The age of an Upper Carboniferous / Lower Permian sedimentary basin and its hinterland as constrained by U-Pb dating of volcanic and detrital zircons (Northern Switzerland)

SCHWEIZ. MINERAL. PETROGR. MITT. 77, 101–111, 1997

The age of an Upper Carboniferous / Lower Permian sedimentary basin and its hinterland as constrained by U–Pb dating of volcanic and detrital zircons (Northern Switzerland)

by *Urs Schaltegger*[1]

Abstract

The Permocarboniferous Trough of Northern Switzerland (PCT) represents an example of a Late Variscan sedimentary basin formed by post-convergence extension in the Stephanian and Lower Permian. U–Pb zircon age determinations of volcanic zircons from ash fall tuffs and from clastic sediments drilled at the site of Weiach help to constrain the evolutionary path for this graben structure.

Two tuff samples from the Stephanian/Autunian boundary sequence (inferred by palynomorph stratigraphy) yield ages of 303 and 298 ± 1 Ma, comparable to magmatism in the Aar massif (Central Alps), now exposed 100 kilometers to the south. This "Aar magmatic event" is proposed as a stratigraphic marker for the Carboniferous-Permian transition in the continental sediments of Central Europe. In addition, detrital zircons from four core samples were dated; the youngest detrital zircons from the lowest sedimentary unit yield an age of 331 ± 2 Ma (topmost Visean), regarded as a maximum age for sedimentation in the PCT. The detrital zircons are derived from a 331 to 326 Ma-old granitic source, similar to the Southern Black Forest with respect to lithological content and age. Zircons of the two lowermost samples from the Weiach well (at 1840 and 1959 meters) indicate an older, 383 Ma basement source. The presence of probably granite-derived Upper Visean detrital zircons in Stephanian sediments implies that granitoids must have been exhumed in the time span between their intrusion at ca. 330 Ma and the formation of the PCT.

The new U–Pb zircon ages help to further constrain the controversial ideas about formation of the PCT, which were hitherto based only on sedimentological/stratigraphical and geophysical constraints. It is suggested that the deformation of the lower part of the PCT took place in response to episodic transpression during strike-slip in the Stephanian and therefore was unrelated to the so-called "Saalian" tectonic phase in the 30 million years younger Saxonian. The new data favour a model of rapid and continuous sedimentation of only a few million years in a continental graben structure.

Keywords: Upper Carboniferous, sedimentary basin, U–Pb zircon ages, Late Variscan extension, Northern Switzerland.

Introduction

The existence of an Upper Carboniferous sedimentary graben beneath the Mesozoic and Tertiary Molasse basin in Northern Switzerland was already postulated by LEMKE (1961). A detailed record of this intracontinental volcano-sedimentary graben, now called Permocarboniferous Trough of Northern Switzerland (PCT), has only recently been obtained from deep drilling and seismic profiling performed by the National Cooperative for Disposal of Radioactive Waste (NAGRA). The PCT is part of a network of Upper Carboniferous / Lower Permian intracontinental graben that were formed by post-convergence extension during the last stages of the Variscan orogeny (MENARD and MOLNAR, 1988; BURG et al., 1994). The sedimentation into these depressions was of continental character in a humid climate in the Stephanian and under semiarid conditions during Lower Permian. Geophysical investigations revealed that the lower part of the graben was transpressively deformed, whereas the sedimentary sequences of the upper part re-

[1] Institut für Isotopengeologie und Mineralische Rohstoffe, ETH Zentrum, Sonneggstrasse 5, CH-8092 Zürich, Switzerland. E-mail: schaltegger@erdw.ethz.ch.

mained undisturbed. This distinction of two units could, however, not be recognized in the drillcores.

This study presents U–Pb age determinations of zircons of both volcanic and sedimentary core samples from the Weiach drillhole, which can be used to constrain the stratigraphic age, the nature and characteristics of the local tectonic environment, as well as defining the age and geodynamic characteristics of possible source regions for the detritus. The new age constraints on the PCT will help to understand the late-orogenic tectonic processes that lead to the formation of Stephanian/Early Permian sedimentary basins in Central Europe.

Geology of the Permocarboniferous Trough of Northern Switzerland (PCT)

The sedimentary record of the PCT is available in drillcores from the NAGRA wells of Weiach and Riniken (MATTER et al., 1987; MATTER et al., 1988; Fig. 1). Detailed seismic profiling of northern Switzerland allowed reconstruction of the shape and extension of this graben, which extends from the Bodensee in the east to the basement below the Tabular Jura in the west, further east to southeastern Germany (KETTEL and HERZOG, 1988) and further west to the southern slope of the Vosges (Stephanian coal deposits of Ronchamps), see discussion in DIEBOLD (1989) and figure 1.

Data on the lateral extension, internal structure, nature of the marginal faults and the degree of deformation of the basin sediments have been obtained from refraction and reflexion seismic and gravimetric investigations. The different geophysical methods gave, however, quite contradictory results, and the present-day interpretations are only of preliminary character so far (LAUBSCHER, 1987; DIEBOLD et al., 1992).

The most complete stratigraphic section of the PCT was drilled at the site of Weiach, which is situated on the northern shoulder of the basin (MATTER, 1987; see Fig. 1). The Permo-Carboniferous sediments reach a thickness of about 1000 m and

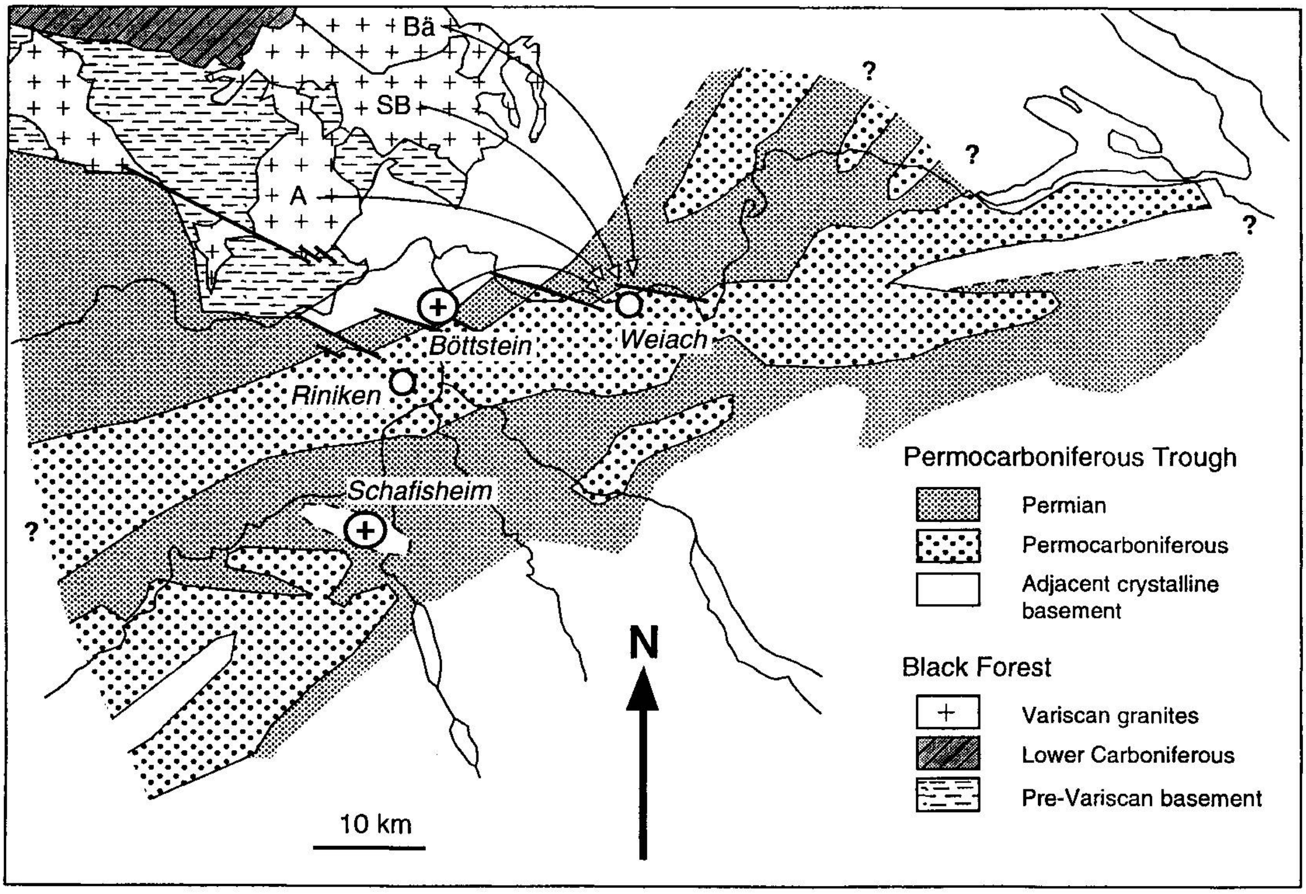

Fig. 1 Simplified tectonic map of the Permocarboniferous Trough of Northern Switzerland and of Southeastern Black Forest; from THURY et al. (1988). The four NAGRA wells of Böttstein, Riniken, Schafisheim and Weiach are indicated. Detrital zircons in Upper Carboniferous clastic sediments may be traced to the granites of Bärhalde (Bä), St. Blasien (SB), Albtal (A), Schafisheim or Böttstein, see text.

are of Stephanian and Lower Permian age. The stratigraphic profile starts with clastic sediments overlying an erosional paleosurface on gneissic basement rocks. The sediments range from conglomerates and coarse-grained sandstones to black shales and black siltstones. The latter are associated with coal measures, tuff layers and kaolinite tonsteins. The tuffs are considered to be primary ash fall deposits, because they are interlayered with varve-like shales containing fish scales (MATTER, 1987). The major part of the sequence is regarded as an anastomosing river deposit, formed during Stephanian times within a relatively narrow intracontinental graben. The deepest sediments in the center of the graben could possibly be of Westphalian age, in accordance with findings from the Entlebuch 1 well (VOLLMAYR and WENDT, 1987). The top of this unit evolved into an Autunian lacustrine sequence, containing a fauna of fish debris, ostracodes and algae. The lacustrine sediments are overlain by thick alluvial fan deposits changing in colour from grey at the bottom to red (sandstones of the "Oberrotliegendes") towards the top; the latter are 250 m thick at Weiach and 1000 m at Riniken, where Stephanian deposits are lacking. The coarse-grained alluvial fan deposits reflect fast erosion of the basin shoulders, which may have formed a pronounced topographic relief due to fast uplift and/or enhanced basin subsidence. The Stephanian/Autunian boundary within these continental sediments has been defined by palynomorphs (NBM/VCI boundary; MATTER et al., 1988; HOCHULI, 1985) in the uppermost part of the anastomosing river deposits (see Fig. 7).

The recorded bore log of Weiach has been considered as a continuous sedimentary record (MATTER et al., 1988); this is, however, not in accordance with the interpretations from seismic profiling, of which the latter argue for a clear division into a Lower and Upper Unit, separated by an unconformity reflecting a period of transpressional deformation of the Lower Unit (LAUBSCHER, 1987; DIEBOLD et al., 1992; Fig. 2). The basin shoulders are thought to have been thrusted onto the sediments of the Lower Unit in the north-western and south-eastern parts of the basin, causing the formation of steep marginal thrust faults and subhorizontal thrust planes within the Lower Unit. This tectonic phase has been termed "Saalian phase" with an implied Saxonian age (ca. 270–260 Ma). Normal faulting continued along with subsidence and deposition of the non-deformed Upper Unit sediments. The basin shoulders were possibly uplifted during a transpressional event, which initiated high erosion rates now reflected by the Lower Permian sediments. The boundary between Lower and Upper Unit could not be located in the Weiach drillcores. The same is true for Riniken, where only sediments from the Upper Unit were found. The reconstruction of the structure of the Lower Unit by LAUBSCHER (1987) or DIEBOLD et al. (1992), which is based on the interpretation of the seismic profiles, is complicated by seismic multiples, diffractions and lateral reflexions. Further, the nature of many of the seismic reflectors is not known, and even the distinction between basement and Permo-Carboniferous sediments remains difficult.

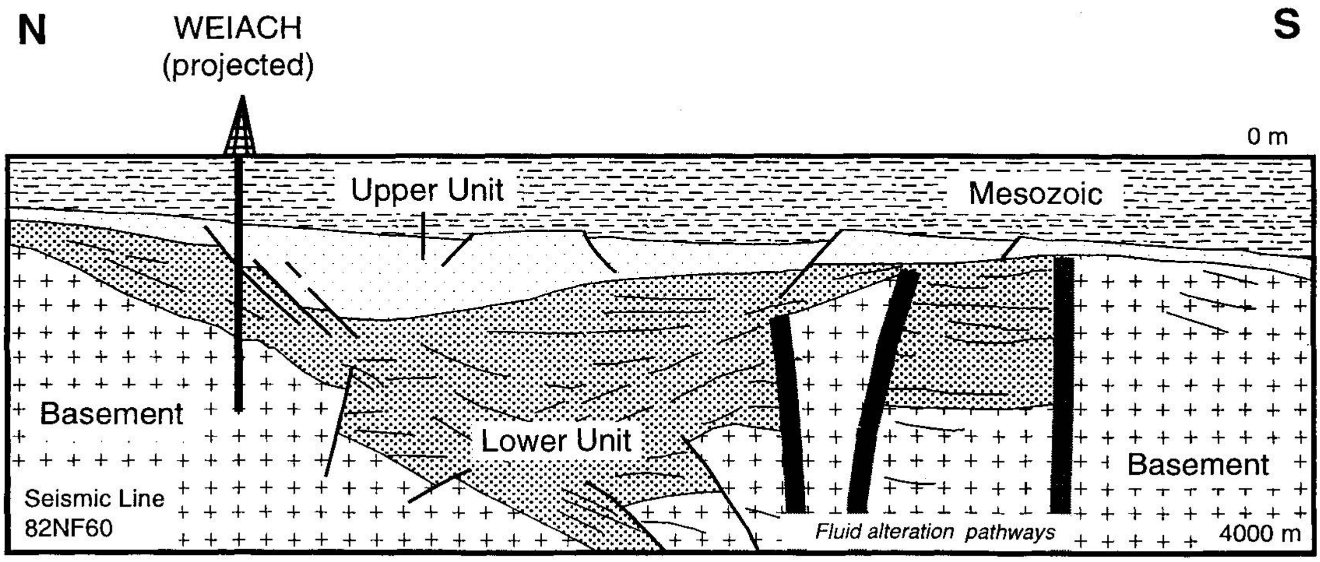

Fig. 2 Schematic cross section through the Permocarboniferous Trough of Northern Switzerland along the seismic line 82NF60 of NAGRA (DIEBOLD et al., 1992) and the Weiach drilling site projected onto it.

Tab. 1 U–Pb analytical results

Number	Description a)	Weight [mg]	nr. of grains	Concentrations U [ppm]	Pb rad. [ppm]	Pb nonrad. [pg]	Th/U b)	206/204 c)	Atomic ratios 206/238 d)	Error 2s [%]	207/235 d)	Error 2s [%]	207/206 d)	Error 2s [%]	Apparent ages 206/238	207/235	207/206	error corr.
WEI 1348.02 Black siltstone																		
1	euh ndls	0.006	12	455	23.4	1.9	0.43	4639	0.05006	0.46	0.3661	0.56	0.05305	0.24	314.9	316.8	330.9	0.91
2	euh lge ndls incl	0.007	8	333	17.2	1.4	0.46	5478	0.04990	0.49	0.3636	0.56	0.05284	0.28	313.9	314.9	321.9	0.87
3	euh tips	0.004	8	565	29.6	2.3	0.44	3119	0.05093	0.46	0.3718	0.59	0.05294	0.31	320.3	321.0	326.2	0.85
WEI 1432.26 Ash fall tuff																		
4	lge ndls	0.014	9	174	9.3	2.4	0.79	3036	0.04747	0.46	0.3426	0.55	0.05234	0.26	299.0	299.1	300.3	0.88
5	euh lge ndls	0.007	6	91	4.9	2.0	0.83	975	0.04721	0.48	0.3396	0.96	0.05217	0.76	297.4	296.9	292.9	0.62
6	euh lge ndls	0.015		194	10.3	2.0	0.77	4282	0.04722	0.48	0.3413	0.58	0.05242	0.28	297.4	298.1	303.6	0.88
WEI 1586.52 Ash fall tuff																		
7	euh lpr P-type incl	0.002	6	480	20.7	2.4	0.47	1073	0.04120	0.52	0.2967	0.87	0.05223	0.67	260.3	263.8	295.7	0.64
8	euh spr cl	0.004	9	199	10.2	1.6	0.59	1521	0.04804	0.54	0.4374	0.76	0.05244	0.56	302.5	302.7	304.8	0.68
WEI 1780.82 Black siltstone																		
9	lge ndls P-type	0.015	14	242	15.8	5.0	1.22	2365	0.05190	0.46	0.3789	0.60	0.05295	0.31	326.2	326.2	326.6	0.86
10	ndls {211}	0.012	11	186	11.5	2.8	0.91	2654	0.05288	0.49	0.3868	0.59	0.05305	0.27	332.2	332.0	331.1	0.89
11	euh prism incl	0.026	1	157	10.3	5.0	1.21	2674	0.05242	0.45	0.3832	0.56	0.05302	0.23	329.4	329.4	329.7	0.92
WEI 1840.10 Tuffaceous greywacke																		
12	euh lpr incl	0.003	4	466	23.2	2.5	0.60	1638	0.04596	0.48	0.3357	0.67	0.05297	0.42	289.6	293.9	327.7	0.78
13	euh pris incl	0.002	4	478	25.7	2.5	1.00	1106	0.04470	0.59	0.3268	0.88	0.05302	0.73	281.9	287.1	329.9	0.57
WEI 1959.87 Black siltstone																		
14	euh ndls non abr	0.024	17	681	29.1	13.8	0.29	3180	0.04248	0.50	0.3118	0.57	0.05323	0.20	268.5	275.6	338.8	0.94
15	euh ndls + tips	0.005	15	388	21.6	1.1	0.37	6115	0.05505	0.47	0.4086	0.56	0.05383	0.20	345.5	347.8	363.8	0.94
16	euh lpr + tips	0.005	11	491	31.0	1.6	0.59	5760	0.05888	0.48	0.4396	0.56	0.05415	0.22	368.8	369.9	377.1	0.92
17	euh lpr	0.001	1	245	13.9	1.4	0.63	578	0.05276	0.69	0.3846	1.65	0.05287	1.42	331.5	330.4	323.3	0.52
18	euh ndls	0.001	1	355	19.3	1.5	0.49	793	0.05235	0.48	0.3822	1.22	0.05295	1.04	329.0	328.7	326.7	0.54
19	euh prism	0.001	1	253	14.8	1.0	0.72	891	0.05270	0.55	0.3889	1.08	0.05353	0.86	331.1	333.6	351.0	0.61

a) euh = euhedral, clrls = colourless, incl = inclusions, ndls = needles, pr = prisms; transp = transparent, frags = fragments; lpr = long prismatic, spr = short prismatic; P-type zircons according to PUPIN (1980); all zircons abraded except where indicated.
b) Calculated on the basis of radiogenic $^{208}Pb/^{206}Pb$ ratios, assuming concordancy.
c) Corrected for fractionation and spike.
d) Corrected for fractionation, spike, blank and common lead (STACEY and KRAMERS, 1975).

Samples and analytical techniques

The samples used for this investigation are the same as those used for a recent K–Ar study of clay minerals in SCHALTEGGER et al. (1995); for a short petrographic description of the samples the reader is referred to table 1 of that paper.

Two yellow-brown tuffs occurring at 1432.26 and 1586.52 meters depth consist of up to 90% clay minerals and rare volcanogenic phenocrysts (quartz, rutile/anatase, zircon). Zircons from four strongly illite-cemented black siltstones ("Kristalltuffite"; MATTER et al., 1988) from 1348.02, 1780.82, 1840.10 and 1959.87 meters depth were also studied, and extended the investigated section down to 70 meters above sediment/ basement contact and up to 350 meters below the base of the Mesozoic. The siltstones occur at the base of coal layers and consists of a mixture of organic-rich material and underlying coarse-grained sandstones.

Samples consisting of 200 to 1000 g of fresh material were taken from the drillcores stored in the NAGRA core depot. The siltstones (WEI 1348.02, 1780.82, 1840.10 and 1959.87) were crushed with a jaw crusher, milled, sieved and passed over a Wilfley Table. The tuff samples WEI 1432.26 and 1586.52 were disaggregated in distilled water by shaking and stirring, the suspension repeatedly decanted and the residue washed and dried in acetone. Zircon was separated in methylene-iodide either from a fraction smaller than 300 μ or from the bulk fraction, depending on the sample size. The bulk zircon fraction or a non-magnetic sub-fraction were examined under a binocular microscope and zircons without cracks, turbidities and inclusions and homogeneous in terms of morphology, length/width ratio, colour and transparency were carefully selected in the case of multigrain analyses. Most grains were air-abraded (KROGH, 1982) to remove zones of marginal lead loss. Prior to analysis, zircons were washed in warm 4N nitric acid and rinsed several times with distilled water and acetone in an ultrasonic bath. Dissolution and chemical extraction of U and Pb were performed following KROGH (1973), using bombs and anion exchange columns that are scaled down to 1/10 of their original size. Total procedure blanks usually were between 0.8 and 2 pg Pb and around 0.1 pg U. Mass spectrometrical analyses were done in the same way as described in SCHALTEGGER and CORFU (1995). The results are summarized in table 1.

Results of U–Pb age determinations

BLACK SILTSTONES

Three fractions of euhedral long-prismatic zircons or fragments (1 to 3) were analyzed from the siltstone sample WEI 1348.02, each consisting of 8 to 12 grains. All three analyses plot near the concordia (Fig. 3), but reflect some lead loss, possibly combined with a minor contribution of inherited lead. The $^{207}Pb/^{206}Pb$ ages range between 322 and 331 Ma, indicating that the zircons are not cogenetic. This rock was initially considered as a tuff ("Kristalltuff", following MATTER et al., 1988) and therefore the analysis of multigrain fractions was chosen as the dating approach. The ages around 330 Ma point to granites of the Southern Black Forest or other granite bodies drilled by the NAGRA, e.g. at Böttstein (PETERS, 1987) as possible source rocks for the detrital zircons.

The zircon population of sample WEI 1780.82 could be divided into three sub-populations with different morphological characteristics: (I) large acicular zircon needles with P-type morphology (PUPIN, 1980); (II) acicular zircons with the {211} bipyramidal face, and (III) euhedral prismatic zircons with {211}, but smaller width/length ratios of about 4. The three multigrain analyses (Fig. 4) yielded three concordant points at 326, 332 and 329 Ma, respectively. They can be interpreted as representing sub-populations from three source rocks of slightly different age, or variable mixtures of zircons of slightly different age and degree of lead loss. The source ages span the range reported for the intrusion of the Southern Black Forest granites (ca. 334 to 326 Ma; TODT, 1976; SCHULER and STEIGER, 1978; SCHALTEGGER, 1995 and unpublished results).

The results of the two lowermost black siltstone samples WEI 1840.10 and 1959.87 are presented together in figure 5. The data set of these two samples consists of three concordant single-grain analyses at 331 ± 2 Ma (17 to 19) from sample 1959.87 and five discordant multigrain analyses from both samples. Fractions 12, 13, 15 and 16 (Tab. 1) straddle a best-fit line intersecting at 383 ± 8 and 174 ± 29 Ma. Fraction 14 consisting of 17 non-abraded, long-prismatic U-rich zircons is clearly off this line with a $^{207}Pb/^{206}Pb$ age of 339 Ma. The data point can best be explained by diffusive lead loss in addition to the episodic loss at 174 Ma. Alternatively, analyses 12 and 13 could also be placed on a lead loss line from 331 Ma (17 to 19); the upper intercept of the two-point line of analyses 15 and 16 would in this case intersect at 386 ± 19 Ma and 196 ± 80 Ma, i. e. indistinguishable within error limits from the values reported above.

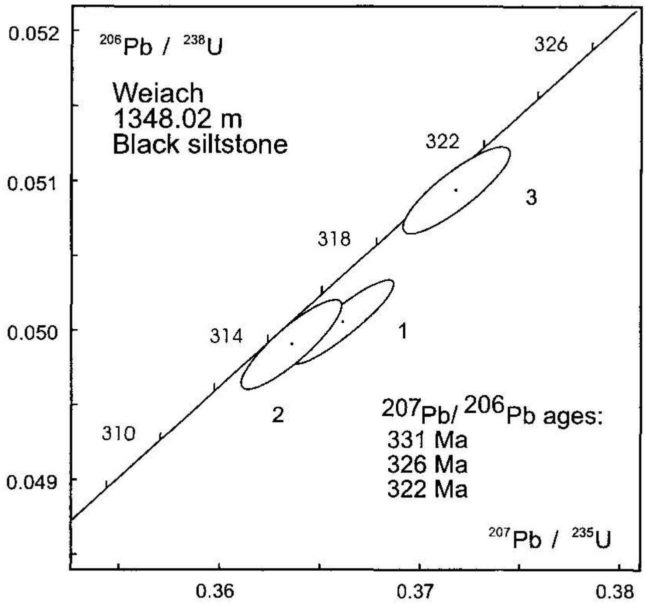

Fig. 3 U–Pb concordia diagram of sample WEI 1348.02 m, black siltstone. Three zircon fractions show some lead loss and $^{207}Pb/^{206}Pb$ ages ranging between 322 and 331 Ma, thus do not consist of cogenetic zircons.

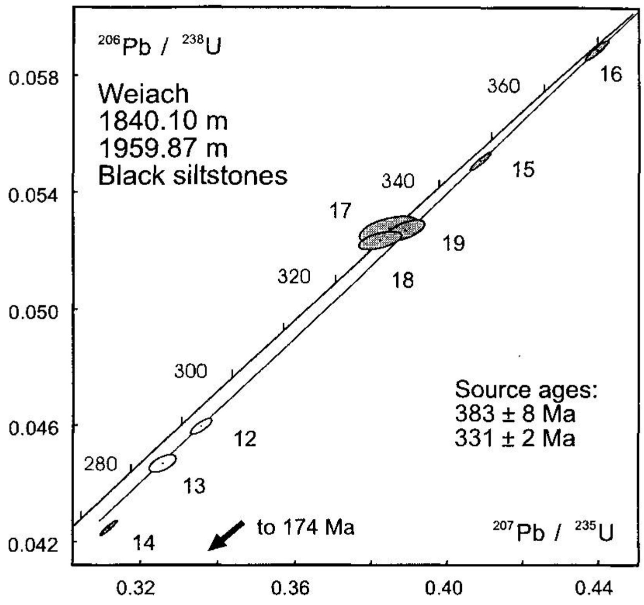

Fig. 5 U–Pb concordia diagram of samples 1840.10 m and 1959.87 m. Four zircon fractions of the two lowermost samples (12, 13, 15 and 16) define a discordia line intersecting at 383 ± 8 Ma and 174 ± 29 Ma. The upper intercept age is interpreted as the age of metamorphism in adjacent basement rocks; the Mesozoic age might reflect hydrothermal alteration of the siltstones, also determined by K–Ar dating of alteration clays (Schaltegger et al., 1995). Three single zircon determinations (17, 18, 19) cluster around an age of 331 Ma.

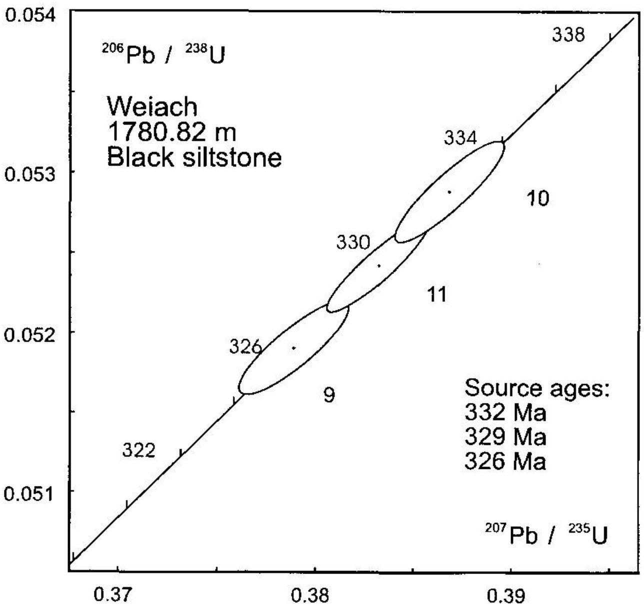

Fig. 4 U–Pb concordia diagram of sample WEI 1780.82 m. Three zircon fractions with completely different morphological characteristics define concordant ages of 326 Ma, 332 Ma and 329 Ma, compatible with the age range reported for the intrusion of the southern Black Forest granites.

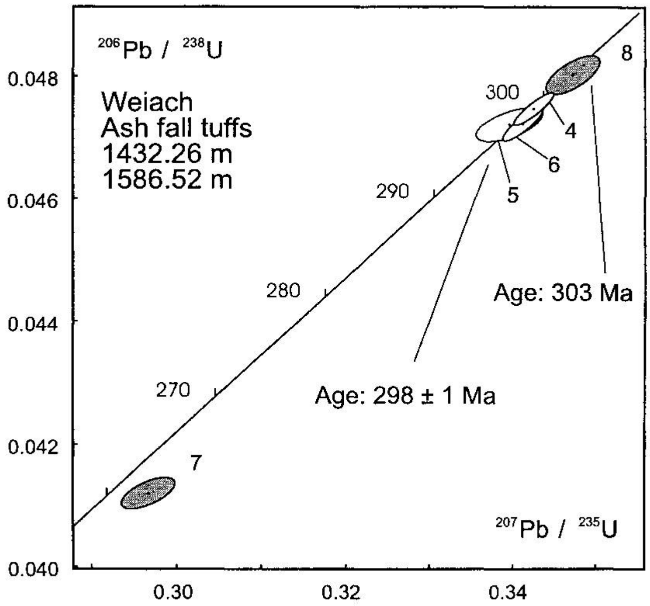

Fig. 6 U–Pb concordia diagram of samples WEI 1432.26 m and 1586.52 m, both volcanic ash-fall tuffs. Three zircon fractions of the stratigraphically higher tuff yield a well defined deposition age of 298 ± 1 Ma; the lower tuff at 1586.52 meters could only be dated by one single concordant fraction at 303 Ma (8); data point 7 is discordant due to secondary lead loss.

ASH FALL TUFFS

The stratigraphically younger sample at 1432.26 meters was taken from 16 meters above the inferred Stephanian/Autunian boundary of MATTER et al. (1988) and provided a homogeneous zircon population consisting of acicular euhedral grains. The mean age of three concordant fractions with low uranium contents of 100–200 ppm (analyses 4 to 6) was calculated at 298 ± 1 Ma (Fig. 6), identical to volcanism in the Northern Vosges (BOUTIN et al., 1995), northern Black Forest (HESS and LIPPOLT, 1986) and the Saar-Nahe basin (LIPPOLT and HESS, 1983), as well as in the Aar massif (SCHALTEGGER and CORFU, 1992, 1995).

A second, stratigraphically older sample yielded one concordant analysis (analysis 8) of nine short-prismatic euhedral grains at 302.5 Ma. Long-prismatic zircons with a considerably higher U concentration than the former ones (analysis 7) yielded a strongly discordant point with a $^{206}Pb/^{238}U$ age of 260 Ma; the $^{207}Pb/^{206}Pb$ age of 295.7 ± 7.7 Ma overlaps the age of the concordant fraction within errors.

Discussion

The PCT sedimentary pile was previously interpreted to be Stephanian to Autunian in age; possible extensions into the Westphalian at the bottom and to the Saxonian at the top have also been envisaged (MATTER et al., 1988; Fig. 7). The initial aim of this study, to constrain the duration of basin sedimentation precisely, could not be achieved due to the lack of ash-fall tuffs in different stratigraphic sites within the sediment pile. The results from this study reveal that the deposition at the base of the PCT took place after 331 Ma (sample 1959.87), i.e. Late Visean (ODIN, 1994). The tuff sample WEI 1432.26, dated at 298 Ma, is overlain by ca 250 meters of Autunian strata in Weiach and 1000 meters at the site of Riniken; a sedimentary facies suggesting rapid deposition suggests a short lifetime for the basin of a few million years only. The apparently concordant analysis of the tuff sample 1586.52 m might be biased by small amounts of young (e.g. 330 Ma old) inherited lead, which would lift the U–Pb age by few million years and rendering the age difference insignificant. With an age difference of 4.5 million years between the two tuff samples a sedimentation rate of 0.04 mm/year would result, which is far too small for the prevailing sedimentary facies. The age brackets of Upper Visean (331 Ma) and Westphalian/Stephanian (before 303 Ma) leave a maximum of 25 million years for the exhumation of the source rocks of the detrital zircons.

The ash fall tuffs at 1432.26 m and 1586.52 m are coeval to voluminous volcanic and plutonic rocks in the Aar massif (SCHALTEGGER and VON QUADT, 1990; SCHALTEGGER and CORFU, 1992, 1995). Contemporaneous volcanic activity is also recorded from ignimbrites and tuffs of the Nideck volcanics in the northern Vosges, dated at 298 ± 9 Ma (Ar–Ar biotite; BOUTIN et al., 1995) and 299 ± 7 Ma (K–Ar biotite, HESS and LIPPOLT, 1986), from a tuff of the Baden-Baden zone of the northern Black Forest, dated at 300 ± 1 Ma (Ar–Ar biotite, HESS and LIPPOLT, 1986) and from tuffs, ignimbrites and subvolcanic rhyolites of the Saar-Nahe basin, ranging between 296 ± 2 Ma and 299 ± 2 Ma (LIPPOLT and HESS, 1983).

Looking in detail at the sampling site of tuff WEI 1432.26, there is a ca. 16 meters distance between this sample and the underlying Stephanian/Autunian boundary (Fig. 7). The use of palynomorph associations typical for the "Autunian" has, however, been strongly questioned by BROUTIN et al. (1986) and BECQ-GIRAUDON (1993), who demonstrated that the composition of palynomorph associations depend on their paleotopographical setting: "Stephanian"-type pollen and spores in humid topographic lows coexist with "Autunian"-type associations on the dry basin shoulders. A real stratigraphic boundary between Stephanian and Autunian can, therefore, not be established with confidence at all. Nevertheless, the age of zircons from the tuff sampled in the proximity to the Stephanian/Autunian boundary of MATTER et al. (1988) from the Weiach borehole compares well with the age of 298 to 296 Ma for the Stephanian/Autunian boundary proposed by MENNING (1995). This suggests that the "Aar volcanic event" may indeed be used as a stratigraphic marker to define the Stephanian/Autunian boundary in continental sediments of central Europe.

The investigated detrital zircons from the clastic sediments (black siltstones) constrain a maximum depositional age of some 330 Ma by the youngest detrital zircon grains. The zircons reflect a dominant detrital source of ca. 332 to 325 Ma age, spanning the age range of Southern Black Forest granite intrusions: 328 ± 6 Ma for the Malsburg granite (TODT, 1976), 328 ± 2 Ma for the Albtal granite (SCHULER and STEIGER, 1978) and 331 +4/–2 and 334 ± 2 Ma for Bärhalde and St. Blasien granites (SCHALTEGGER, 1995, and unpublished results). Granitoids of the same age range have also been found in the Böttstein and Schafisheim wells (MAZUREK and PETERS, 1992) and seem to have constituted the major part of the outcropping crystalline basement in the north and south of the PCT. We can therefore speculate that the detritus was eroded from an area similar to todays' Southern Black Forest. The Late Visean granites were exhumed/unroofed and exposed along the basin sholders by normal faulting 300 Ma ago. The lowermost samples (1840.10 and 1959.87 m) are the only ones containing 385 Ma-old zircons. The upper intercept age of 383 ± 8 Ma of a lead loss line (Fig. 6) may represent a high-

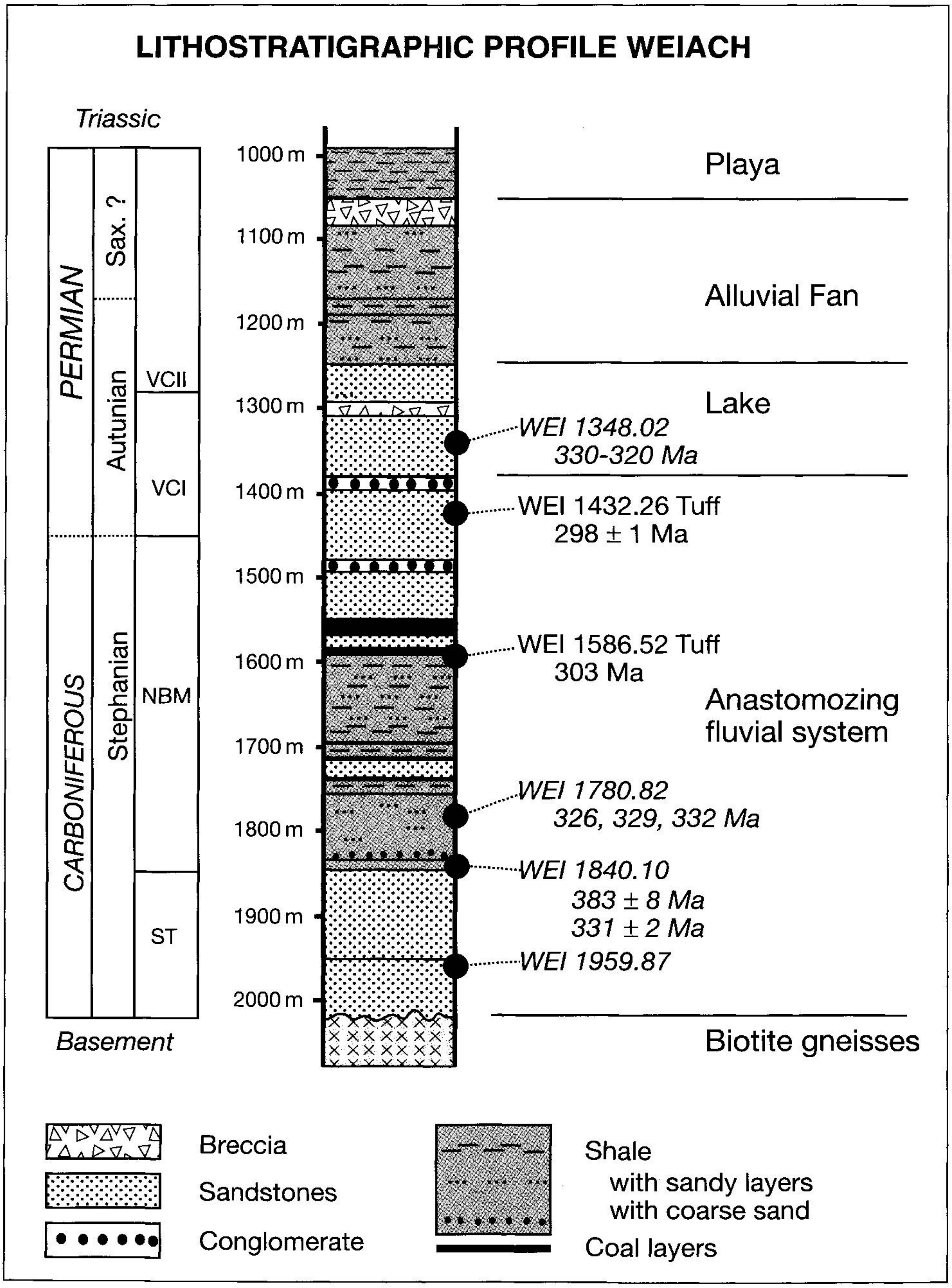

Fig. 7 Lithostratigraphic column of the Permocarboniferous of Weiach (NAGRA drilling; after MATTER et al., 1987), with sample numbers and U–Pb zircon ages; detrital zircon ages in italics. NBM, VCI and VCII are palynomorph associations according to HOCHULI (1985).

grade metamorphic or magmatic event in the adjacent basement, which has, however, not been reported for this area so far. This age compares very well with a concordant age of 386 ± 2 Ma from two detrital zircons in an Upper Devonian tuff of the Southern Vosges Basin (SCHALTEGGER et al., 1996) and suggests the existence of 385 Ma-old basement portions. The lower intercept age of 174 ± 29 Ma is in close agreement with K–Ar ages of 183 ± 5 Ma of clay minerals from the tuff (1432.26 m) and the siltstone sample (1959.87 m), interpreted as the result of strong hydrothermal alteration (SCHALTEGGER et al., 1995), and is therefore considered to be geologically relevant.

The deformation of the Lower Unit inferred from the interpretation of seismic cross-sections, has been assigned to the so-called "Saalian" tectonic phase, originally defined by H. Stille in 1920 as a deformation phase in the top of the Unterrotliegendes (Saxonian, 270–260 Ma). Sedimentation in the PCT thus precedes this tectonic activity by 30 million years, which contradicts the interpretations in LAUBSCHER (1987) and DIEBOLD et al. (1992). In addition, tectonic unconformities in extensional basins are not necessarily related to large-scale tectonic activity: parts of the extensional domains may become periodically compressive, probably due to slight variations of stress vector directions, or unconformities may be formed by block tilting and rotation during normal faulting along listric faults, without a break in sedimentation (BECQ-GIRAUDON and VAN DEN DRIESSCHE, 1993). The unconformity in the PCT, which was probably formed during dextral strike-slip (EDEL and WEBER, 1995), is therefore suggested to be the result of local transpression within the graben and not the response to a change of the large-scale tectonic environment. An angular unconformity in Upper Carboniferous sediments could recently be dated at a Lower Stephanian age (i.e. 310 to 303 Ma) in the Aar massif by SCHALTEGGER and CORFU (1995).

The PCT formed during post-convergence extension and strike-slip faulting in the collapsing Variscan crust (EDEL and WEBER, 1995; MÉNARD and MOLNAR, 1988; BURG et al., 1994; ZIEGLER et al., 1986). The present U–Pb results provide evidence that the formation of the PCT is coeval with the formation of volcano-sedimentary basins in the area of the Aar massif further to the south (SCHALTEGGER and CORFU, 1995); the same event is reflected in a series of Stephanian coal-bearing basins in the French Massif Central, e.g. the "sillon houiller" or the basin of St. Etienne (BURG et al., 1994; CAEN-VACHETTE et al., 1982). This indicates a large-scale tectonic process being responsible for the formation of Stephanian basins in Central Europe. The U–Pb data reveal that distant magmatism was contemporaneous with the subsidence of the PCT.

Conclusions

The age of sedimentation in the Permocarboniferous Trough of Northern Switzerland (PCT) was dated by U–Pb on zircon from tuffs of the Weiach borehole. Zircons from two ash fall tuffs from a distant volcanic center are 303 and 298 ± 2 Ma old. Coeval volcanism and plutonism is known from the Aar massif in the Central Alpine basement as well as from the Saxo-Thuringian domain to the north. The tuffs of this "Aar volcanic event" can be used as a stratigraphic reference level for the Stephanian/"Autunian" boundary in the continental sediments of Central Europe, for which an age estimate of 298 ± 2 Ma is proposed.

Detrital zircons yield Lower Devonian and Upper Visean ages. The youngest detrital zircons in the deepest sample define a maximum age of 331 ± 2 Ma for the beginning of sedimentation at Weiach on the northern basin shoulder. Lower Devonian zircons (383 ± 8 Ma) are interpreted to have been derived from metamorphic basement rocks, whereas zircons with ages around 332 to 326 Ma could have been derived from granitoids of areas adjacent to the PCT and similar to today's Southern Black Forest. The U–Pb zircon data furthermore imply that the deformation of the lower part of the PCT is due to late Variscan, Stephanian extension/transtension and is not related to the previously assumed "Saalian" tectonic phase. Angular unconformities in the sedimentary succession of extensional basins can be explained by episodic compression in a strike-slip environment and do not necessarily infer discontinuous sedimentation. The geodynamic setting and the sedimentological facies of red-bed sandstones in the upper part of the basin suggest rapid sedimentation and formation of the PCT within a short time span of only a few million years.

This study demonstrates the importance of geochronological information for testing geological interpretations based on geophysical, sedimentological and biostratigraphic data.

Acknowledgements

The U–Pb determinations were carried out at the Royal Ontario Museum in Toronto/Canada, during a short-time fellowship in fall 1993. The staff of the ROM is thanked for help and support, especially F. Corfu for discussions and some of the analyses. Financial support of the "Paul-Niggli-Stiftung", Zürich, the "Stiftung Vulkaninstitut Immanuel Friedländer", Zürich, and ETH Zürich is kindly acknowledged. The National Cooperative for Disposal of Radioactive Waste (NAGRA, Wettingen) kindly provided the sample material from the Weiach drill-cores. The use of the facilities at the Mineralogy Department of Basel, the Isotope Geology Laboratory in Bern and the Centre de Géochimie de la Surface in Strasbourg for sample preparation is kindly acknowledged. Comments of W. Leu (Geoform, Winterthur), J. Kramers (Bern) and D. Seward (Zürich) helped to improve the manuscript. R. Frei (Bern) carefully reviewed and improved the rather chaotic first version of this manuscript.

References

BECQ-GIRAUDON, J.F. (1993): Problèmes de la biostratigraphie dans le Paléozoïque supérieur continental (Stéphanien-Autunien) du Massif Central. Geodin. Acta 6, 219–224.

BECQ-GIRAUDON, J.-F. and VAN DEN DRIESSCHE, J. (1993): Continuité de la sédimentation entre le Stéphanien et l'Autunien dans le bassin de Graissessac-Lodève (sud du Massif Central): implications tectoniques. C.R. Acad. Sci. Paris II, 317, 939–945.

BOUTIN, R., MONTIGNY, R. and THUIZAT, R. (1995): Chronologie K–Ar et ^{40}Ar–^{39}Ar du métamorphisme et du magmatisme des Vosges. Comparaison avec les massifs varisques avoisinants et détermination de l'âge de la limite Viséen inférieur – Viséen supérieur. Geol. France 1/1995, 3–25.

BROUTIN, J.J., DOUBINGER, J., LANGIAUX, X. and PRIMEY, D. (1986): Conséquences de la coexistence de flores à charactères stéphaniens et autuniens dans les bassins limniques d'Europe occidentale. Mem. Soc. Géol. Gr. 149, 15–25.

BURG, J.P., VAN DEN DRIESSCHE, J. and BRUN, J.P. (1994): Syn- to post-thickening extension in the Variscan Belt of Western Europe: mode and structural conséquences. Géol. de la France 3, 1994, 33–51.

CAEN-VACHETTE, M., COUTURIÉ, J.P. and DIDIER, J. (1982): Ages radiométriques des granites anatectiques et tardimigmatiques du Velay (M. C. F.). C. R. Acad. Sci. Paris 294, 135–138.

DIEBOLD, P. (1989): Der Nordschweizer Permokarbon-Trog und die Steinkohlenfrage in der Nordschweiz. Beitr. Geol. Schweiz, Kl. Mitt. 81, 174 pp.

DIEBOLD, P., NAEF, H. and AMMAN, M. (1992): Zur Tektonik der zentralen Nordschweiz. Geol. Ber. 14, Landeshydrol. u. -geol., Bern 276 pp.

EDEL, J.B. and WEBER, K. (1995): Cadomian terranes, wrench faulting and thrusting in the central Europe Variscides: geophysical and geological evidence. Geol. Rundschau 84, 412–432.

HESS, J.C. and LIPPOLT, H.J. (1986): ^{40}Ar–^{39}Ar ages of tonstein and tuff sanidines: new calibration points for the improvement of the Upper Carboniferous time scale. Chem. Geol. (Isot. Geosci. Sect.) 59, 143–154.

HOCHULI, P.A. (1985): Palynostratigraphische Gliederung und Korrelation des Permokarbons der Nordschweiz. Eclogae geol. Helv. 78, 719–831.

KETTEL, D. and HERZOG, M. (1988): Das Permokarbon der süddeutschen Westmolassse – Ein Muttergestein für Öl- und Gaslagerstätten? Erdöl-Erdgas-Kohle 104/4, 154–157.

KROGH, T.E. (1973): A low contamination method for the hydrothermal decomposition of zircon and extraction of U–Pb for isotopic age determinations. Geochim. Cosmochim. Acta 37, 637–649.

KROGH, T.E. (1982): Improved accuracy of U–Pb zircon ages by the creation of more concordant systems using an air abrasion technique. Geochim. Cosmochim. Acta 37, 637–649.

LAUBSCHER, H.P. (1987): Die tektonische Entwicklung der Nordschweiz. Eclogae geol. Helv. 80, 287–303.

LEMCKE, K. (1961): Ein jungpaläozoischer Trog unter dem Süddeutschen Molassebecken. Z. dtsc h. geol. Ges. 113/1, 176–181.

LIPPOLT, H.J. and HESS, J.C. (1983): Isotopic evidence for stratigraphic position of the Saar-Nahe Rotliegend volcanism. I. ^{40}Ar–^{39}K and ^{40}Ar–^{39}Ar investigations. N. Jb. Geol. Paläont. Mh. 12, 713–730.

MATTER, A. (1987): Faciesanalyse und Ablagerungsmilieu des Permokarbons im Nordschweizer Trog. Eclogae geol. Helv. 80, 345–367.

MATTER, A., PETERS, T., ISENSCHMID, C., BLÄSI, H.R. and ZIEGLER, H.J. (1987): Sondierbohrung Riniken – Geologie. NAGRA Tech. Ber. NTB 86-02.

MATTER, A., PETERS, T., BLÄSI, H.-R., MEYER, J., ISCHI, H. and MEYER, CH. (1988): Sondierbohrung Weiach – Geologie. NAGRA Tech. Ber. NTB 86-01.

MAZUREK, M. and PETERS, TJ. (1992): Petrographie des kristallinen Grundgebirges der Nordschweiz und Systematik der herzynischen Granite. Schweiz. Mineral. Petrogr. Mitt. 72, 11–36.

MÉNARD, G. and MOLNAR, P. (1988): Collapse of a Hercynian Tibetan Plateau into a late Paleozoic European Basin and Range Province. Nature 334, 235–237.

MENNING, M. (1995): A numerical time scale for the Permian and Triassic Periods: An integrated time analysis. In: SCHOLLE, P.A., PERYT, T.M. and ULMER-SCHOLLE, D.S. (eds): The Permian of Northern Pangea. Vol. 1., Springer Berlin, 77–97.

ODIN (1994): Geological time scale (1994), C. R. Acad. Sci. Paris 318, II, 59–71.

PETERS, T. (1987): Das Kristallin der Nordschweiz: Petrographie und hydrothermale Umwandlungen. Eclogae geol. Helv. 80, 305–322.

PUPIN, J.P. (1980): Zircon and granite petrology. Contrib. Mineral. Petrol. 73, 207–220.

SCHALTEGGER, U. (1995): High-resolution chronometry of Late Variscan extensional magmatism and basin formation: examples from the Vosges, Black Forest and Alpine basement. Alfred-Wegener-Stiftung, Bonn. Terra Nostra 7/95, 109–111.

SCHALTEGGER, U. and CORFU, F. (1992): The age and source for late Hercynian magmatism in the Central Alps: Evidence from precise U–Pb ages and initial Hf isotopes. Contrib. Mineral. Petrol. 111, 329–344.

SCHALTEGGER, U. and CORFU, F. (1995): Late Variscan "basin and range" magmatism and tectonics in the Central Alps: Evidence from U–Pb geochronology. Geodin. Acta 8, 82–98.

SCHALTEGGER, U. and VON QUADT, A. (1990): U–Pb zircon dating of the Central Aar Granite (Aar Massif, Switzerland). Schweiz. Mineral. Petrogr. Mitt. 70, 361–371.

SCHALTEGGER, U., ZWINGMANN, H., CLAUER, N., LARQUÉ, PH. and STILLE, P. (1995): K–Ar dating of a Mesozoic hydrothermal activity in Carboniferous to Triassic clay minerals of northern Switzerland. Schweiz. Mineral. Petrogr. Mitt. 75, 163–176.

SCHALTEGGER, U., SCHNEIDER, J.L., MAURIN, J.C. and CORFU, F. (1996): Precise U–Pb chronometry of basin formation and magmatism related to syn-convergent extension (Central Variscan Belt, Southern

Vosges, France). Earth Planet. Sci. Lett. 144, 403–419.

SCHULER, C. and STEIGER, R.H. (1978): On the genesis of feldspar megacrysts in granites: an Rb–Sr isotopic study. ICOG 4, Abstracts; ZARTMAN, R.E. (ed.), 386–387.

STACEY, J.S. and KRAMERS, J.D. (1975): Approximation of terrestrial lead isotope evolution by a two-stage model. Earth Planet. Sci. Lett. 26, 207–221.

THURY, M., GAUTSCHI, A., MAZUREK, M., MÜLLER, W.H., NAEF, H., PEARSON, F.J., VOMVORIS, S. and WILSON, W. (1994): Geology and hydrogeology of the crystalline basement of Northern Switzerland. Geol. Ber. 18, Landeshydrol. u. -geol., Bern.

TODT, W. (1976): Zirkon U/Pb-Alter des Malsburg-Granits vom Süd-Schwarzwald. N. Jb. Miner. Mh. H.12, 532–544.

VOLLMAYR, T. and WENDT, A. (1987): Die Erdgasbohrung Entlebuch 1, ein Tiefenaufschluss am Alpennordrand. Bull. Ver. schweiz. Petroleum-Geol. u. -Ing. 53, 67–79.

ZIEGLER, P.A. (1986): Geodynamic model for the Paleozoic crustal consolidation of Western and Central Europe. Tectonophysics 126, 303–328.

Manuscript received May 23, 1996; revised manuscript accepted January 20, 1997.