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Determining sedimentation ages of high-grade metamorphic gneisses by their palynological record: a case study in the northern Schwarzwald (Variscan Belt, Germany)

Abstract In the northern Schwarzwald (Moldanubian Zone of the Variscan belt), paragneisses drilled from approximately 2500 m depth at the Bühl-1 drilling site have experienced amphibolite-facies metamorphism and were later partly transformed to mylonites under greenschist-facies conditions. Completely graphitised acritarchs and chitinozoans were recovered from these paragneisses and mylonitic gneisses. Whereas both groups of palynomorphs give evidence of a marine depositional environment, only the chitinozoans are stratigraphically useful in this case and indicate a Paleozoic age. Previous findings of acritarchs in a different high-grade metamorphic gneiss unit within the Schwarzwald indicate an Upper Proterozoic marine sedimentation age. The spectrum of palynomorphs found thus far in the Schwarzwald in combination with petrological data suggests that within the Moldanubian domain of the Armorican microplate, rocks with different sedimentary records later experienced diverging prograde metamorphic histories. In general, the results reveal that palynological studies in combination with petrological data are a promising tool for reconstructing pre-orogenic settings in collisional belts.

Key words Palynology · Sedimentation age · Amphibolite-facies gneisses · Schwarzwald · Variscan belt

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Introduction

Metasedimentary amphibolite-facies gneisses and migmatites of pelitic to psammitic compositions are the most abundant rocks in the internal zone of the Variscan belt in central Europe. These rocks are hence the key to understanding the sedimentary, metamorphic and deformational evolution of a major part of the Variscan orogenic belt. However, high-grade metamorphism and deformation during Devonian and Carboniferous collision have largely obliterated features of the previous Variscan geological record.

In general, three tools are available to investigate the pre-metamorphic evolution of high-grade metamorphic rocks:

1. Chemical and isotopic composition may serve to distinguish between sedimentary and magmatic protoliths, and may allow for a very limited characterisation of the geodynamical settings in some cases (e.g. Müller 1989; Finger and Steyrer 1995).
2. Radiogenic isotope systems with high blocking temperatures, such as the U–Pb system in zircon, may yield age information on pre-metamorphic events despite later high-grade overprint (e.g. Todt and Büsch 1981; Gebauer et al. 1989; Wendt et al. 1993).
3. In rare cases microfossils that can be used for stratigraphic and palaeo-environmental assignments are preserved in high-grade graphite-bearing gneisses (e.g Pacltová 1986; Reitz and Höll 1988).

The first palynological studies on metamorphic rocks from the internal parts of the Variscan belt (Saxothuringian and Moldanubian Zones of Kossmat 1927; Fig. 1) indicate that organic-walled microfossils, such as spores and acritarchs, can be preserved under favourable circumstances up to amphibolite-facies conditions (e.g. Pacltová 1980, 1994; Reitz 1992). The potential of palynological studies of high-grade metamorphic gneisses may thus be greater than recognised previously.

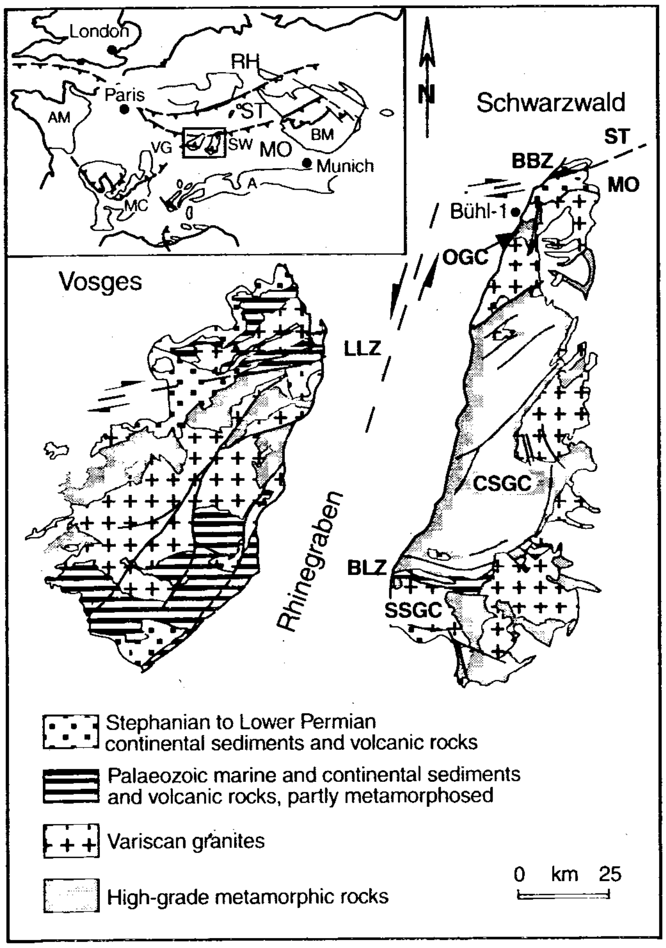

Fig. 1 Map of the Schwarzwald and Vosges showing the main geological features, tectonometamorphic blocks in the Schwarzwald, the location of the Bühl-1 drilling site and the Omerskopf Gneiss Complex. The *inset* shows the Variscan belt in Europe (modified after Franke 1989). *LLZ* Lalaye-Lubine Zone; *BBZ* Baden-Baden Zone; *OGC* Omerskopf Gneiss Complex; *CSGC* Central Schwarzwald Gneiss Complex; *BLZ* Badenweiler-Lenzkirch Zone; *SSGC* Southern Schwarzwald Gneiss Complex; *RH* Rhenohercynian Zone; *ST* Saxothuringian Zone; *MO* Moldanubian Zone; *AM* Armorican Massif; *MC* Massif Central; *VG* Vosges; *SW* Schwarzwald; *BM* Bohemian Massif; *A* Alps

The Moldanubian Zone of the Variscan belt is a composite unit in terms of lithology, P–T evolution and age of metamorphism (Matte 1986; Franke 1989; Dallmeyer et al. 1995). Particularly in the Bohemian Massif, different Moldanubian tectonometamorphic units have been identified (Drosendorf unit with a Monotonous Series and Varied Series, Gföhl unit, Teplá-Barrandian unit; see compilations in O'Brien and Carswell 1993, and Dallmeyer et al. 1995) that have only the last high-temperature low-pressure (HT–LP) overprint at approximately 320–325 Ma in common (e.g. Kreuzer et al. 1989; Dallmeyer et al. 1992). To date, the question remains as to whether or not these Moldanubian units have different sedimentation ages in addition to their diverging early metamorphic histories. For the Drosendorf unit of the Bohemian Massif, microfossils found in metasediments (Andrusov and Corna 1976; Pacltová 1980, 1994; Reitz 1992) and recent U–Pb data on zircons from gneisses interpreted as synsedimentary volcanic rocks (e.g. Fiala and Wendt 1995) indicate Paleozoic sedimentation ages, but this does not necessarily apply to the entire Moldanubian Zone.

Similar to the Bohemian Massif, the Moldanubian part of the Schwarzwald consists of distinct tectonometamorphic units that have shared the last HT–LP overprint at approximately 330 Ma (Kalt et al. 1994; Lippolt et al. 1994) but are characterised by different earlier metamorphic histories. Findings of Upper Proterozoic acritarchs in one of the tectonometamorphic units (Montenari 1996) confirm the previous assumption of a Precambrian sedimentation age (Wimmenauer 1988) and indicate deposition in a marine environment. However, more systematic palynological and petrological data are needed in order to unravel sedimentation age, palaeoenvironment and metamorphic evolution of all tectonometamorphic units in the Schwarzwald. These data in comparison with results from other Variscan massifs will provide constraints on pre-Variscan and Variscan palaeogeography, in particular on the distribution of marine basins. In this paper, the sedimentary and metamorphic evolution of amphibolite-facies microfossil-bearing gneisses from one metamorphic unit in the northern Schwarzwald is presented and compared with palynological results from other areas within the Moldanubian Zone.

Geological setting and sample location

From north to south, the Schwarzwald can be divided into four fault-bounded tectonic blocks (Fig. 1). The northernmost part of the Schwarzwald around the Baden-Baden area is assigned to the Saxothuringian Zone (Fig. 1; Kossmat 1927), separated from the Moldanubian Zone in the south by the NE/SW-trending Lalaye-Lubine-Baden-Baden thrust and wrench fault zone (Fig. 1; Eisbacher et al. 1989; Wickert et al. 1990). Relative to the Vosges, the Baden-Baden branch of this fault zone has been displaced approximately 30–40 km to the NE by a system of late sinistral faults which are partly hidden under the sedimentary pile of the upper Rhinegraben (Edel and Weber 1995).

The Saxothuringian domain of the northern Schwarzwald (Baden-Baden Zone, BBZ; Fig. 1) is characterised by isolated kilometre-sized slices of low- to medium-grade metamorphic rocks (Wickert et al. 1990) within Permian sediments and volcanics. A second zone of low- to medium-grade metamorphic rocks in tectonic contact with unmetamorphosed Upper Devonian to Lower Carboniferous volcano-sedimentary sequences, is the Badenweiler-Lenzkirch Zone (BLZ; Fig. 1; Eisbacher et al. 1989; Maass et al. 1990) in the south. During Variscan convergence in the Carboniferous, the Central Schwarzwald Gneiss Complex

(CSGC; Fig. 1), consisting mainly of HT–LP gneisses and migmatites, was tectonically emplaced over the BBZ in the north and the BLZ in the south. The BLZ is bordered to the south by the Southern Schwarzwald Gneiss Complex (SSGC; Fig. 1) containing essentially gneisses of a metamorphic grade similar to that of the CSGC. The metamorphic rocks are intruded by Lower to Upper Carboniferous granites (e.g. Brewer and Lippolt 1972; Todt 1976; von Drach 1978).

Metamorphic rocks of the CSGC have experienced HT–LP metamorphism at approximately 330 Ma (Kalt et al. 1994; Lippolt et al. 1994) but diverge in their earlier P–T evolution. Hanel and Wimmenauer (1990) proposed a sudivision of the CSGC into three distinct units:

1. Monotonous gneisses and migmatites with numerous intercalations of eclogites (Klein and Wimmenauer 1984) and some ultramafic high-pressure rocks (Kalt et al. 1995; Kalt and Altherr 1996) are dominant.
2. Heterogeneous gneisses with more variegated lithologies crop out at the southern and eastern margins of the CSGC, in the central Kinzig valley area and in the Omerskopf Gneiss Complex (Fig. 1). This unit is devoid of high-pressure rocks and contains rare relicts of a previous medium-pressure metamorphic stage (Rehfeld 1983; Flöttmann and Kleinschmidt 1989).
3. Gneisses with relicts of a granulite-facies metamorphic stage (Röhr 1990; Hanel et al. 1993) are restricted to both sides of the lower Kinzig valley in the central part of the CSGC and also occur in the SSGC.

The gneisses investigated in this study were recovered from the Bühl-1 drilling site (Fig. 1) approximately 1700 m west of the Rhinegraben master fault, most likely located above a late sinistral displacement zone (see above). Approximately 2400 m of Quaternary to Mesozoic sediments were penetrated. After crossing the master fault at a depth of 2490–2493 m, fine-grained gneisses were drilled. Drill cores of gneisses were taken from depths of 2519.5–2550 m (cores 1–5) and 2692.0–2699 m (core 6). The recovered gneisses are very likely part of the Omerskopf Gneiss Complex cropping out some kilometres to the east and southeast of the Bühl-1 drilling site (Fig. 1). Both, drill cores and the Omerskopf Gneiss Complex, consist of banded gneisses and paragneisses, the latter having in addition orthogneisses and migmatites.

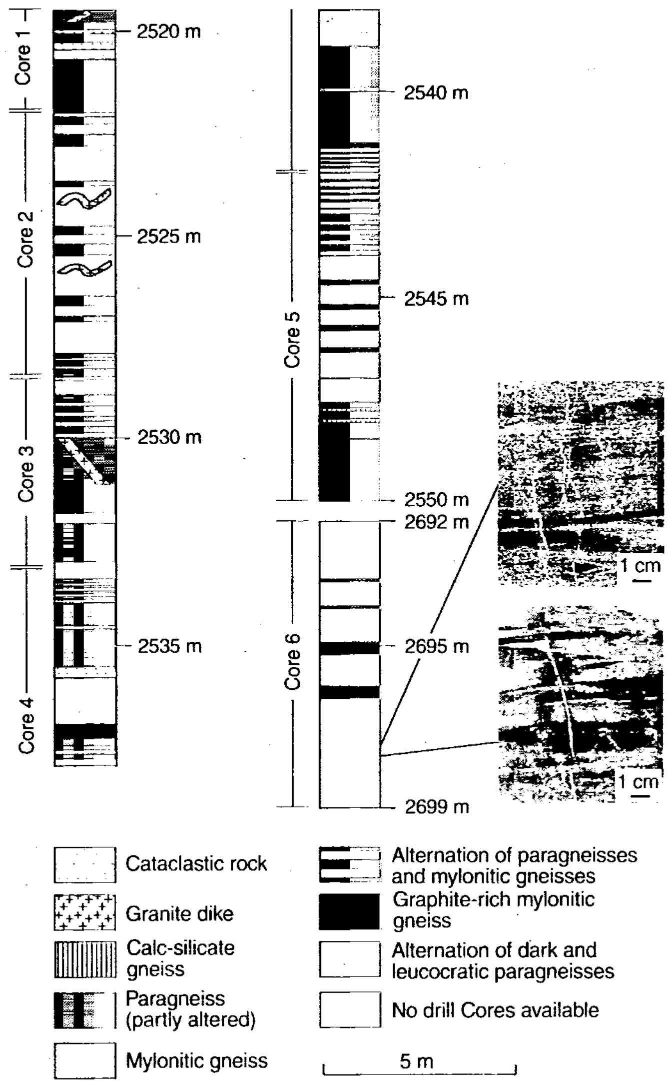

Fig. 2 Drawing of the Bühl-1 gneiss profiles (drill cores 1–6). *Photographs* show some typical fine-grained paragneisses with leucocratic and dark layers

Petrography

Drill cores 1–5 of the Bühl-1 drilling site consist of dark to light-coloured paragneisses alternating with dark-coloured mylonitic rocks (Fig. 2). Both rock types are fine grained. The mylonitic bands range in thickness between a few millimetres and 1 m and make up 30–40% of the cores (Fig. 2). Concordant calcsilicate gneiss layers, discordant thin aplitic dikes and cataclasites with angular mylonitic gneiss fragments occur (Fig. 2). All rocks types are cut by late millimetre- to centimetre-thick quartz and/or carbonate veins along which the rocks may be bleached. Drill core 6 shows a monotonous layering of dark and light-coloured paragneisses (Fig. 2) alternating with graphite and pyrite-rich mylonitic gneisses. The gneisses are cut by quartz-carbonate veins, but bleaching is much less pronounced than in drill cores 1–5.

Paragneisses

In all drill cores paragneisses show a compositional banding of biotite-poor and biotite-rich layers. Most paragneisses are altered and bleached. The most common primary mineral assemblage of unaltered rocks is plagioclase + quartz + biotite ± K-feldspar.

Accessory minerals are graphite of organic origin, zircon, apatite, rutile, tourmaline, pyrite and pyrhotite. Secondary minerals which formed at the expense of biotite and feldspars are chlorite, fine-grained muscovite (sericite) and carbonates. In some gneiss layers fibrolitic sillimanite occurs as lens-shaped brown aggregates arranged parallel to foliation. The sillimanite aggregates are often completely transformed into fine-grained sericite which has partly recrystallised to coarser grained muscovite. In one sample (B-2548 m) a layer containing small anhedral and slightly poikiloblastic garnet grains in addition to quartz, plagioclase, biotite and secondary chlorite and muscovite was found. The garnets bear inclusions of rounded chlorite and quartz grains and show embayments in which plagioclase, biotite and quartz have grown by a garnet-consuming reaction.

Microscopically, the paragneisses show deformation fabrics. Quartz grains show strong undulose extinction, elongate subgrains and minor dynamic recrystallisation. Subgrain boundaries are oblique to the main foliation. Plagioclase shows tapering deformation twins and bent twins. Recrystallisation of feldspars was not observed. Biotite is usually red-brown and shows undulose extinction, kinks and occasionally mica-fish like forms.

Mylonitic rocks

Mylonitic rocks developed from the paragneisses and can be divided into mylonitic gneisses and graphite-rich mylonitic gneisses, the latter macroscopically resembling graphite schists. The grey-green to bluish-grey mylonitic gneisses show a spaced foliation with millimetre-sized quartz-feldspar microlithons (Passchier and Trouw 1996) and anastomosing discrete cleavage domains up to several millimetres thick composed mainly of chlorite and muscovite. Main microlithon minerals are primary plagioclase, quartz, biotite and some secondary chlorite and muscovite. The shear bands consist of muscovite + chlorite + quartz ± plagioclase ± K-feldspar ± biotite. Accessory minerals are calcite, rutile, zircon, apatite, tourmaline and opaques. Quartz in the shear bands forms elongate platy grains with subgrain formation but only minor dynamic recrystallisation. Larger muscovite and chlorite grains show undulose extinction, kinks and folding. Shear band cleavage, occasional asymmetrical microfolds and σ-type feldspar porphyroclasts indicate a non-coaxial deformation. On foliation planes, a weak lineation is present.

The graphite-rich mylonitic gneisses (up to 12 vol.% graphite) display anastomosing foliation planes that are coated with graphite. Graphite-rich layers may be up to 2 mm thick. The primary mineral assemblage is quartz + plagioclase + K-feldspar + biotite + graphite with secondary muscovite and chlorite. Accessory minerals are zircon, apatite, rutile, titanite, tourmaline and Fe-rich carbonates. The graphite-rich rocks from drill core 6 are additionally enriched in anhedral pyrites parallel to foliation. Shear bands have the mineral assemblage chlorite + muscovite + albite + K-feldspar + quartz ± biotite + graphite + pyrite. Microlithons consist mainly of feldspars and quartz. Microscopic deformation features of disc-shaped to platy quartz aggregates include subgrains, rare deformation lamellae and irregular grain boundaries. Plagioclase grains occur occasionally as σ-type porphyroclasts or as elongated sheared grains with bent twins. Both types are wrapped by muscovite flakes. Muscovite occurs as subhedral grains and as fine-grained aggregates which presumably formed at the expense of sillimanite, the latter occurring rarely as very fine needles in adjacent quartz grains. Muscovites always display kinks and undulose extinction. Graphite occurs as small round- to bottle-shaped grains of organic origin and as elongated and deformed flakes parallel to the main foliation; the latter are lamellar intergrowths with muscovite and chlorite.

Metamorphic evolution

Paragneisses of the Bühl-1 drilling site are characterised by a primary amphibolite-facies metamorphic stage and by later mylonitisation under greenschist-facies conditions. There is no indication as to whether mylonitisation was immediately subsequent to amphibolite-facies metamorphism.

The primary amphibolite-facies stage is characterised by a lack of primary muscovite and by the occasional coexistence of sillimanite and K-feldspar. Thus, the reaction muscovite + quartz = K-feldspar + sillimanite + H_2O gives a minimum temperature for the primary mineral assemblage. A maximum temperature is given by the lack of any indication of partial melting reactions in the investigated rocks. The coexistence of graphite, pyrite and pyrhotite in some samples places upper limits on X_{H_2O} in a coexisting fluid phase (approximately 0.40–0.65; Poulson and Ohmoto 1989; Connolly and Cesare 1993), assuming pressures between 0.2 and 0.6 GPa (Hanel et al., in preparation). The low X_{H_2O} shifts both reaction temperatures (Kerrick 1972; Johannes and Holtz 1996), resulting in a temperature bracket of 580–710 °C (Hanel et al., in preparation). The primary mineral assemblage of the paragneisses is transformed to a secondary greenschist-facies assemblage of muscovite + chlorite + quartz ± feldspar during mylonitisation of the rocks. Based on the deformation features of micas, quartz and feldspars (Passchier and Trouw 1996), and on reaction textures of muscovite, biotite, quartz, chlorite and K-feldspar, only a wide temperature range of 300–500 °C can be deduced (Hanel et al., in preparation).

Palynology

Analytical procedures

Microfossils were separated from small samples (20–30 g) of graphite-bearing rock domains. The blocks were carefully washed and then treated with hot HCl to remove carbonates from joints. Graphite and graphitised microfossils were isolated by dissolving the silicate minerals with hydrofluoric acid (73%). Upon completion of the silicate dissolution, the liquid was decanted and the solid residue was neutralised with distilled water. In order to dissolve any fluorides produced during the HF dissolution step, the residue was treated with hot concentrated HCl and then neutralised again with distilled water. Finally, the residue was sieved to grain-size fractions of 10–120 and >120 μm and stored in air-tight glass containers with alcohol. For conventional microscopic investigations using transmitted and reflected light an aliquot of the maceration residue was transferred to strew slides with a micropipette and embedded in glycerine in order to fix the palynomorphs. Another aliquot was used for scanning electron microscopy (SEM) stub preparation. For SEM investigations a Jeol JSM 6300 F scanning microscope with an energy-dispersive X-ray analyser (EDX) at the "Labor für Elektronenmikroskopie", University of Karlsruhe, was used. Palynomorph compositions were qualitatively checked with the EDX equipment. All palynomorphs illustrated in Figs. 3 and 4 consist of pure carbon.

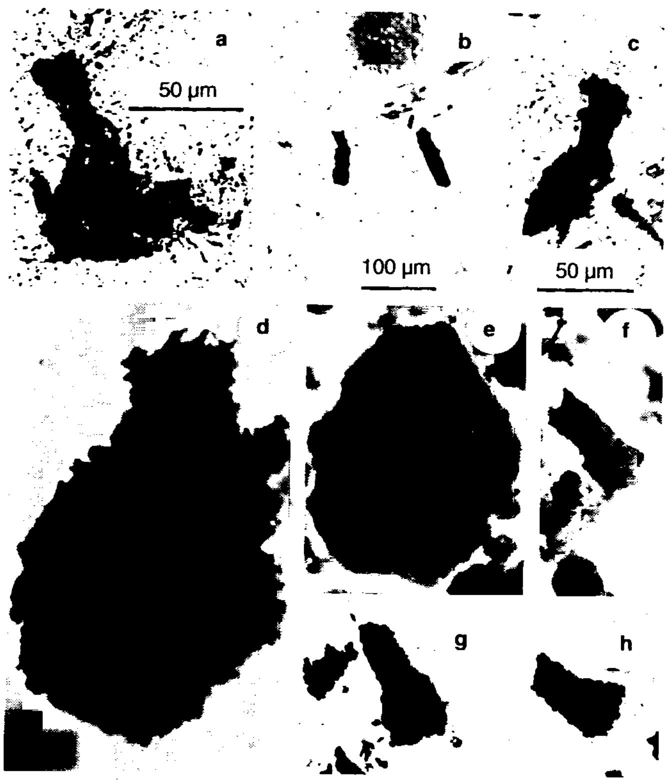

Fig. 3a–h Microphotographs of thin sections and maceration residues with graphitised microfossils. **a–c** Possible chitinozoans with bottle-shaped outlines in thin sections (Bühl-1 2697 m). The microfossils are included in quartz (**a, b**) and in sericitised plagioclase (**c**). **d–h** Graphitised chitinozoans in maceration residues from the grain size fraction 10–120 μm after dissolution of the silicate minerals with HF (Bühl-1 2695.5 m). Note that the presence of potential microfossils both in the maceration residues and in the thin sections rules out contamination

Results

Microfossils could be identified in thin sections of paragneisses (Fig. 3) and microlithons of mylonitic gneisses from all drill cores of the Bühl-1 drilling site. The examination of thin sections clearly shows that microfossils occur along grain boundaries between quartz, feldspars, micas and chlorites, and as inclusions in the rock-forming minerals. The microfossils are graphitised and display round, elongated or roughly bottle-shaped contours (Fig. 3). Sizes vary between 10 and 200 μm; however, most of the graphite present in thin sections gives little evidence of potential microfossils. The SEM images reveal that preserved microfossils in the maceration residues are chitinozoans (Fig. 4) and compressed sphaeromorphic acritarchs.

Group Chitinozoa Eisenack 1931 are extinct, exclusively marine, organic-walled microfossils with flask-, urn- or bottle-shaped morphologies and with single to multiple-layered vesicle walls (Eisenack 1968; Laufeld 1967; Paris 1981; Miller 1996). Based on their wide geographic distribution in different marine environments (shallow water, continental shelf and slope sediments) and their occurrence in sediments devoid of benthic fauna, a planktonic mode of life is generally assigned to chitinozoans (Paris 1996). Although chitinozoans have some similarities to dinoflagellates, tintinnids, rhizopods and certain funghi, their biological affinity and nature is still under debate (for a detailed discussion of different interpretations see e.g. Sutherland 1994; Miller 1996). Despite these uncertainties, chitinozoans have a global, very well established stratigraphic range from the Lower Ordovician to the Upper Devonian (Paris 1996) and possibly into the Lower Carboniferous (Sutherland 1994). Therefore, chitinozoans are index fossils, particularly for the Early Paleozoic, and potentially useful in biostratigraphical, palaeogeographical and palaeoenvironmental research (Paris 1981; Paris 1996; Paris and Robardet 1990; Achab et al. 1992; Oulebsir and Paris 1995; Miller 1996).

The chitinozoans found in the maceration residues are conical to bottle-shaped (Fig. 4). Compressed vesicles and necks, as well as aperture-like structures are discernible. One specimen even displays a double-layered vesicle wall (Fig. 4a, b). Some specimens show negative marks of a cubic mineral, presumably pyrite (Fig. 4e). Most chitinozoans tend to transform into small recrystallised graphite flakes (Fig. 4d), a feature

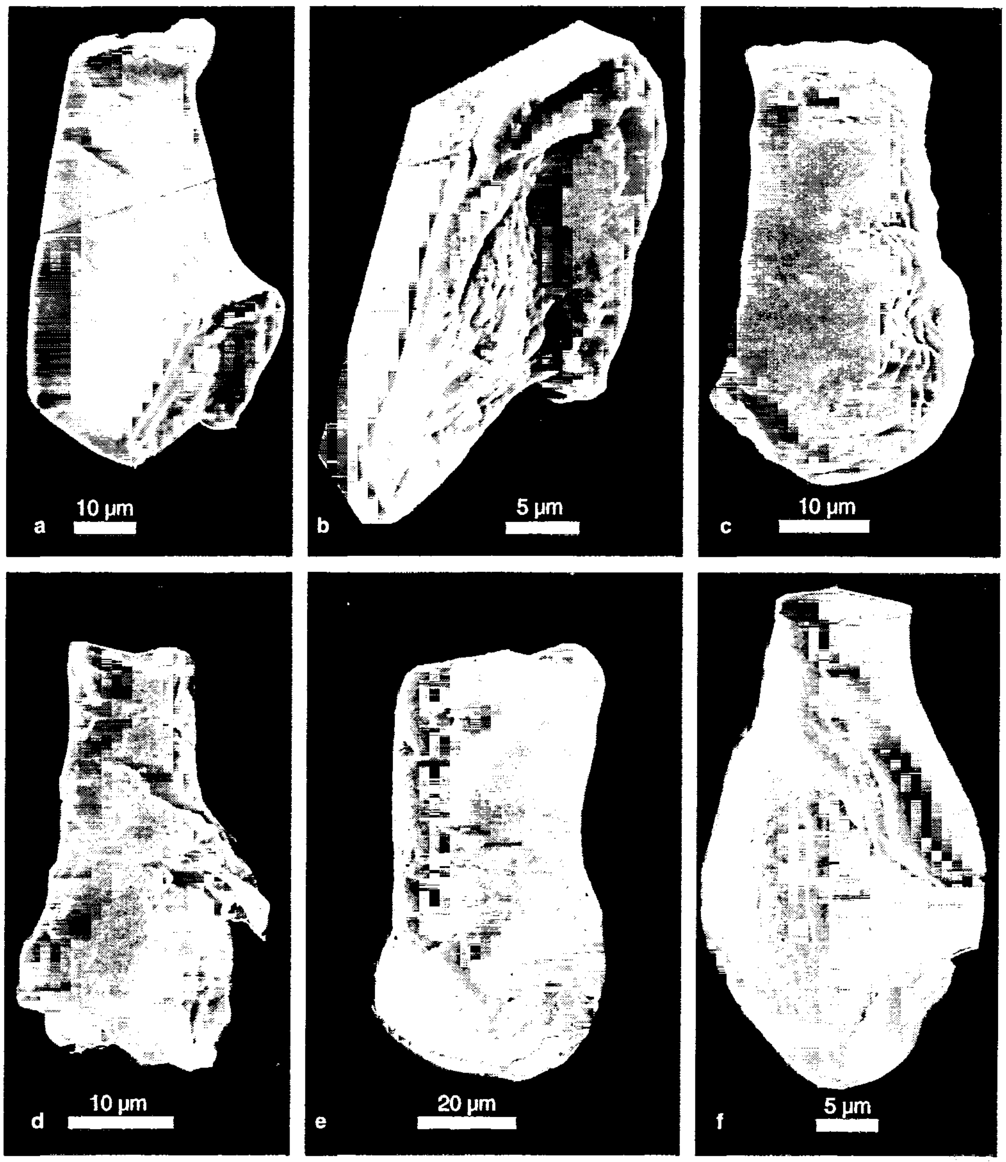

Fig. 4a–f Scanning electron microscopy images of isolated chitinozoans and chitinozoan fragments from Bühl-1 paragneisses (**a–c** Bühl-1 2697 m, **d** Bühl-1 2548 m, **e, f** Bühl-1 2695.5 m). All specimens are compressed, graphitised and poorly preserved compared with chitinozoans from non-metamorphic rocks. **a–f** Chitinozoans showing differentiation into neck and vesiculum. **a** ?*Conochitina* sp. with partially preserved bi-layered wall. **b** Detail from **a**. **d** Chitinozoan fragment which tends to fall into graphite flakes. **e** Chitinozoan remain with negative marks, possibly derived from secondary pyrite growth. **f** ?*Angochitina* sp. with still observable aperture

assigned to the intense deformation of the paragneisses. As expected, delicate structures important for taxonomic classification, such as, for example, spines and ornamentations, have been destroyed during graphitisation. Additionally, geometrical relationships important for taxonomic classification, such as width and length ratios of vesicles and necks or the form of the flexure between neck and body chamber, have changed through deformation. Figure 5 illustrates for comparison important morphological features and two examples of chitinozoans from non-metamorphic rocks. Hence, a classification of the chitinozoans on the species level is impossible. Based on the preserved morphologies, the chitinozoans can be tentatively assigned to the genera ?*Angochitina* sp. and ?*Conochitina* sp. that range from Caradoc to Famenian (455–355 Ma; Odin 1994) and from Arenig to Ludlow (480–415 Ma; Odin 1994), respectively (Miller 1996). The genus *Angochitina* was established by Eisenack (1931) and comprises chitinozoans with a round, bottle-shaped body which gradually transforms into a neck. In comparison with the body, the neck is slightly longer and exhibits a little widening at the aperture. Classically, the chitinozoans assignable to the genus *Angochitina* (Eisenack 1931) show numerous spines at the body which disappear towards the aperture. Spines at the aboral pole are absent. Although no spines can be identified on the specimens found in the Bühl-1 gneisses, the partly rough surface structure of the specimens can probably be interpreted as the remains of spine bases. The representatives of the genus *Conochitina* (Eisenack 1931) display a very different morphology. They are generally characterised by a conical vesicle and a poorly differentiated flexure, and the maximum diameter is often located near the aboral pole (Sutherland 1994). The structures observed on the Bühl chitinozoans are of little taxonomic value. The specimens found are kept therefore in open nomenclature. Nevertheless, the presence of chitinozoans and chitinozoan fragments clearly prove a Paleozoic deposition

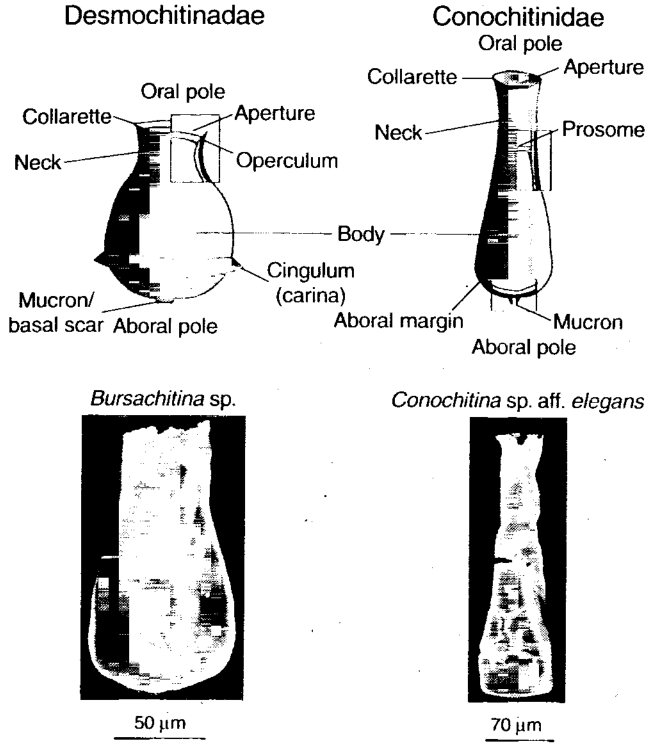

Fig. 5 Line drawings of chitinozoan morphology of the families Desmochitinidae and Conochitinidae and SEM pictures of two chitinozoans from non-metamorphic sediments. (From Sutherland 1994; reproduction with kind permission of the Paleontological Society London)

age for the sedimentary precursor rocks of the Bühl-1 paragneisses under marine conditions.

The compressed sphaeromorphic acritarchs probably belong to the group *Leiosphaeridia* (Eisenack 1968). Their stratigraphic range (Precambrian to Cenozoic) is too wide to be of any biostratigraphical use.

Discussion

Preservation of microfossils in high-grade metamorphic gneisses

The palynological results presented herein and in other studies (e.g. Andrusov and Corna 1976; Reitz 1992; Paeltová 1994) indicate that microfossils, such as acritarchs and chitinozoans, and their morphological features, may be preserved even at high-grade metamorphic conditions. This seems surprising because prograde metamorphism of sediments usually involves deformation and mineral growth, processes enhancing destruction of fossils except under extraordinary circumstances (e.g. Boucot and Thompson 1963; Boucot and Rumble 1980; Franz et al. 1991; Vogler 1995).

Acritarchs are composed of sporopollenin (Traverse 1988). The wall of chitinozoans is thought to be composed of a chitin-like material (Eisenack 1968), but the exact composition is still unknown (Miller 1996). Both materials are known to be very stable under reducing conditions (Traverse 1988). If these conditions prevail during diagenesis, acritarchs and chitinozoans may survive, their hollow bodies suffering only compression and a change of colour during temperature increase from translucent light-yellow to opaque black. During prograde metamorphism, all organic hydrocarbons that survived diagenesis will be irreversibly transformed to graphite. Graphitisation involves many stages most of which are characterised by the release of hydrogen, oxygen and nitrogen (Gorokhov et al. 1973; Buseck and Bo-Jun 1985). Planar layers of carbon must develop that can finally be stacked to form the parallel layers characteristic of the graphite structure. From studies of carbonaceous matter that experienced contact or regional metamorphism a positive correlation between metamorphic grade and carbon crystallinity is obvious (e.g. Landis 1971; Grew 1974; Itaya 1981; Wada et al. 1994). The latter is mainly controlled by increasing temperature. Fully ordered graphite with well-developed (002) diffraction peaks is normally formed at temperatures of 400–500 °C (Landis 1971; Grew 1974; Diessel et al. 1978; Wang 1989). However, the graphitisation process is also influenced by pressure, deformation, fluids and kinetics, and is further dependent on the type of hydrocarbon precursor and on bulk composition (Wopenka and Pasteris 1993).

Although completely graphitised, the original form of acritarchs and chitinozoans may still be recognisable; however, delicate structures important for taxonomic classifications are usually destroyed by graphitisation. Thus, forms with simple morphologies (e.g. chitinozoans without ornamentations or spines) have the best chance of preserving their primary features, although their length/width ratio may be changed by deformation. During metamorphism and deformation, microfossils have the best chance of preserving their forms as inclusions armoured by rock-forming metamorphic minerals and in low-strain domains of a deforming rock. Observation of thin sections from the samples studied here reveals that both cases are possible (see Palynology).

Comparison with palynological studies of other Moldanubian metamorphic rocks

Although the chitinozoans in the Bühl-1 gneisses are poorly preserved compared with those in non-metamorphic sediments, they indicate a Paleozoic sedimentation age. The stratigraphic ranges of the genera *Angochitina* sp. (455–355 Ma) and *Conochitina* sp. (480–415 Ma) overlap between 455 and 415 Ma (Caradoc to Ludlow). Hence, the deposition age of the sedimentary precursors to the Bühl-1 paragneisses and mylonitic gneisses can be further confined to the Early Paleozoic (Ordovician/Silurian), provided that no resedimentation took place after deposition; however, it cannot be entirely excluded that sedimentation continued until Famenian (365–355 Ma, Upper Devonian) whereby Early Paleozoic deposits were reworked.

The presence of chitinozoans implies the existence of an Early Paleozoic marine basin as depositional environment for tectonometamorphic unit 2 of the CSGC (heterogeneous gneisses devoid of high-pressure relicts; see Geological setting). Parts of this basin were filled with clastic greywacke-like sediments as is evident from the geochemical composition of the Bühl-1 gneisses (Hanel et al., in preparation); however, these clastic sediments must have been fine grained, because otherwise the fragile microfossils would have been mechanically destroyed during deposition of the detrital material.

In garnet–cordierite gneisses of tectonometamorphic unit 1 in the CSGC (monotonous gneisses and migmatites with high-pressure relicts; see Geological setting) acritarchs from the Neoproterozoic (1000–540 Ma) were found (Montenari 1996), implying marine sedimentation much earlier than indicated for unit 2 by chitinozoans. Two interpretations are possible. The precursors to both paragneiss associations may be products of continuous sedimentation in a single marine basin or environment from Neoproterozoic up to Early Paleozoic. In this case tectonic processes must have subsequently separated the two units because their prograde metamorphic history was most likely different. During Carboniferous collision and stacking, the two domains must have been juxtaposed. Alternatively, the sediments were deposited in two spatially isolated basins, metamorphosed at different conditions and finally welded together during the Carboniferous collision event. Due to the lack of palynological results from other gneisses of the CSGC, this important issue remains unresolved at the moment, but further investigations are forthcoming.

The tectonically dismembered lower-grade metamorphic rocks of the Baden-Baden Zone in the north and the Badenweiler-Lenzkirch Zone in the south of the CSGM (Fig. 1) comprise Silurian and Lower Ordovician marine sediments (Montenari and Maass 1996; Montenari and Hanel 1998). It may be tempting to correlate the Bühl-1 paragneisses with these metasediments; however, at the present state of knowledge, further investigations must clarify whether high-grade and low-grade metamorphic rocks share a common sedimentary evolution.

Up to now a correlation of the high-grade metasedimentary units of the Moldanubian Zone in the different Variscan massifs has been based mainly on lithological composition, structural evolution and metamorphic grade. Sedimentation ages which are critical for a meaningful correlation and for reconstruction of the early geological evolution are presently available only from a few localities. In the Moldanubian Zone of the Bohemian Massif, marbles of the Varied series of the Drosendorf unit near the town Cesky Krumlov in southern Bohemia are reported to contain remnants of graphitised acanthomorphic acritarchs, chitinozoans and spores (Andrusov and Corna 1976; Pacltová 1980, 1994) which point to an Early Paleozoic, possibly Silurian sedimentation age. The significance of this age has been discussed controversially because low $^{87}Sr/^{86}Sr$ ratios of approximately 0.7060 from marbles of the Varied series are interpreted to reflect the Sr isotope composition of seawater at Neoproterozoic times (Fuchs 1995).

From the Drosendorf unit in eastern Bavaria near the town of Rittsteig, Reitz and Höll (1988) and Reitz (1992) report microfossils from low-grade phyllitic micaschists forming part of a Varied series with quartzites, marbles and amphibolites (Blümel 1972). The microfossils reported from different samples and localities are miospores (Reitz 1992) indicating middle to upper Silurian clastic sedimentation in a proximal near-shore environment, and sphaeromorphic acritarchs indicating sedimentation near the Precambrian/Cambrian boundary (Reitz and Höll 1988).

In summary, microfossil findings point to both Paleozoic and late Proterozoic sedimentation ages of metasediments in the Moldanubian Zone of the Bohemian Massif and in the Schwarzwald; however, the very low number of palynological studies does not allow for any correlation between the two Variscan massifs at the moment.

Geodynamic context of the Early Paleozoic sedimentation ages

Based on palaeomagnetic results (Torsvik et al. 1996; Tait et al. 1997), U–Pb age spectra of zircons in gneisses (Gebauer et al. 1989) and paleontological evidence (Achab et al. 1992), it is generally accepted that the Moldanubian and Saxothuringian domains of the Variscan belt were part of the Armorican microplate. Until Arenig times, Armorica resided in high peripolar latitudes at the northern margin of the Gondwana continent. In the Llanvirn to Caradoc time range, Armorica broke away from the Gondwana margin and began drifting northward until it collided with the southern margin of Baltica/Avalonia in the Devonian (Tait et al. 1997). The cryptic suture zone of this collision in central Europe is thought to be in the Northern Phyllite Zone (Franke et al. 1995). Northward drifting of Armorica must have been initiated by rifting processes leading to the formation of at least one marine basin between Gondwana and Armorica and to the formation of Cambrian to Lower Ordovician magmatic rocks. The latter is documented in numerous Cambrian to Ordovician U–Pb ages of zircons (upper and lower intercepts with discordia) from metamorphic and magmatic rocks in the Moldanubian Zone (e.g. Todt and Büsch 1981; Pin and Lancelot 1982; Menot et al. 1988; Zulauf et al. 1997).

The (?Early) Paleozoic basin indicated by chitinozoans found in high-grade gneisses of the Schwarzwald is most likely related to these rifting processes during the separation of Armorica and Gondwana. However, geometry, size, number, location and lifetime of the rift-related basins in the Moldanubian Zone are presently completely unknown. The intra-plate palaeogeography of Armorica during the Paleozoic, particularly the spatial relation between the future Saxothuringian and Moldanubian domains, is still unclear, although palaeomagnetic evidence suggests that the Saxothuringian domain was located at the northern margin of Armorica, whereas the Teplá-Barrandian as a part of the Moldanubian domain was situated more to the south in Silurian times (Tait et al. 1997). Hence, the Early Paleozoic marine environment of the Schwarzwald may be related either to a truely oceanic domain, probably at the southern margin of Armorica or to rift-related smaller basins within the Armorican microplate.

Conclusions

The following conclusions were reached as a result of this study:

1. Paragneisses and mylonitic gneisses recovered from depths between 2519.5 and 2699 m at the Bühl-1 drilling site in the northern Schwarzwald (Moldanubian Zone of the Variscan belt) are assigned to tectonometamorphic unit 2 of the crystalline basement of the Schwarzwald (heterogeneous gneisses devoid of high-pressure relicts) on the basis of lithology, metamorphic grade and location.
2. The gneisses have experienced amphibolite-facies metamorphic conditions (580–710 °C at 0.3–0.4 GPa) and were later partly transformed to mylonites under greenschist-facies conditions.
3. Completely graphitised acritarchs and chitinozoans were recovered from the paragneisses and mylonitic gneisses of the Bühl-1 drilling site. Chitinozoans could possibly be assigned to the genera ?*Angochitina* sp., ?*Conochitina* sp. indicating a Paleozoic sedimentation age and a marine depositional environment.
4. Comparison of these results with findings of Upper Proterozoic acritarchs in high-grade metamorphic gneisses of tectonometamorphic unit 1 of the crystalline basement of the Schwarzwald (monotonous gneisses and migmatites with high-pressure relicts) suggests that within the Moldanubian Zone of the Armorican microplate, rocks with different sedimentary records later experienced diverging prograde metamorphic histories before they were brought together during Variscan collisional tectonics approximately 330 Ma ago.
5. The results reveal that palynological studies on high-grade metamorphic rocks that are petrologically and tectonically well characterised are a promising tool for reconstructing pre-orogenic settings in collisional belts despite pervasive metamorphism and deformation.

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