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Autor: Gebauer, Dieter / Williams, Ian S. / Compston, William

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The development of the Central European continental crust since the Early Archaean based on conventional and ion-microprobe dating of detrital zircons up to 3.84 b.y. old*

with 10 figs and 2 tabs

by DIETER GEBAUER 1, IAN S. WILLIAMS 2, WILLIAM COMPSTON 2 and MARC GRÜNENFELDER 1

Zusammenfassung

U-Pb Ionensondendatierungen an detritischen Zirkonen aus Sedimenten und Metasedimenten der europäischen Varisziden zeigen, dass sich die entsprechende, kontinentale Kruste spätestens ab 3.84 Mrd.J. in vielen geologischen Ereignissen ge-und umgebildet hat. Das variszische Europa besteht v.a. aus Teilen Gondwanas bzw. aus Detritus, der von Gondwana aberodiert wurde und heute in den weitverbreiteten, post-Panafrikanischen Sedimenten und Metasedimenten wiederzufinden ist.

Abstract

Archean components up to 3.84 b.y. old have been detected by ion-microprobe dating of zircon from various sediments and metasediments of the European Hercynides (Moldanubicum of NE Bavaria and French Central Massif). The Early Archean age of 3.84 b.y. was obtained within the euhedral core of a detrital grain from a Moldanubian paragneiss. The same detrital zircon grain reveals at least 3 ages of metamorphic overprints — 2.59 b.y., 1.94 b.y. and 460 m.y. — and at least two cycles of mechanical abrasion during surface recycling in the Early Proterozoic and after the Pan-African cycle. It is thus the crystal with the most complex geological history ever detected. Further Archean ages for the crystallization of primary magmatic zircons, probably in the course of continental crust formation in the first cycle provenances of the two studied areas, were found at 3.15 b.y., 2.9 b.y., 2.76 b.y., 2.65 b.y. and in a few cases between 2.5 b.y. and 2.6 b.y.

Early Proterozoic crust-forming events between about 1.75 b.y. and 2.15 b.y. play an important role especially for the sediments and metasediments of the Montagne Noire at the southern rim of the French Central massif. Middle and Upper Proterozoic ages cluster around 1.0 b.y. and ca. 600 m.y. for all analysed samples. Consequently, the deposition of the metasedimentary precursors took place after the Pan-African cycle which is in line with the Rb-Sr whole-rock systematics of Central European metasediments.

The ages of metamorphism in the different source areas could be inferred in some cases by lower intercept ages obtained on single detrital grains. The following sequence coinciding with times of magmatic events, has been established so far: 2.59 b.y., 1.94 b.y., 1.0 b.y. and 600 m.y.. Thus, ion probe dating is also capable of defining secondary effects in the respective provenances which are typical for orogenic cycles.

The ubiquitous presence of Pan-African detrital zircons in European metasediments is a strong indication that the detrital material was derived from Gondwana. Howerer, from the presence of metamorphic units including eclogite-facies rocks which probably formed at different continental margins and at various times between about 500 m.y. and 330 m.y. ago it is probable that various Gondwana-derived micro-continental plates contributed to the different basin fillings. The Gondwana-derived detritus is also supported by the observation of two periods of relative quiescence or non-activity around 2.3 b.y. and especially around 1.5 b.y. which is a typical feature observed in Gondwana (CAHEN et al., 1984) but not in Laurasia, the other possible source of the detritus. The lack of zircons crystallized between 3.84 b.y. and 3.15 b.y. might have different causes.

Thus, the continental crust of the European Hercynides probably developed since the Early Archean and grew via many crust adding events to its present state.

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1 Laboratory for Isotope Geochemistry and Mass Spectrometry, Swiss Federal Institute of Technology, 8092 Zürich (Switzerland)

2 Research School of Earth Sciences, The Australian National University, Canberra, A.C.T. 2601 (Australia)

Introduction

The presence of Early and Middle Proterozoic components in many parts of the continental crust of the European Hercynides could have been inferred from a number of conventional analyses of mostly detrital zircons made during the last 20 years. However, because most Rb-Sr data were interpreted to suggest continental crust formation at the earliest in the Late Proterozoic after about 700 m.y. (e.g. JÄGER, 1977; VIDAL, 1977 VIDAL et al. 1981), the upper intercept ages of about 2 b.y. for the conventional zircon data were largely ignored. They were generally interpreted to reflect average provenance ages of areas far from their respective depositional sites, as it was known that zircons can travel very long distances. Unfortunately, this interpretation completely neglected the depositional environment of the host rocks of the analysed zircons that were mainly metagreywackes, metamorphosed sandstones, in parts flyschlike, metaquartzites and even metaconglomerates. These suggest depositional environments close to a continental margin and consequently it is also probable that the rest of the detritus was derived from the same source region. The apparent conflict with the numerous Rb-Sr data is overcome if one considers the fact that Rb-Sr whole-rock systems are easily opened during weathering, transport and deposition, producing higher Rb-Sr ratios, and that erosion preferably taps the upper continental crust where Rb-Sr ratios are much higher than in the average crust. Thus, applying average crustal Rb-Sr ratios to the observed or inferred Sr-isotopic ratios increases the respective model ages to values close to the Sm-Nd model ages. The latter became available in the early 80's and also contradict the original interpretation of the Rb-Sr model ages, as they are nearly always older than 700 m.y. and usually younger than about 2 b.y.. Consequently, there still remains a time gap between the Nd-model ages, which average around 1.5 b.y., and ages inferred from conventional zircon data, which average about 2 b.y.. It has been suggested (GEBAUER, 1986) that neither of these methods gives reliable information on the average age of the continental crust of the European Hercynides because of multiple mantle interaction in case of the Nd-model ages and mainly lead loss during metamorphism in the case of the zircons. Both processes would lower the respective mean ages, especially the Nd-model ages which are about 500 m.y. younger than the corresponding conventional U-Pb zircon ages. From this it is concluded that U-Pb data on single zircon grains, preferably on cores, are the most likely to give good estimates of the ages of the crust-forming events producing the material which we find today in the basement and sedimentary cover of the European Hercynides. For this reason numerous detrital zircons extracted from a variety of sedimentary and metasedimentary host-rocks were analysed for U-Pb using SHRIMP (Sensitive High Resolution Ion Micro-Probe) at the Research School of Earth Sciences at ANU. However, as the over 300 SHRIMP analyses cannot be discussed in detail in this summary paper as given at the 1987 EUG meeting in Strasbourg, we will deal here only with the significance of the concordant and extrapolated Concordia ages obtained. A full description of the SHRIMP data is being prepared and will be published elsewhere.

Samples were taken from two geological units of the Central European Hercynides, the Moldanubian zone of NE Bavaria and the Montagne Noire at the southern rim of the French Central Massif. The latter unit not only comprises high-grade metamorphic rock as in the Moldanubicum, but also includes unmetamorphosed and anchimetamorphic Palaeozoic sediments.

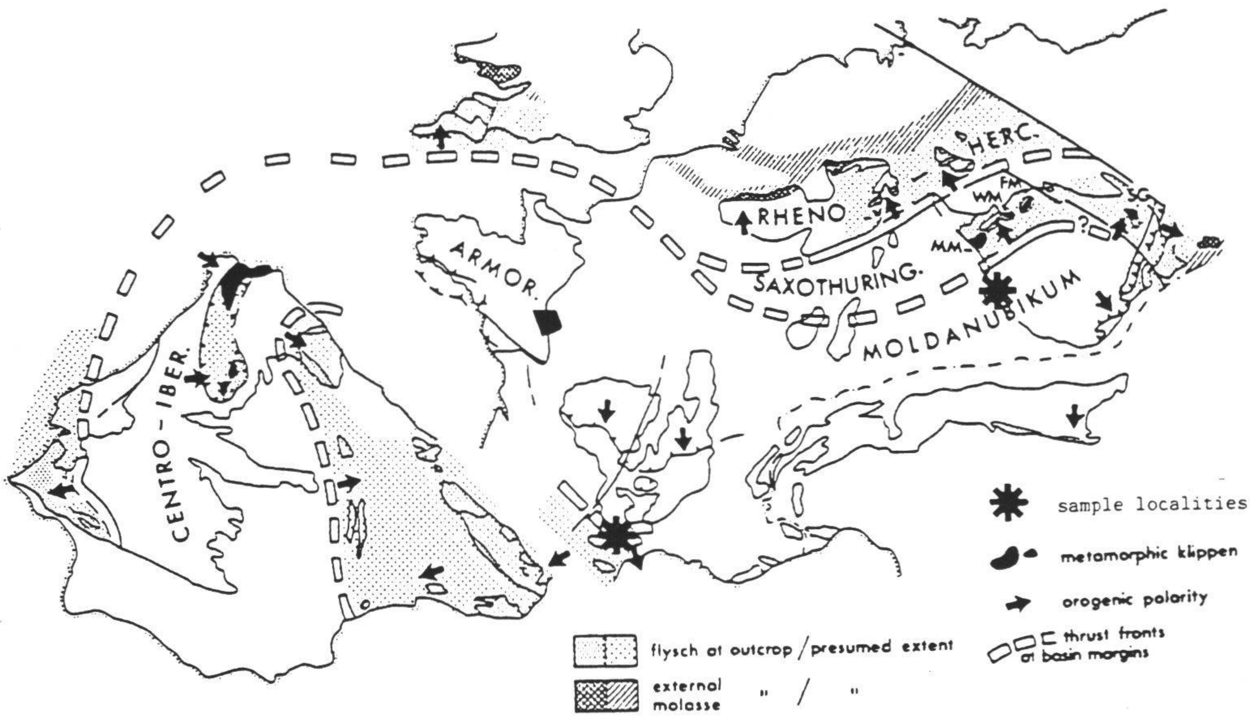

Fig. 1 Major geological units of the European Hercynides (after FRANKE and ENGEL, 1983). Sample localities are in the Moldanubian basement of NE-Bavaria and in the Montagne Noire at the southern rim of the French Central Massif (big stars).

Analytical Techniques

For the conventional zircon analyses and the Rb-Sr analyses we refer to GEBAUER and GRÜNENFELDER (1974 and 1976). The ion microprobe technique is described by COMPSTON et al. (1984 and 1986). All ionprobe ages are referenced to an age of 552 m.y. for the SL 3 standard.

Moldanubian rocks of NE Bavaria

Sampling

Samples were taken within about 30 m of a small quarry in the Moldanubian basement of NE-Bavaria ca. 35 km ENE of the city of Regensburg (fig. 1 and 2). This quarry, near the village of Völling, is situated within a 2-5 km wide and about 16 km long paragneiss syncline which is surrounded by a coarse-grained, porphyritic granite of S-type affinity and-according to KÖHLER and MÜLLER-SOHNIUS (1976) — of Carboniferous age. A detailed description of the geological and geochronological development of the Bavarian part of the Moldanubicum is given by GEBAUER (1984). Fig. 2 shows the lithological setting of the quarry with a zone of fine-grained biotite-plagioclase gneisses (palaeosome) grading on either side into completely melted, medium grained derivatives (diatexites). Calc-silicate gneisses and amphibolites resisted melting and thus swim as relics in the diatectic melts which frequently show nebulitic textures. Regionally, similar sedimentary sequences are typical of large areas of the Moldanubian block. They are intruded by numerous granitoids of mainly Carboniferous age. The time of first metamorphism of the metasedimentary sequences varies between Early Ordovician and Carboniferous depending on the tectonic unit under consideration.

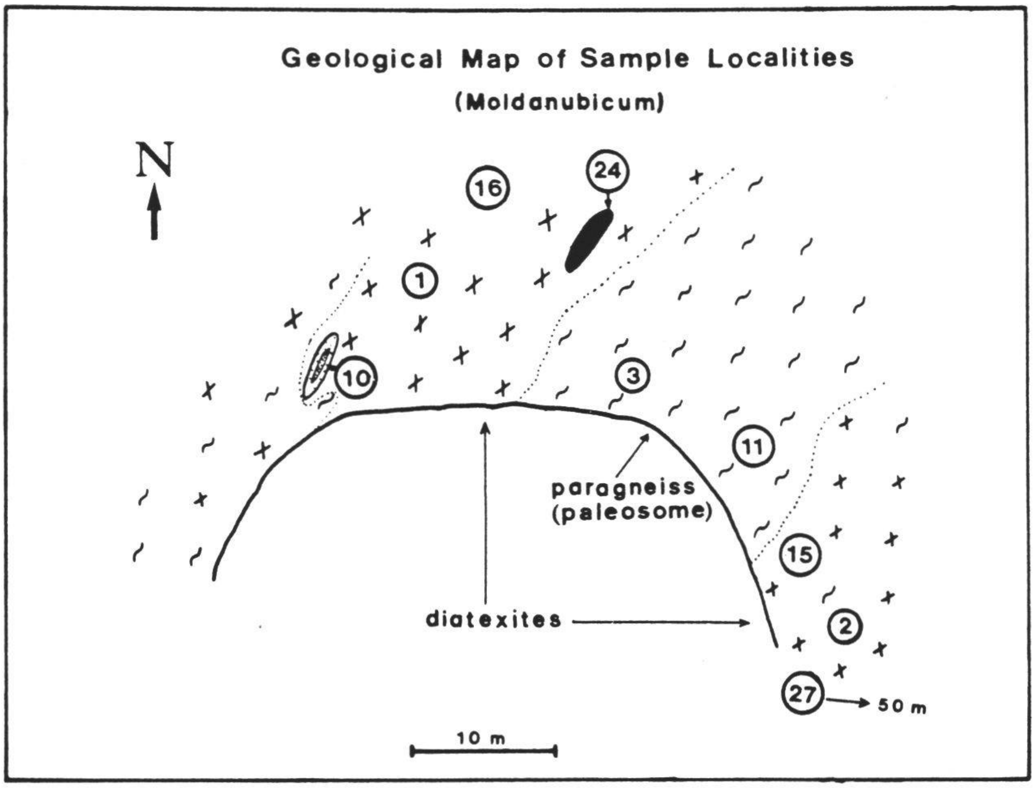

Fig. 2 Geological — petrological sketch map of the quarry Völling in the Regensburg Forest with sample localities. The two boudins of a calcsilicate-gniess (10) and an amphibolite (24) are not to scale.

Analytical results

To set the scene for the zircon ion-probe data we will first discuss Rb-Sr data obtained on whole-rocks and minerals from the quarry at Völling and then proceed to conventional zircon and xenotime data obtained on the gneisses and their in situ anatectic end products.

Rb-Sr data

Rb-Sr results on ca. 20 kg whole-rock samples indicate that the nonanatectic source rock, the completely melted paragneisses as well as the inner and outer zone of a zoned calc-silicate boudin swimming in a nebulitic part of a diatexite equlibrated isotopically 459 ± 21 m.y. ago (fig. 3). This age, which is also reflected in the zircon data, is interpreted to correspond to the time of high-grade metamorphism and anatexis. The amphibolite boudin obviously did not equilibrate for Sr-isotopes and/or gained some Rb relative to Sr during possible K-metasomatism. A following Hercynian event at 320 ± 7 m.y. did not penetratively deform any of the analysed rock-systems but reset mineral systems of the palaeosome (biotite, plagioclase, k-feldspar and apatite) as well as small adjacent whole-rock systems (leucosome and melanosome). Equally, U — Pb systems in various grain-size fractions of xenotime extracted from both non-anatectic starting material and 2 diatexites date this later Hercynian event at 322 ± 2 m.y. (figs. 4 and 5).

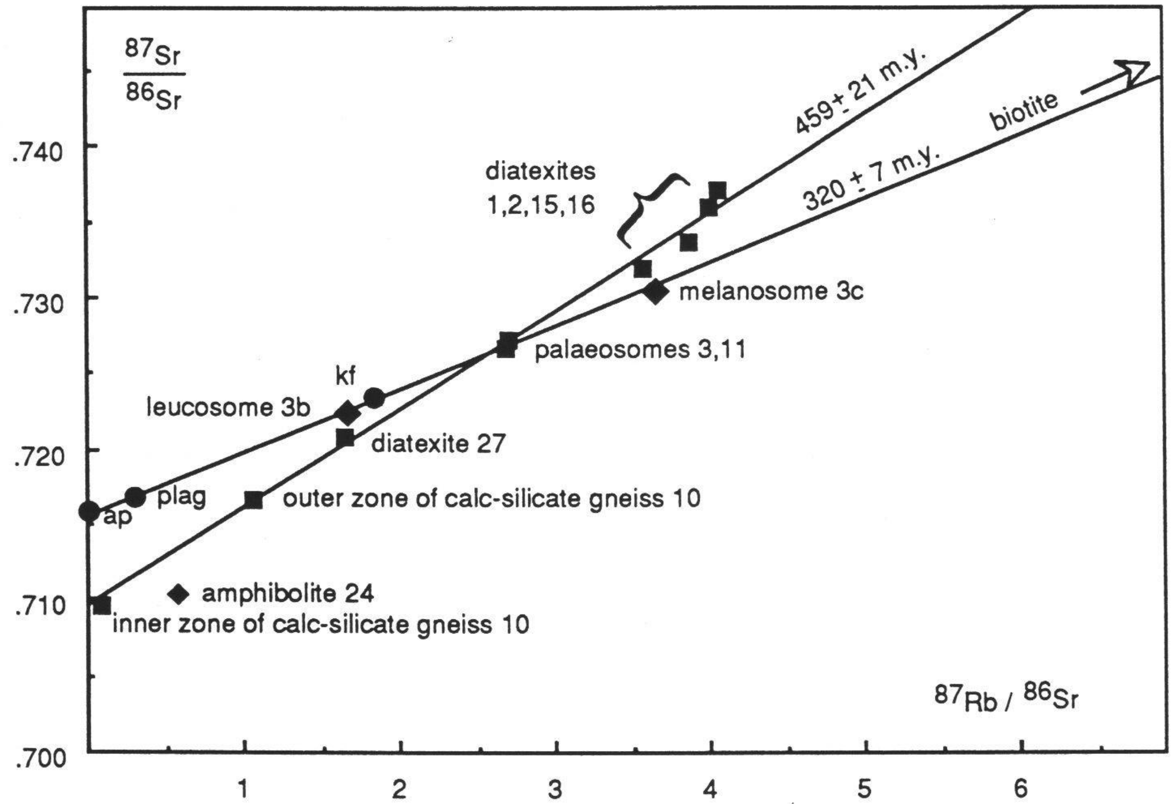

Fig. 3 Rb-Sr isochron diagram for whole-rocks and minerals from the quarry at Völling (Moldanubicum of NE-Bavaria). The initial 87Sr/86Sr for whole-rocks is 7096 ± 8, for the minerals 7152 ± 4.

Sample No. in Figs. 2 and 3	Rb (ppm)	Sr (ppm)	$^{87}Rb/^{86}Sr$	$(^{87}Sr/^{86}Sr)_{norm.}$
WHOLE ROCKS				
1	160	120	3.87	.73374 ± 19
				.73385 ± 27 (duplicate)
2	168	120	4.06	.73722 ± 40
3	159	173	2.67	.72681 ± 39
3b	130	224	1.68	.72246 ± 23
3c	160	129	3.62	.73056 ± 60
10 (inner zone)	26.7	928	.083	.70977 ± 16
10 (outer zone)	96.1	264	1.06	.71675 ± 22
11	171	183	2.69	.72735 ± 28
15	168	122	4.00	.73609 ± 40
16	125	102	3.57	.73217 ± 49
24	31.0	154	.582	.71047 ± 57
27	118	209	1.64	.72089 ± 34
MINERALS FROM WHOLE ROCK NO.3 (PALEOSOME)				
apatite	1.63	178	.0266	.71585 ± 70
plagioclase	40.8	392	.3015	.71671 ± 24
k-feldspar	242	381	1.839	.72353 ± 40
biotite	542	17.7	92.42	1.1384 ± 44

Tab. 1 Rb-Sr analytical data of whole-rocks and minerals of the quarry at Völling in the Regensburg Forest

Conventional zircon data

Calc-silicate gneiss boudin

The conventional zircon data were largely produced in the early seventies in the course of the Ph.D thesis of the first author and are shown in figs. 4 and 5. Four size-and magnetic fractions extracted from the core of the calc-silicate gneiss boudin swimming within a nebulitic part of a diatectic melt plot on a discordia trajectory intersecting the Concordia curve at 464 + 39/-48 m.y. and 1943 + 240/-206 m.y., respectively (fig. 4). As we are dealing within each analysed fraction with many thousands of individual detrital grains which can be heterogeneous in age patterns both between and within themselves, the upper intercept age can only be an average of the individual discordance patterns which, as we will see later, can vary on a submicron scale. Consequently, the figure of about 2 b.y. in fig. 4 represents a minimum estimate for the average primary crystallization age of the analysed zircon mixture. This is so because any disturbance occurring within the individual U-Pb domains after their primary magmatic formatin will generally decrease the respective ages. Thus, the provenance which delivered the detrital zircons into the original dolomitic-marly siltstone has an average crustal residence age greater than 2 b.y.. Probably also due to the large number of individual grains

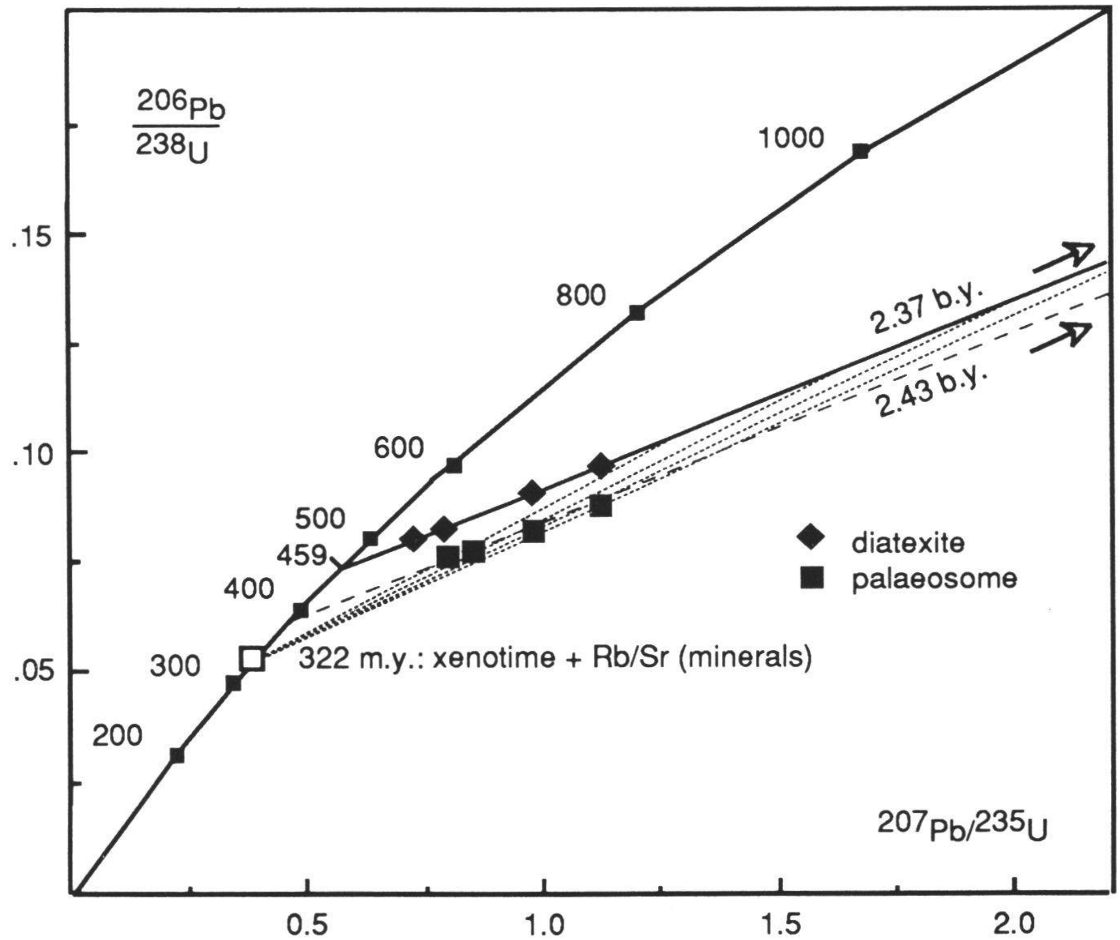

Fig. 4 Concordia-diagram with conventional U-Pb data obtained on size-and magnetic fractions of zircons from the core of a calcsilicate gneiss and a diatexite (completely melted paragneiss). The 2 sigma errors on the lower intercept of the calcsilicate gneiss trajectory (464 m.y.) are +39 m.y. and -48 m.y.. Upper intercept errors are +240 m.y. and -206 m.y. for the calcsilicate gneiss discordia and +100 m.y. and -96 m.y. for the diatexite.

Sieve fraction (microns)	U (ppm)	Pb rad. (ppm)	$\frac{^{206}Pb}{^{204}Pb}$	radiogenic lead in % 206	207	208	atomic ratios $\frac{^{206}Pb}{^{238}U}$	$\frac{^{207}Pb}{^{235}U}$	$\frac{^{207}Pb}{^{206}Pb}$	apparent ages (m.y.) $\frac{^{206}Pb}{^{238}U}$	$\frac{^{207}Pb}{^{235}U}$	$\frac{^{207}Pb}{^{206}Pb}$
CALCSILICATE GNEIS : ZIRCONS												
- 53 m.	724	70.9	5017	84.91	6.22	8.87	.09657	.975	.07322	594	691	1020
53- 65	653	64.5	2143	84.52	6.44	9.04	.09701	1.019	.07620	597	714	1101
total fraction	633	67.9	4692	84.29	6.64	9.07	.10510	1.141	.07877	644	773	1166
+ 65 n. m.	546	64.1	5361	83.78	7.05	9.17	.11440	1.328	.08412	699	858	1296
BIOTITE-PLAGIOCLASE GNEIS : ZIRCONS												
- 42 m.	917	70.2	6982	86.80	6.56	6.63	.07727	.806	.07562	480	600	1085
repetition	893	68.0	3895	86.69	6.56	6.74	.07682	.802	.07568	477	598	1087
42- 53	864	65.8	15500	87.17	6.95	5.87	.07719	.849	.07977	479	624	1191
53- 75	849	70.3	3056	86.11	7.32	6.57	.08302	.974	.08504	514	690	1317
75-100	812	72.7	6252	85.20	7.82	6.98	.08876	1.123	.09176	548	764	1462
+100 n. m.	725	74.1	12216	83.73	8.22	8.05	.09962	1.349	.09822	612	867	1591
DIATXITE I : ZIRCONS												
- 42 m.	967	79.9	7995	83.78	5.46	10.77	.08049	.723	.06514	499	552	779
- 42 n. m.	742	61.2	7155	85.98	5.96	8.06	.08250	.788	.06928	511	590	907
75-100	640	59.8	5188	83.89	6.51	9.60	.09114	.975	.07757	562	691	1136
+100	566	56.6	7151	83.95	7.10	8.95	.09766	1.138	.08451	601	772	1304
BIOTITE-PLAGIOCLASE GNEIS : XENOTIME												
- 53	4377	718	10103	71.64	1.43	26.94	.05107	.373	.05291	321	322	325
DIATEXITE I : XENOTIME												
- 53	6580	700	15870	56.30	2.20	41.51	.05113	.373	.05289	322	322	324
DIATEXITE II: XENOTIME												
- 36	4495	787	5018	25.45	1.35	73.20	.05152	.376	.05297	324	324	328

* U/Pb ratio in the spike solution about 20/1 compared to 5/1 for all the other analyses.
m. and n. m. refers to fractions which moved along the "magnetic" resp. "not magnetic side " of the Frantz isodynamic separator if it was run at 1.6 amps, 1° tilt and 20° slope.

Tab. 2 U-Pb analytical data of zircons and xenotimes of various rock types of the quarry at Völling in the Regensburg Forest.

in the analysed fractions, the degree of discordance increases with increasing U-content (546-724 ppm) and decreasing grain size, an observation typically found for cogenetic, but also for many detrital zircon suites showing no metamorphic new-or overgrowth. The lower intercept at 464 ± 39/-48 m.y. agrees very well with the Rb-Sr whole-rock age of 459 ± 21 m.y.. It can best be explained by episodic loss of radiogenic lead in the course of high-grade Caledonian metamorphism. Evidently, the largely thermal overprint in the Hercynian did not reopen a significant number of U-Pb domains in the detrital zircons from the relatively dry core of the calc-silicate gneiss boudin.

Diatexite 1

Diatexite 1, the host rock of the calc-silicate boudin from the central part of the quarry (fig. 2), shows a similar discordance pattern with an almost identical lower intercept age at 459 + 7/-8 m.y. (fig. 4). The degree of discordance again is correlated with grain-size, U-content and magnetic susceptibility. When compared to the zircon population of the calc-silicate gneiss the upper intercept age at 2373 + 100/-96 m.y. indicates significantly older zircons in its provenance. It clearly shows that the depleted mantle Nd-model age of diatexite I at about 1.5 b.y. (unpublished data) yields a much lower average crustal residence age than the zircon data would suggest. Similar discrepancies are symptomatic of the Central European continental crust and might be explained with the presence of young, zircon-free or zircon-poor, Nd-rich components in the respective sedimentary, magmatic or metamorphic rocks, multiple mantle interaction increasing 143Nd/144Nd and / or with open system behaviour of Sm-Nd during recycling.

Biotite-plagioclase gneiss (palaeosome)

Five grain size - and magnetic fractions extracted from the fine-grained palaeosome of the quarry (fig. 2) do not fall on a single discordia line but scatter very slightly about a regression line intersecting the Concordia curve at 384 m.y. and 2429 m.y., respectively (fig. 5). Nevertheless, there is the usual relationship between degree of discordance and U-content, grain size and magnetic susceptibility. Both the slight scatter just outside analytical error limits and the «new lower intercept age» at 384 m.y. favour the probability that all of the analysed fractions suffered, besides the strong Caledonian lead loss around 460 m.y., an additional loss of radiogenic lead in the Hercynian. Based on the ion-probe data new growth of zircon in the Hercynian, which also could explain the observed discordancy patterns, is missing. As mentioned above, xenotimes of the palaeosome and 2 diatexites yield ages of 322 m.y. (fig. 4) while Rb-Sr mineral - and small whole-rock systems of the palaeosome, respectively a contiguous leucosome and melanosome, equilibrated isotopically at 320 ± 7 m.y. (fig. 3). Thus, the combination of parameters necessary to partly reopen U-Pb systems in zircon were fulfilled for the palaeosome but not, or possibly just not, for the diatexite I and the calc-silicate boudin swimming in it. These parameters will include not only temperature and pressure but also type and amount of fluid activity, individual trace element characteristics and crystallographic state of zircon domains, amount, type, distribution and history of strain and stress and further uncontrollable or unknown factors. The upper intercept age at 2429 m.y. agrees well within analytical error limits with that of its completely melted derivative, diatexite I which is at 2373 m.y.. In order to better understand the «polymetamorphic U-Pb zircon systematics» in this rock, ion probe analyses were performed on single spots of numerous, individual grains. In addition, single grains and zones within grains were multiply analysed in order to obtain information on their respective magmatic and metamorphic histories.

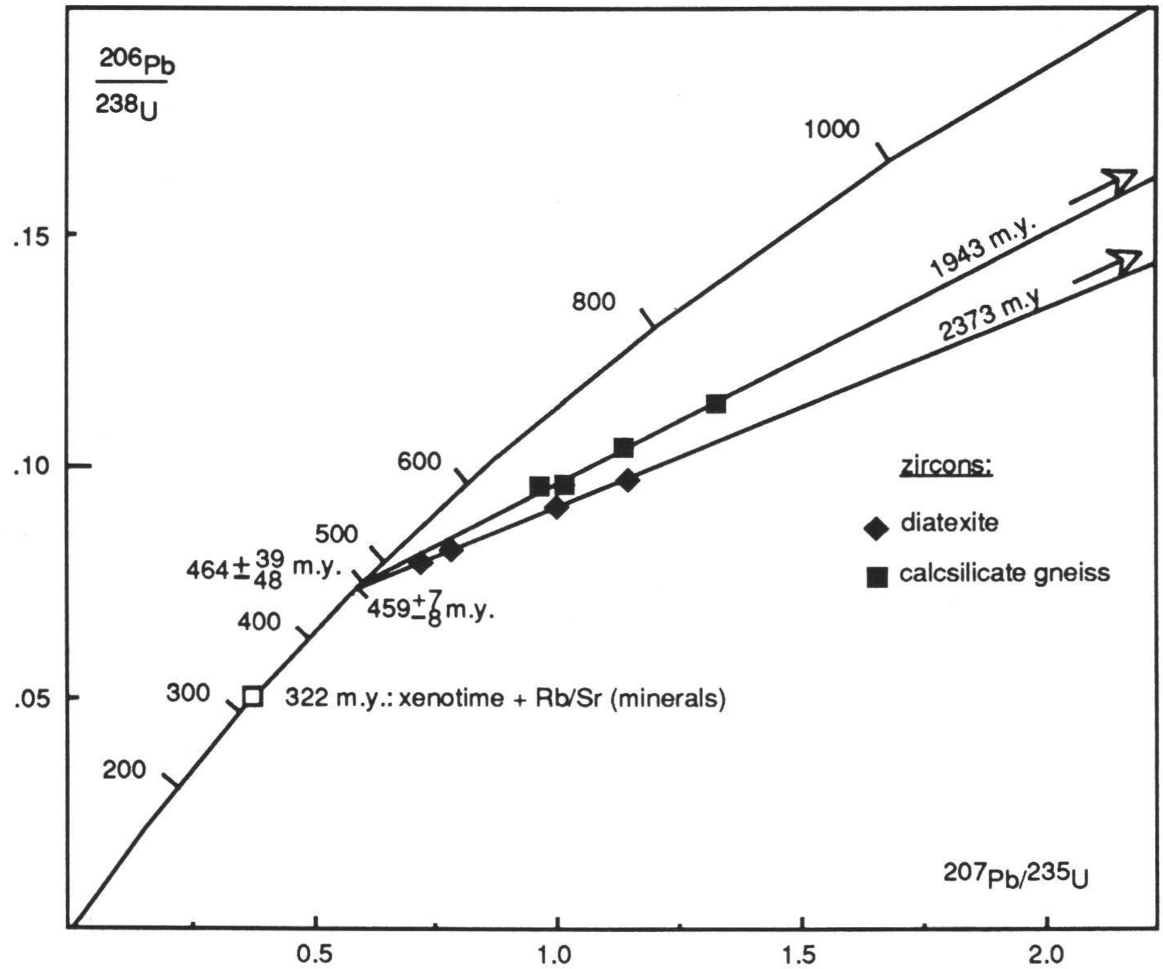

Fig. 5 Conventional U-Pb zircon and xenotime data from the non-anatectic paragneiss and a diatexite. The data are interpreted to reflect episodic lead loss during formation of the paragneiss at 460 m.y. and reheating under static amphibolite-facies conditions at 320 m.y., the age of concordant xenotimes extracted from both the palaeosome and two diatexites. The data of the diatexite (fig. 4) are plotted for reference purposes. Intercepts of the 4 dotted lines with the diatexite discordia indicate the position of the data points assuming no isotopic disturbance in the Carboniferous. The dashed line represents a reference line through the scattered data points of the palaeosome.

Ion probe multi-spot analyses on single grains

Grain 11 with a primary age of the core at 3.84 b.y.

In line with the goal of this paper the ion probe data are discussed here only with respect to Concordia-discordia intercepts or concordant ages, these being the important parameters for an understanding of crust forming events. A detailed discussion of the U-Pb systematics for individual grains is in preparation and will be published in separate steps. Fig. 6 shows a photomicrograph of grain 11, which like all the other grains in this section, was extracted from the palaeosome. The length along the longest diagonal of the grain is about 240 μ. The euhedral core is overgrown by a zone showing a rounded surface against the outermost zone. The latter exhibits

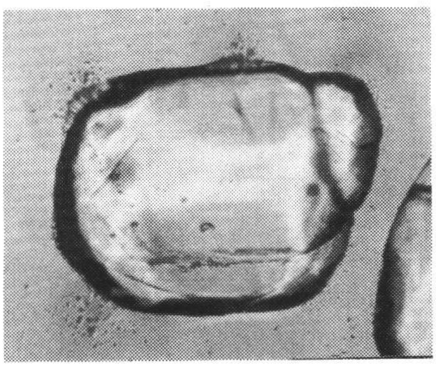

Fig. 6 Zircon grain 11 (size: ca. .25 mm) extracted from a biotite-plagioclase gneiss of the quarry at Völling in the Regensburg Forest. Four geological ages were detected in the euhedral core and the two zones surrounding it: 3.84 b.y., 2.59 b.y., 1.94 b.y. and 460 m.y..

the present detrital shape produced during transport of the grain between provenance and depositional site. Based on element distributing patterns in the first zone overgrowing the core, it is likely that the rounded surface between the two zones of overgrowth is also due to mechanical abrasion, implying that grain 11 passed twice through a cycle of erosion and sedimentation. Fig. 7 depicts intercept ages obtained on the euhedral core as well as on the two zones surrounding it (ages with asterisk). After the first set of data was obtained the grain was repolished, thereby removing previous analyses pits which were a few microns deep. The spots obtained on the core give very precise intercept ages at 3.84 b.y. and 2.59 b.y.. In addition, some spots also record one or both Phanerozoic events which, however, cannot be distinguished from each other due to too large analytical uncertainties. Due to the narrowness of the outermost zone no data were obtained which can be used to define a significant age difference for the zone contacting the core. All data points showing a wide range of discordance plot between 1.94 b.y. and 460 m.y., the independently known age of metamorphic formation of the grain 11 host rock. However, it can be deduced from the position of data points obtained on spots overlapping both zones that the formatin of the outermost zone is unlikely to be much younger than about 1.8 b.y.. There is no proof that any of the analysed spots has been reopened for U-Pb during the Carboniferous event at 320 m.y..

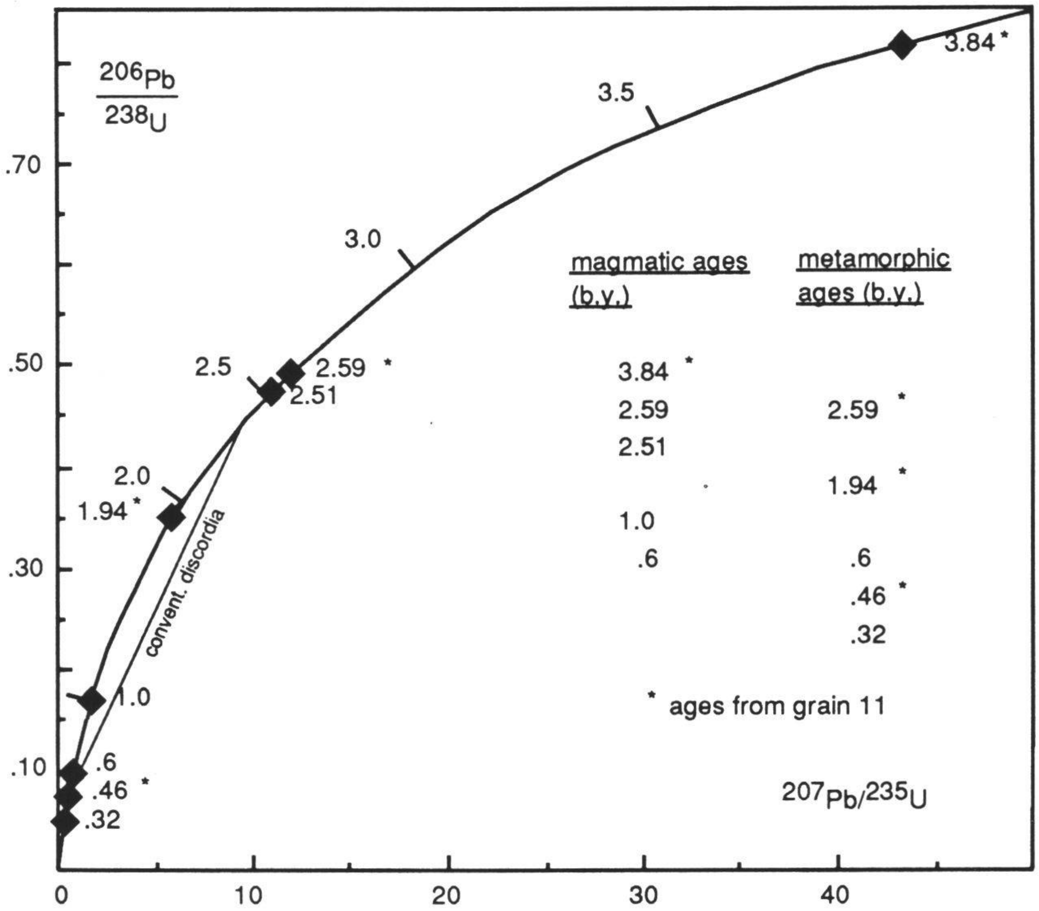

Fig. 7 Concordia intercept ages and concordant ages obtained by multi-spot and single ion — microprobe analyses of detrital zircons from the paragneiss of the quarry at Völling. Note that most diamonds do not represent analysed concordant ages but extrapolated intercept ages for individual zones or single crystals. The diamonds at 1.0 b.y. and .6 b.y. represent the detection of zircons probably formed at different times within the two orogenic cycles around 1.0 b.y. and .6 b.y. (see text). Grain 11 (ages indicated with stars) not only records the age of metamorphic formation of the present host rock at ca. 460 m.y. but reveals with at least 3 further intercept ages a detailed geological history with probably 2 or more cycles of erosion and deposition.

In summary, the core of grain 11 formed euhedrally from a melt of probably granitic composition at 3.84 b.y. At 2.59 b.y. it lost variable amounts of radiogenic lead probably during high-grade metamorphism of the protolith. At about 1.94 b.y. at the latest, the first zone overgrew the core during either magma generation or the highest-grade of metamorphism. After its formation the host rock probably was eroded and the zircon grain mechanically rounded during transport away from its provenance. The new sedimentary host rock again underwent highest-grade metamorphism and/or magma formation and as a consequence of this today's outermost zone formed. As it is mechanically rounded and occurring in a paragneiss the grain must have gone through another erosion and deposition cycle. At 460 m.y. the new host rock reached its present high-grade metamorphic state and again variable amounts of radiogenic lead were lost from various sites within the crystal. Thus, this crystal is the oldest found so far in the European Hercynides. In addition it also reveals the most complex history ever found for a crystal in our solar system.

Other multi-spot analyses on single grains

Other detrital grains of the palaeosome also give well defined discordia trajectories, some of which resemble the metamorphic age of the core of grain 11 (fig. 7). Two grains for example have upper intercept ages at 2.59 b.y. and 2.51 b.y., respectively. In one case the lower intercept ages reflect the Caledonian tranformation of the host rock into a paragneiss, while in the other, the Hercynian effect caused an additional lead loss. Another, rather elongated and clear grain formed around 1 b.y. and was opened to radiogenic lead loss during both the Caledonian and Hercynian.

Single spot analyses on single grains

Most data obtained by analysing only one spot per grain fall within analytical error limits (2 sigma) on the Concordia curve between about 530 m.y. and 750 m.y.. In fig. 7, this range is represented by the symbol at 600 m.y.. A few grains probably formed around 1 b.y. and lost lead in the Pan-African provenance around 600 m.y.. Other grains probably were newly formed between 2.5 b.y. and 2.6 b.y. and lost variable amounts of radiogenic lead during the Caledonian and possibly also during the Hercynian metamorphism. In any case a Cadomian input of detrital grains into the sedimentary protolith of the palaeosome is very likely similar to that into the sediments and metasediments of the Montagne Noire, as we will see later. A post-Cadomian deposition of the sedimentary precursor of the palaeosome is also indicated by the Rb-Sr whole-rock systematics of these rocks. This is due to the high, but for European paragneisses typical, Rb-Sr ratios and the initial Sr-isotopic ratio of about .71 at 460 m.y.. Thus, assuming that metamorphism did not change the Rb-Sr ratios in the whole-rock samples, as is generally found, deposition took place probably after about 600 m.y..

Sediments and metasediments of the Montagne Noire (Southern France)

Geological situation and sampling

The Montagne Noire at the southern rim of the French Central Massif (fig. 1 and 8) can be divided into a crystalline part, the gneiss dome of the «zone axiale» consisting generally of high-grade para - and orthogneisses intruded by Hercynian granites, and an allochtonous, sedimentary part to the south of the axial zone. Below the tectonic

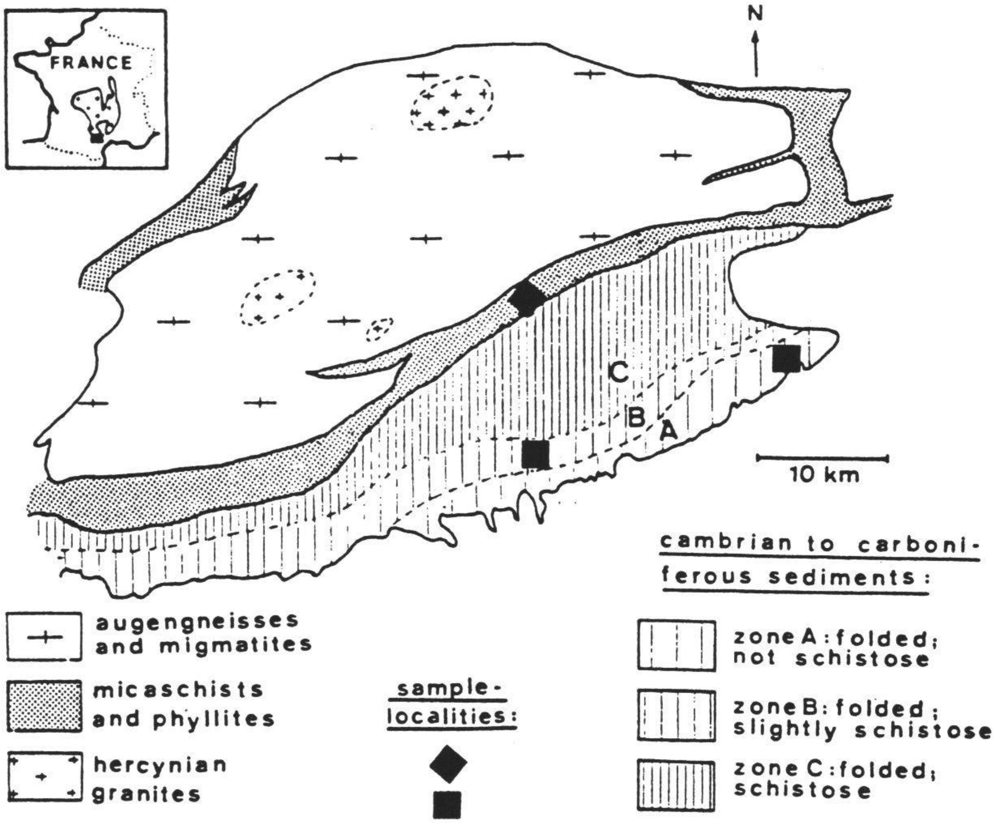

Fig. 8 Schematic, geological map of the Montagne Noire in Southern France. The Cambrian to Carboniferous sediments south of the «zone axiale» belong to a series of nappe units overthrusted to the south during updoming of the basement in the course of the Carboniferous orogeny.

contact between the two units there is a metamorphic transition zone of about 4 km (fig. 8). It consists of generally metasedimentary rocks between sillimanite- and chlorite-grade metamorphism. Multigrain zircon samples from the chlorite-, garnet- and staurolite-grade zones have been analysed previously (GEBAUER and GRÜNENFELDER, 1976). The three resulting discordia trajectories, as well as Rb-Sr whole-rock data, indicated a Caledonian metamorphic transformation of the host rock of the detrital zircons at around 430 m.y., as widely observed all over the European Hercynides. Upper intercept ages range from 1.94 to 2.16 b.y..

Single zircons from the garnet-grade sample were analysed using SHRIMP, together with two other samples from the sedimentary, allochtonous part of the Montagne Noire (fig. 8), comprising rocks which were deposited between Cambrian and Lower Carboniferous.

Garnet-grade argillaceous sandstone (axial zone)

Fig. 9 shows the conventional zircon suite data, lower and upper ion probe intercept ages as well as concordant ion probe ages from multi- and single spot analyses of individual, detrital grains. It is evident that zircon formed, very probably magmatically, at 3.15 b.y., 2.54 b.y., 2.14 b.y., 1.85 b.y., around 1 b.y. and 600 m.y.. Metamorphic events in the provenance (s) can be inferred from lower intercept ages which scatter for 3 trajectories around 1 b.y.. The youngest detrital grain has an age of 556 m.y. which is simultaneously a maximum age for the deposition of the present host rock. Like the case of the Moldanubian paragneiss, the Rb-Sr data of the progressively metamorphosed sediments of the Montagne Noire agree very well with this maximum depositional age.

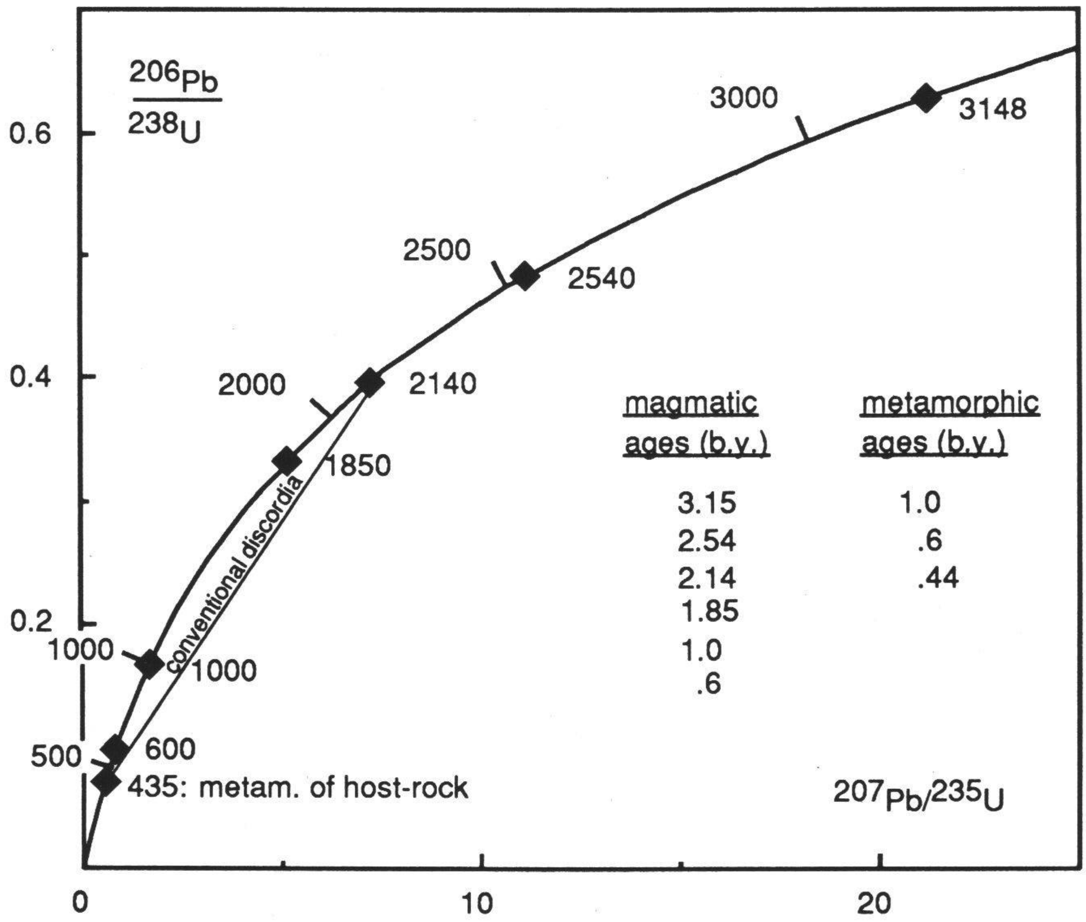

Fig. 9 Ion-probe intercept ages and concordant ages of single — and multi-spot analyses of detrital zircons from a garnet-grade, argillaceous sandstone of the axial part of the Montagne Noire. The conventional zircon discordia (GEBAUER and GRÜNENFELDER, 1976) is given as reference. Except for the 435 m.y. age of metamorphism of the host rock, all other ages refer to rock-forming and metamorphic events in the respective provenances. Deposition took place after ca. 556 m.y., the age of the youngest detrital grain.

Interestingly, there is no evidence in the analysed spots for a Caledonian lead loss. This, however, has to be postulated in view of the data for the conventional multi-grain analyses (fig. 9). Empirically, we can say that spots that are most discordant are found mostly along the rims of the individual zircon grains and along cracks and borders to intergrown minerals and inclusions. Naturally, for the purpose of this study such spot positions were avoided. Omitting the 3.15 b.y. and possibly the 2.14 b.y. zircon-forming event, it is interesting to note the similarity with those detected in the Moldanubian paragneiss. The Cadomian or Pan-African event around 600 m.y. especially suggests Gondwana-derived detritus.

Unmetamorphosed sediments of the Montagne Noire

Both samples used for ion probe dating have been analysed previously as multigrain samples for U-Pb zircon and monazite, and minerals and whole-rocks for Rb-Sr (GEBAUER and GRÜNENFELDER, 1977; GEBAUER, 1986). One is a Middle Cambrian sandstone taken in zone B of fig. 8, the other a Lower Ordovician (Middle Arenig) argillaceous siltstone taken in Zone A of fig. 8. The data are again summarized as intercept and concordant ages of both single-and multispot analyses of individual detrital grains, together with the conventional U-Pb results (fig. 10). A detailed geological and

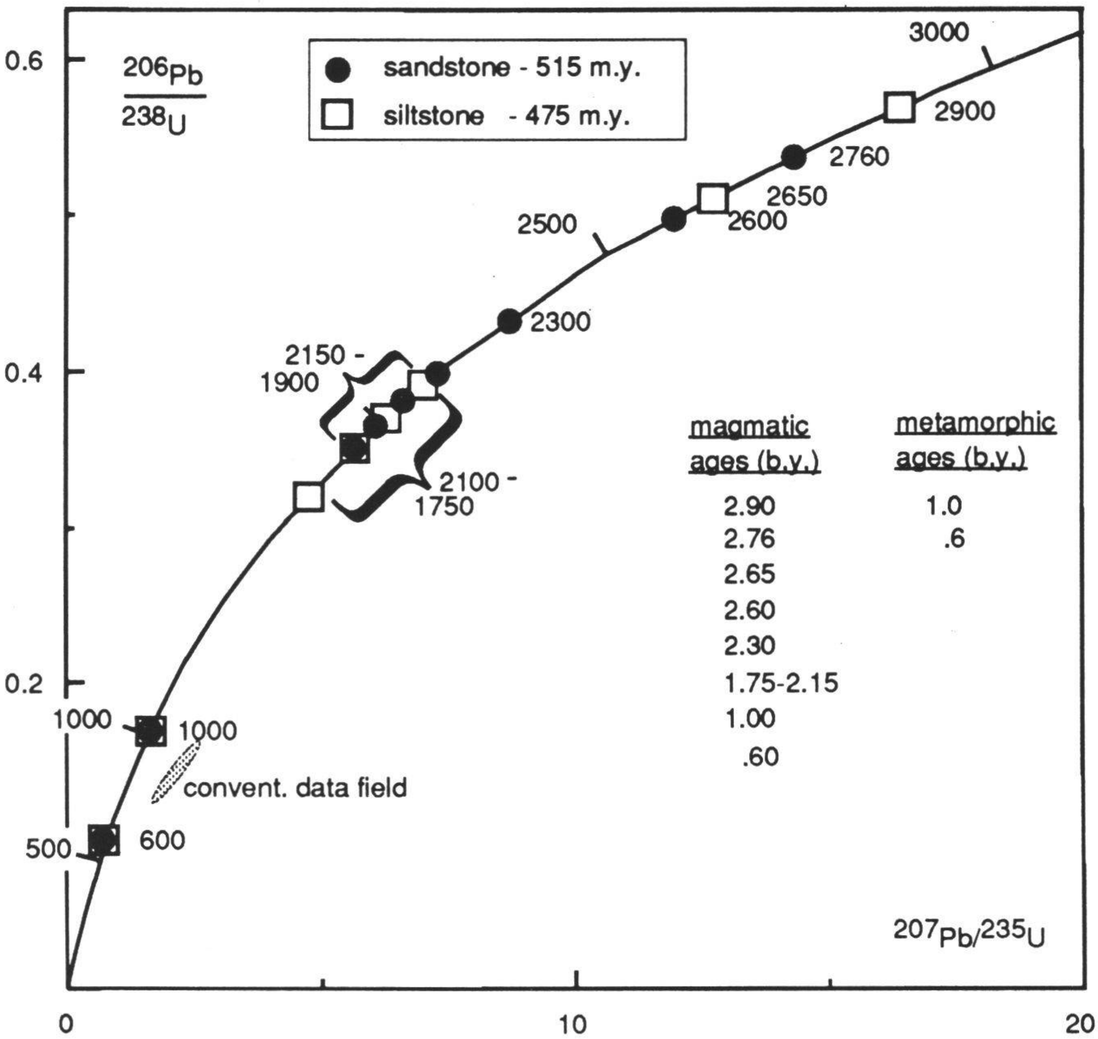

Fig.10 Ion-probe intercept ages and concordant ages based on single — and multi-spot analysesof detrital zircons from a Middle Cambrian sandstone and a Lower Ordovician siltstone of the Montagne Noire. In both rocks there is a significant increase in zircons crystallized around 2 b.y.. There is a period of non-activity around about 1.5 b.y.. Note that, like in figs. 7 and 9, the age symbols at 1 b.y. and .6 b.y. do not represent zircon formation during a single event but during a series of events within the probably very complex orogenic cycles at 1 b.y. and in the Pan-African.

mineralogical description of the samples is given in GEBAUER and GRÜNENFELDER (1977). For the Lower Ordovician siltstone, zircon forming events very likely took place in the course of magmatic events which were linked to orogenic events at about 2.9 b.y., 2.65 b.y., a series of events between 2.10 b.y. and 1.75 b.y., 1.0 b.y. and in the Cadomian, with the youngest detrital grain at about 543 m.y.. Metamorphic overprints in the respective provenance(s) are indicated for the Cadomian and the 1 b.y. cycle. In the case of the Middle Cambrian sandstone, crust forming events took place in the Upper Archean at 2.76 b.y. and 2.6 b.y., in the Lower Proterozoic at about 2.3 b.y. and in a few cases between 2.15 b.y. and about 1.9 b.y., in the Middle Proterozoic at 1.0 b.y. and in the Pan-African around 600 m.y.. Metamorphic overprints in the provenance(s) were detected at 1.0 b.y. and 600 m.y.. The youngest detrital grains scatter just below 600 m.y..

It is interesting to note that the Pan-African event is the only one which could be detected with reasonable probability previously using multigrain Rb-Sr and U-Pb analyses on detrital muscovites, monazites and zircons (GEBAUER and GRÜNENFELDER, 1977 and GEBAUER 1986).

Discussion

The detection of zircon formation at 3843 ± 7 m.y. in the first cycle provenance of the sedimentary precursor of the Moldanubian paragneiss is the most conspicuous result for the development of the continental crust of the European Hercynides. When compared to the oldest ages obtained previously in the northern hemisphere of our globe this Early Archean age is significantly older than the age of felsic metavolcanics (3807 ± 1 m.y.) occurring as agglomerates in the Isua supracrustal belt of West Greenland (BAADSGAARD et al., 1984; COMPSTON et al., 1986). It is also slightly but significantly older than the SHRIMP zircon data on the tonalitic Amîtsoq gneiss which give 3822 ± 5 m.y. (KINNY, 1986). It is, however, slightly younger than rounded zircons included within igneous zircons from the Early Archean Uivak gneiss in northern Labrador from which 207Pb/206Pb ages of 3.86 b.y. have been obtained recently (Schiotte et al., in press). Thus, it is amongst the oldest ages obtained so far in the northern hemisphere and confirms the observation that differentiation processes started very early in the history of our planet (e.g. FROUDE et al., 1983). Naturally, it is impossible to assign any presently exposed provenance for the source rock of the core of this grain, considering its complex history since primary magmatic formation. In addition to its 3.84 b.y. core-age, grain 11 is unique in that it records at least 3 further ages related to magmatic and/or metamorphic imprints. Furthermore, two probable stages of mechanical rounding indicate the presence of at least two erosion and depositional cycles. Thus, this mineral carries with at least 4 ages (3.84 b.y., 2.59 b.y., 1.94 b.y., .46 b.y.) the most complex geological history ever found in a single grain.

In addition, the rock from which grain 11 was separated reveals the presence of detrital zircons which formed in their first cycle provenances at 2.59 b.y., 2.51 b.y., around 1 b.y. and in the Pan-African around 600 m.y.. These data imply that deposition of the present host rock took place after the Pan-African cycle, which is in good agreement with the maximum age of deposition as derived from the Rb-Sr systematics of this rock (GEBAUER, 1975). It also implies that Gondwana-type basement must have delivered the zircons and the other detritus also, because Pan-African ages are insignificant in Laurasia, the other possible source region.

The data do not indicate whether the immediate source was in the N or in the S, as it is probable that microcontinents or terranes rifted off from Gondwana after the Pan-African cycle. A southern source only could be inferred if one assumes the presence of a single ocean between Gondwana and Laurasia (Proto-Tethys). However, due to the presence of suboceanic-derived high-pressure rocks which formed, like many other high-to lowgrade metamorphic rocks, in different geotectonic sites and at various times between 500 and 330 m.y., this interpretation is too simple. Instead, we prefer a model involving post Pan-African deposition of the protoliths of Central European metasediments into different basins (continental, oceanic, back-arc) between Gondwana-derived terranes and newly formed island arcs (GEBAUER, 1986). In the course of subsequent closure of the various basins between ca. 500 m.y. and 330 m.y., the basins fillings are likely to have been thrust on top of the Pan-African composite basement, leaving tectonic windows only in few areas, e.g. in Brittany (France) and Bohemia (CSSR).

For the Palaeozoic sediments and the medium-grade metamorphic argillaceous sandstone of the Montagne Noire, a common Pan-African provenance is also well established. This confirms earlier results obtained by conventional zircon dating and Rb-Sr dating of white micas (GEBAUER and GRÜNENFELDER, 1977) as well as U-Pb dating of detrital monazites (GEBAUER, 1986). Thus, conclusions similar to those for the Moldanubian rocks can be drawn concerning the youngest crust-forming and/or crust-adding events in the imediate provenance. In addition, the age of deposition of the sedimentary protoliths of the present metasedimentary units of the Montagne Noire must also be post Pan-African. Furthermore, provenance events around 1 b.y., 1.9 b.y. and 2.5 — 2.6 b.y. are common for all 4 studied rocks from NE-Bavaria and southern France. A common difference between the samples from the Montagne Noire and the Moldanubicum is the event around 2.15 b.y., so far lacking in the latter area. Other zircon forming events are restricted, at the present state of research, to one of the 3 studied rocks of the Montagne Noire: 2.3 b.y. and 2.76 b.y. are found only in the Middle Cambrian sandstone, 2.9 b.y. in the Lower Ordovician siltstone and 3.15 b.y. in the garnet-grade argillaceous sandstone.

Counting all the zircon forming events detected in this study — 3.84 b.y., 3.15 b.y., 2.9 b.y., 2.76 b.y., 2.5-2.6 b.y., 2.3 b.y., 2.15 b.y., ca. 1.9 b.y., 1.8 b.y., ca. 1 b.y. and ca. 550 — 700 m.y. — we arrive at a series of at least 11 events. These events very probably are connected in one way or another to orogenic processes and consequently to the formation of continental crust. Naturally, in much smaller proportions the latter can also take place in anorogenic scenarios. Inherited, predepositional lower intercept ages are a further hint for orogenic activities in the former source areas. They agree well with the formation of new, magmatic zircons. For the Montagne Noire samples especially, Pan-African ages and ages around 1 b.y. could be resolved. For the Moldanubian sample, Archean metamorphic activity at 2.59 b.y., Early Proterozoic metamorphism at 1.94 b.y. as well as an Pan-African overprint is probable.

It can easily be predicted that by analysing more grains of the studied zircon populations or especially by analysing other detrital zircon populations from other areas of the European Hercynides, many more crust forming events will be detected. Taking for example the numerous geochronological data summarized by CAHEN et al. (1984) for rocks of the African part of Gondwana, which is the probable large scale provenance for the samples studied in this work, many more events in the respective source areas must be expected. This is all the more so, because with increasing primary age of the zircons and the other detritus, the probability of multiple recycling also increases and with it the spectrum of primary and metamorphic ages. Thus, the development of continental crust of the European Hercynides had started already in the Early Archean and grew via many episodic crust adding events and reworking cycles to its present state.

Conclusions

1) Contrary to many earlier estimates of the age of the Central European crust, there is now compelling evidence for the presence of crustal material already extracted from the mantle in the Early Archean. Although numerous conventional zircon analyses on detrital zircon populations suggested Archean components, this could never be proven as the corresponding upper intercept ages usually indicated average Middle and Early Proterozoic values. Additionally, Sm-Nd model ages indicated average crustal residence ages ranging around 500 m.y. younger than the conventional upper intercept ages for detrital zircons. As expected, ion-microprobe studies give a much more detailed chronology of crustal evolution. For the Archean period, the following sequence could be established by this study: 3.84 b.y., 3.15 b.y. 2.9 b.y., 2.76 b.y., 2.65 b.y. and a series of magmatic events between 2.5 b.y. and 2.6 b.y.. The earliest evidence for metamorphic overprinting in a provenance was found in the euhedral core of a detrital grain of a Moldanubian paragneiss. A metamorphic age of 2.59 b.y. resulted from the lower intercept age of a discordia trajectory and a primary magmatic age of 3.84 b.y. from the corresponding upper intercept. The latter age is amongst the oldest found so far for rocks and minerals from the northern hemisphere.

2) Early Proterozoic ages (1.6 b.y. — 2.5 b.y.) play an important role in crustal evolution in the provenances of the Early Palaeozoic sediments of the Montagne Noire. Between ca. 1.9 b.y. and 2.15 b.y. there are numerous crust-forming events indicating production of large amounts of continental crust in the respective source areas. Metamorphic effects within this time period could only be inferred in one zone of the 3.84 b.y. old grain of the Moldanubian paragneiss at 1.94 b.y.

3) There seems to be two periods of relatively reduced or even missing activities in the provenances of the analysed samples. The first is between about 2.2. b.y. and 2.5 b.y. with only one exception in the provenance of the Middle Cambrian sandstone of the Montagne Noire giving ca. 2.3 b.y.. No evidence for crust-forming processes exists so far for a time period of ca. 500 m.y. in the Early and Middle Proterozoic around 1.5 b.y.. In contrast with the situation in Laurasia, this conforms very well with the age records in Gondwana and thus gives a first hint of an originally southern provenance of the respective basin fillings. Although there is also a time gap of ca. 700 m.y. between 3.15 b.y. and 3.84 b.y. in our data, it seems rather unsafe to conclude that this early period in the development of the planet was relatively quiet. Various reasons might account for this. One might be that such old, active crust existed but by chance not in one of the provenances of the studied samples. Another might be that the probability of finding such old zircons is strongly reduced as multiple recycling largely destroyed them. A third reason might be that less crust formed in the Early Archean than later on. Of course, a combination of all reasons would also explain the observed lack of data in this time period.

4) Middle Proterozoic ages (1.6 b.y. — 900 m.y.) form a single cluster around 1.0 b.y. with a maximum range from about .9 b.y. to about 1.2 b.y.. The lower part of the Middle Proterozoic is missing in our data probably due to a period of relative non-activity, as described under 3). Based on lower intercept ages, the period around 1.0 b.y. also records the presence of metamorphic overprints of rocks crystallized in the Archean and Early Proterozoic.

5) Upper Proterozoic ages (900 m.y. — 530 m.y.) with a peak around 600 m.y. and related to both magmatic and metamorphic events between 550 m.y. and ca. 700 m.y., are common in all studied samples. They are the best evidence that the youngest rocks in the respective provenances were formed and/or metamorphosed in the course of a pervasive Pan-African orogenic cycle which, as is true probably for most orogenic belts, comprises telescoping of a series of micro-continental plates.

6) Gondwana-derived detritus probably makes up most, if not all of the unmetamorphosed protoliths of metasediments occurring in the basement of the Central European Hercynides. Consequently, their depositional ages are post-Pan-African, i.e. much younger than previously assumed by many geologists. This finding is in line with estimates of depositional ages via Rb-Sr whole-rock systematics on Central European metasediments.

7) The original Gondwana source of uppermost Proterozoic and Early Palaeozoic sediments and metasediments does not imply that all the immediate source areas of the respective sediments have to be situated to the south of the depositional site. This is because micro-continental plates probably rifted off from Gondwana after the Pan-African cycle and thus could have shed their detritus also into basins to the south assuming a rather elongated shape of these microcontinents or terranes.

8) The different ages of metamorphisms, including high-pressure metamorphisms, within the European Hercynides support the microcontinent model. Due to successive closure of the post-Pan-African basins and thrusting of the respective sedi-

ments onto the Pan-African and older Gondwana-derived microcontinents, the latter are largely covered by these younger rocks leaving only few tectonic windows in the European Hercynides.

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