ETH-Zürich, pp. 127.

—, OBERHÄNSLI, R. & WENGER-SCHENK, K. (1989a): Hf-Nd isotopic and trace element constraints of the genesis of alkaline and calc-alkaline lamprophyres. – Earth and Planet. Sci. Lett. (submitted).

—, CLAUER, N. & ALBRECHT, J. (1989b): Nd isotopic composition of Jurassic Tethys seawater and the genesis of alpine Mn-deposits: evidence from Sr-Nd isotope data. – Geochim. Cosmochim. Acta, **53**, pp. 5.

SUN, S. S. & NESBITT, R. W. (1977): Chemical heterogeneity of archaen mantle, composition of the earth and mantle evolution. – Earth planet. Sci. Lett., **35**, 429–448.

TOLLMANN, A. (1987): The Alpidic evolution of the Eastern Alps. – In: Flügel, H. & Faupl, W. (ed.): Geodynamics of the Eastern Alps, 361–378, Wien, Deutike.

TRÖGER, E. (1969): Spezielle Petrographie der Eruptivgesteine. – Schweizerbart Stuttgart.

TROMMSDORFF, V. (1962): Über Lamprophyre aus den nördlichen Kalkalpen (Ehrwaldit). – Tscherm. mineral. petrogr. Mitt. **8**, 2, 281–325.

ULMER, P., TROMMSDORFF, V. & DIETRICH, V. J. (1989): The genesis Cretaceous basanites from the Calcareous Alps (Austria): Experimental, Geochemical and Field Constraints. IAVCEI Abs. New Mexico Bureau of Mines and Mineral Resources Bull, **131**, P. 274.

WEDEPOHL, K. H. (1985): Origin of the Tertiary basaltic volcanism in the northern Hessian Depression. – Contrib. Mineral. Petrol., **89**, 2/3, 122–143.

WEISSERT, H. J. & BERNOULLI, D. (1985): A transform margin in the Tethys: Evidence from the Swiss Alps. – Geol. Rdsch., **74**, 3, 665–679.

WINKLER, W. (1988): Mid-to Early Late Cretaceous flysch and mélange formations in the western part of the Eastern Alps. Palaeotectonic implications. – Jb. Geol. B.-A., **131**, 2, 341–389.

WOOD, D. A., JORON, J.-L., TREUIL, M., NORRY, M. J. & TARNEY, J. (1979): Elemental and Sr isotope variations in basic lavas from Iceland and surrounding ocean floor. – Contrib. Mineral. Petrol., **70**, 319–339.

WÖRNER, G., STAUDIGEL, H. & ZINDLER, A. (1985): Isotopic constraints on open system evolution of the Laacher See magma chamber (Eifel, West-Germany). – Earth and Planet. Sci. Lett., **75**, 37–49.

—, ZINDLER, A., STAUDIGEL, H. & SCHMINCKE, H.-U. (1986): Sr, Nd and Pb isotope geochemistry of Tertiary and Quaternary alkaline volcanics from West Germany. – Earth and Planet. Sci. Lett., **79**, 107–119.