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The age of the continental crust of Central, Southern and Western Europe – arguments from geochemistry and isotope geology

by *Emilie Jäger**

Abstract

Recent findings by stable isotope and geochronological work still favor the model of continent formation presented by VIDAL, 1977, and JÄGER, 1977: Upper Proterozoic ocean sedimentation, with magmatism and metamorphism since the end of Proterozoic or Cadomian time.

Keywords: continental crust, isotope geochemistry, geochronology, crustal evolution, Europe.

Introduction

In 1974 COGNE organized a meeting in Rennes, «la chaîne varisque d'Europe moyenne et occidentale», at which the majority of geologists considered the continental crust of Europe to be of Precambrian age, with granulites (FORESTIER, 1977) and eclogites (DUDEK, 1977) being part of the oldest crust.

During this meeting, VIDAL and JÄGER presented geochronological evidence for a younger age of the Central and Western part of the European continent: VIDAL had compiled the available $^{87}Sr/^{86}Sr$-initial ratios in relation to the measured Rb-Sr ages, with all the data pointing to magma evolution not older than about 600 Ma. VIDAL proposed the existence of an oceanic crust, with addition of mantle derived magmatic material starting in Cadomian time, about 600 Ma ago. Using geochronological data gained with different methods, JÄGER came to a similar conclusion: pre-Cadomian, probably upper Proterozoic ocean sedimentation, with magma formation and metamorphism also starting in Cadomian time. In the areas under consideration, the Alps, the Bohemian massif, the French Massif Central, Vosges and Schwarzwald, no real geological evidence against this model of continent evolution has been found.

Since this meeting, many new geochronological data are available, a new method, Sm-Nd, has been introduced and in some respect the interpretation of

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geochronological data has been refined. It is the aim of this paper to test whether the proposed model of the age of continent formation is still valid, and in which way it has to be adapted to the new data and recent data interpretation. It is especially important to test the possibility of an intensively overprinted Precambrian continent which could have resulted in the rejuvenation of the Rb-Sr total rock systems. Of equal importance is the dating of sedimentation, the response of the different geochemical systems used for dating to weathering, erosion and sediment deposition; is it possible to distinguish between old sedimentation and young sedimentation of material derived from an old continent?

Geochemical Background

The geochronological clocks are reset by chemical reactions which change the ratio of radioactive to radiogenic element, i.e. the Rb/Sr-, U/Pb- and Sm/Nd-ratios.

In mineral systems, the main chemical reaction takes place during crystallization, but it is important to state that minerals at elevated temperatures react as open systems for their radiogenic daughter products. Therefore cooling ages are measured when the minerals crystallize at temperatures above the blocking temperature. Only in cases of mineral crystallization below the blocking temperature of the system, will these systems close with crystallization, and crystallization ages be measured.

In total rock systems, reactions which change the ratio of radioactive to radiogenic elements, can be caused by magma formation, by trace element mobilization when fluids pass the rocks and by the process of weathering to sedimentation which produces a new total rock system. Since dating of the sedimentation would be of prime importance to understand the evolution of the European continental crust, one should try to analyze the influence of ocean water on the geochemical system used for dating. Two factors seem important: the fractionation of the parent-daughter system, for example Rb vs. Sr, between continental crust and ocean water, and the degree to which a particular element is dissolved in ocean water.

Although it is certainly an over-simplification to compare element concentrations in the mean crust and ocean water and the residence time in ocean water, such a comparison still clarifies the chemical reaction which influences the geochronological clocks. Table 1 summarizes the concentrations of the relevant elements in the mean continental crust and in ocean water, together with the ocean residence time which according to BARTH, 1952, is defined as being equal to A/(dA/dt), A being the total amount of this element in the ocean and dA/dt the in- or efflux rate (HENDERSON, 1982).

Table 1 The elements relevant to geochronology: abundance in the earths crust and ocean water, crust/ocean water fractionation, ocean water residence time and degree of entering the ocean water solution.

Element	crustal average in ppm	ocean water concentration in µg/l	crust/ocean* fractionation	ocean water residence time in years	degree of** ocean water solution
Rb	90	120	16.2	$4 \cdot 10^6$	0.3
Sr	375	8100		$4 \cdot 10^6$	5.4
U	2.7	3.2	0.0014	$3 \cdot 10^6$	0.4
Pb	12.5	0.02		$4 \cdot 10^2$	4
Sm	6	0.0008	1.1	$2.5 \cdot 10^3$	0.05
Nd	28	0.0042		$2.5 \cdot 10^3$	0.06

Abundances in mean continental crust and ocean water of 35‰ salinity, and ocean water residence time from HENDERSON, 1982; Sm and Nd ocean water concentrations and residence time from ELDERFIELD and GREAVES, 1982.

* crust/ocean fractionation: Rb/Sr in crust/ocean water
U/Pb in crust/ocean water
Sm/Nd in crust/ocean water

** degree of ocean water solution: $$\frac{\text{conc. ocean water (in µg/l)} \cdot 10^6}{\text{conc. crust (in ppm)} \cdot \text{residence time (in years)}}$$

The proposed fractionation factor is a measure of resetting the geochronological clock. A factor of 1 means no change of the parent-daughter system, our dating method does not register the passing through the ocean water cycle. As can be seen from Table 1, this fractionation factor is around 1 for Sm/Nd. Thus Sm-Nd dating on sediments does not register the time of ocean water sedimentation. Accordingly O'NIONS and HAMILTON, 1982, have been able to date the original foreland by Sm-Nd sediment dating. Sm-Nd dating therefore is no means by which to date sedimentation. In contrast, the Rb/Sr and U/Pb systems show high fractionation in ocean water as compared to the continental crust, Sr and U being enriched in solution.

The proposed degree of ocean water solution sets the rate of ocean influx in relation to the concentration of the element in the continental crust. It is therefore a measure of the probability of a particular element to pass the ocean water cycle. Both parameters, the crust/ocean water fractionation and the degree of ocean water solution together determine the extent of change in the parent/daughter ratio. Since average concentrations and residence time bear a considerable uncertainty, it is not the number itself, but the order of magnitude and the ranking of these factors which is important. Comparison of the «degree of ocean water solution» (see Table 1) for the different elements shows that Sr and Pb have a higher chance to pass through the water than Rb and U, and a much higher chance than Sm and Nd. The small degree of ocean water solution for Sm and Nd demonstrates that these elements have a much smaller probability of passing the ocean water solution, a second argument that Sm-Nd dating cannot be the method for dating sedimentation. It must also be stated, that, although the ocean residence time for Rb, Sr and U is quite high, several Ma, all the relevant elements in ocean water solution are replaced several times during geological periods.

For the evalution of the Rb-Sr method for sediment dating it is important that Sr is enriched against Rb in ocean water, with a relative high probability of passing the ocean water solution. The high Sr concentration in ocean water distributes the influx of radiogenic ^{87}Sr considerably. Therefore, the Rb-Sr clock in ocean sediments is better reset than any other clock. Thus Rb-Sr is the most appropriate system to register sedimentation.

CLAUER et al., 1982, state that in ocean sediments authigenic minerals incorporate Sr in isotopic equilibrium with ocean water. During diagenesis, ^{87}Sr is preferentially migrating from the sediment to the pore water. During metamorphism from sediment to paragneiss a similar effect could occur. These reactions could lower the sedimentation age, gained by Rb-Sr dating on paragneisses. However, as GRAUERT, 1969, could show, such sedimentation ages are rather insensitive to changes in the Rb/Sr-ratios of the sediment pile. Further, the Rb-Sr sedimentation age is only reset when Sr is lost from the sedimentary pile of rocks, Rb-Sr redistribution within the paragneiss has no influence on the sedimentation age; it is thus not easy to rejuvenate Rb-Sr sedimentation ages.

Experience of Interpretation of Geochronological Data

It is commonly accepted that U-Pb systems in zircons and the total rock Rb-Sr systems are less easily reset than the Rb-Sr and K-Ar systems in minerals. Zircons from paragneisses usually give discordant U-Pb ages, with the upper intersect in the concordia diagram (WETHERILL, 1956) often pre-dating erosion and sedimentation, a memory of the pre-erosion state in the continental crust. This means high resistivity of the mineral zircon and its U-Pb system during weathering, erosion and sedimentation, and high stability at low temperatures in the presence of water. The fact, that in zircons from granitic rocks often an older, pre-granitic Pb-component can be detected (as for example in the Alpine Bergell granite, GULSON and KROGH, 1973) points to high-temperature stability of U-Pb in zircon. MATTINSON, 1982, has been able to demonstrate that U-Pb ages of minerals also represent cooling ages when these minerals cool from high temperatures. He has proposed a blocking temperature of 400 °C for U-Pb in apatite and 450 to 500 °C for sphene. Non-metamict zircon retains most of its radiogenic lead above 600 °C, but according to Prof. L.T. SILVER (personal communication) there is no single blocking temperature for U-Pb in zircon, it depends on the minerals crystalline state.

The Rb-Sr total rock system has been commonly regarded as rather stable, but sensitive to circulating fluids at low temperatures. Rock-crushing and shearing which opens the paths for passing fluids, has been dated with Rb-Sr total rock analyses, RÅHEIM and BERG, 1977. Such results gave the general impression that the Rb-Sr total rock system is less stable than the U-Pb system in zircon. This is in contrast to recent results:

ZINGG and HUNZIKER, 1982, state that under amphibolite to granulite facies conditions in the Ivrea zone, Southern Alps, the total rock Rb-Sr systems for large samples (30–50 kg) as well as for cm-bands close earlier than the U-Pb systems in zircon and monazite. Further, VAN BREEMEN et al., 1982, report U-Pb lower intersect zircon ages of 345 Ma for the granulites from the Bohemian massif, while banded granulites, see ARNOLD and SCHARBERT, 1973, retain a 466 Ma (new constants) Rb-Sr isochron age between adjacent layers in the cm-size. Since, according to SCHARBERT and KURAT, 1974, during the granulite metamorphism temperatures of 760 °C have been reached, the U-Pb zircon age of 345 Ma must be considered as a cooling age and not as the date of granulite metamorphism. Both cases, the Ivrea zone and the Moldanubian granulites demonstrate that in dry rocks, the Rb-Sr total rock system survives high temperatures very well, better than the U-Pb system in zircons, when lower intersect ages are considered.

Common lead model ages of galenas and other lead-rich ore minerals record the time when the lead has separated from an environment with a definite, constant or growing U/Pb ratio. After this chemical U/Pb separation, lead deposits can be dissolved, transported and redeposited without changing the model age. Only by mixing with a more radiogenic lead can the model age be rejuvenated. Thus, model lead ages have a strong memory to primary ore formation which cannot be easily rejuvenated, since the memory is kept by the main element of the ore.

Implications for Evolution Models of the Continental Crust in Europe

Based on many geochronological data from the European continent the following conclusions can be drawn:

1. Granulite and eclogite facies metamorphism is of Phanerozoic and not pre-Cambrian age. The climax of these phases of high-grade metamorphism can only be dated by Rb-Sr total rock methods, since U-Pb lower intersect data on zircons only give cooling ages, as the examples from the Ivrea zone, ZINGG and HUNZIKER, 1982, and the granulites from the Moldanubicum, ARNOLD and SCHARBERT, 1973, and VAN BREEMEN et al., 1982, demonstrate.
2. No pre-Cadomian formation of continental crystalline rocks, no pre-Cambrian granites and orthogneisses have been found.
3. Rb-Sr sedimentation ages of about 500 to 800 Ma have been determined in several areas in Europe; no early Proterozoic or older sedimentation ages

have ever been found. However, detrital zircons from paragneisses give U-Pb upper intersect ages frequently greater than 2000 Ma, pointing to detrital material derived from an old continental crust.

4. No pre-Cadomian common lead model ages have been measured so far, only ages around the pre-Cambrian/Cambrian boundary and younger, Phanerozoic ages (PH. VIDAL, oral communication at the discussion during the symposium «The pre-Alpine central southern European basement» at the EUG-meeting in Strassbourg, 1983) and KÖPPEL, 1983. KOBER and LIPPOLT, 1983, interpret the high lead model ages found in total rocks and feldspars from the Schwarzwald as resulting from mantle lead injection into the crust in Caledonian time.
5. Only in rocks of oceanic origin have pre-Cambrian ages been recorded. PEUCAT et al., 1982, found U-Pb upper intersect ages around 1200 to 1300 Ma on zircons from high grade metamorphic mafic and ultramafic rocks from Brittany, France, with lower intersect ages around 400 Ma. PEUCAT et al. offer two interpretations: The upper intersect ages *either* represent an undefined mantle process and the 400 Ma ages correspond to the tectonic emplacement of this part of the mantle into the continental crust, *or* the protoliths were extracted from the mantle and emplaced into the crustal environment 1200 to 1300 Ma ago, with a subsequent metamorphism 400 Ma ago. GEBAUER and GRÜNENFELDER, 1983, also report pre-Cambrian U-Pb upper intersect ages from several places in Europe, 2230 Ma from the Gotthard massif in the Central Alps. GEBAUER and GRÜNENFELDER consider these ages as proof of a pre-Cambrian continental crust, although they propose tectonic emplacement of these rocks into the crust.

The geochronological results points 1–4 support the model proposed by VIDAL, 1977, and JÄGER, 1977: pre-Cadomian ocean sedimentation, with detritus from an eroding pre-Cambrian continental crust; magma generation and metamorphism starting at the end of Proterozoic, beginning of Phanerozoic time. Only point 5, U-Pb upper intersect ages on rocks of oceanic origin support a pre-Cambrian crust. But the model of a pre-Cambrian continental crust in Europe raises several doubts: The implication is that only U-Pb zircon ages on these high grade rocks could survive, whilst all the other systems have been rejuvenated. Further, why should only the zircons from orthogneisses lose their memory and not the paragneiss-zircons? It is certainly more realistic to assume that there are no continental pre-Cadomian magmatites. Cadomian and post-Cadomian model lead ages also mean that there is no older pre-Cadomian magmatism which could have produced the Pb/U fractionation; mixing with more radiogenic lead alone could not erase all the older memory, somewhere unmixed lead should be found.

Thus we are left with a problem: since there is no unique interpretation of the pre-Cambrian data on the basic and ultrabasic rocks of oceanic origin, it is not possible to describe definitively their genesis and evolution, and their relationship to the European continental crust. Until we know what these pre-Cambrian ages mean, it is premature to speculate about a pre-Cambrian continental crust in Central, Southern and Western Europe.

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