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Ordovician and Silurian protolith ages of metamorphosed clastic sedimentary rocks from the southern Schwarzwald, SW Germany: a palynological study and its bearing on the Early Palaeozoic geotectonic evolution

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Abstract – Sedimentation ages of metamorphosed clastic sedimentary rocks in the southern Schwarzwald were determined by associations of palynomorphs. In the northern subunit of the Badenweiler–Lenzkirch Zone, two lithostratigraphic assemblages could be discerned in low-grade metamorphic units by their facies and age, thus revealing a more complex internal structure of this zone than previously assumed. Lower Ordovician metagreywackes and metapelites were discerned from Silurian metasiltstones. In the cataclastically overprinted metasiltstones and phyllites of the southern subunit of the Badenweiler–Lenzkirch Zone, only poorly preserved microfossil remains could be detected. These show that the sedimentation ages must be Ordovician or younger, but still probably Early Palaeozoic. High-grade metapelitic rocks of the South Schwarzwald Gneiss Complex contain chitinozoans in lenses and layers of schists, that are rich in biotite and graphite. They yielded mid-Silurian ages and show that this crystalline complex does not represent an older basement unit but was the result of marine sedimentation at that time. The new age determinations have a bearing on geodynamic reconstructions of the internal Variscides in Early Palaeozoic time. They show that sedimentation in the oceanic realm of the Badenweiler–Lenzkirch Zone or its margins did not occur before the Ordovician. After transformation of the northern passive into an active continental margin, younger greywackes not older than Middle Devonian received detritus from a volcanic arc, forming above the subduction zone.

Keywords: palynomorphs, sedimentation, lithostratigraphy, ocean basins, plate tectonics.

1. Introduction

The Schwarzwald and the Vosges, on opposite sides of the Middle Rhein Graben, have a central position within the Variscan orogen (Fig. 1). Most of the Schwarzwald belongs to the Moldanubian Zone of the Central European Variscides, which is generally considered to be separated from the Saxothuringian Zone in the northern Schwarzwald by an oceanic suture (Eisbacher, Lüschen & Wickert, 1989). From north to south, the Moldanubian Zone of the Schwarzwald is subdivided into three units, the Central Schwarzwald Gneiss Complex, the Badenweiler–Lenzkirch Zone and the South Schwarzwald Granite and Gneiss Complex (Figs 2, 3). The Badenweiler–Lenzkirch Zone was described as a post-collisional, Upper Carboniferous shear zone (Sittig, 1981; Matte, 1986*a*; Krohe & Eisbacher, 1988; Eisbacher, Lüschen & Wickert, 1989; Maass, Prosch & Schuler, 1990; Echtler & Chauvet, 1992; Krohe, 1996). Recent studies, moreover, demonstrate that the Badenweiler–Lenzkirch Zone in fact also represents a Variscan Suture Zone (Loeschke *et al.* 1998; Gruler *et al.* 1999; Hann *et al.* 2000; Hann *et al.* 2003) formed by the collision of crustal blocks in Early Carboniferous time. Late Variscan granites and dykes intruded the two gneiss complexes and the Badenweiler–Lenzkirch Zone after their tectonic juxtaposition. The intrusions occurred between 334 and 330 Ma (Brewer & Lippolt, 1972; Todt, 1976; Schaltegger, 2000).

The Badenweiler–Lenzkirch Zone and its tectonic frame reflect a collisional event in the central part of the Variscan orogen (Hann & Sawatzki, 2000). S-vergent nappe thrusting brought the three Moldanubian units of the Schwarzwald into their present relative positions (Fig. 2). Additionally, nappe structures of regional extent were proven by thorough field studies both in the Central Schwarzwald Gneiss Complex (Hanel & Wimmenauer, 1990; Hann & Sawatzki, 2000) and in the South Schwarzwald Granite and Gneiss Complex (Hann & Sawatzki, 1998).

Since the Badenweiler–Lenzkirch Zone was unveiled as a suture zone, it has gained significance

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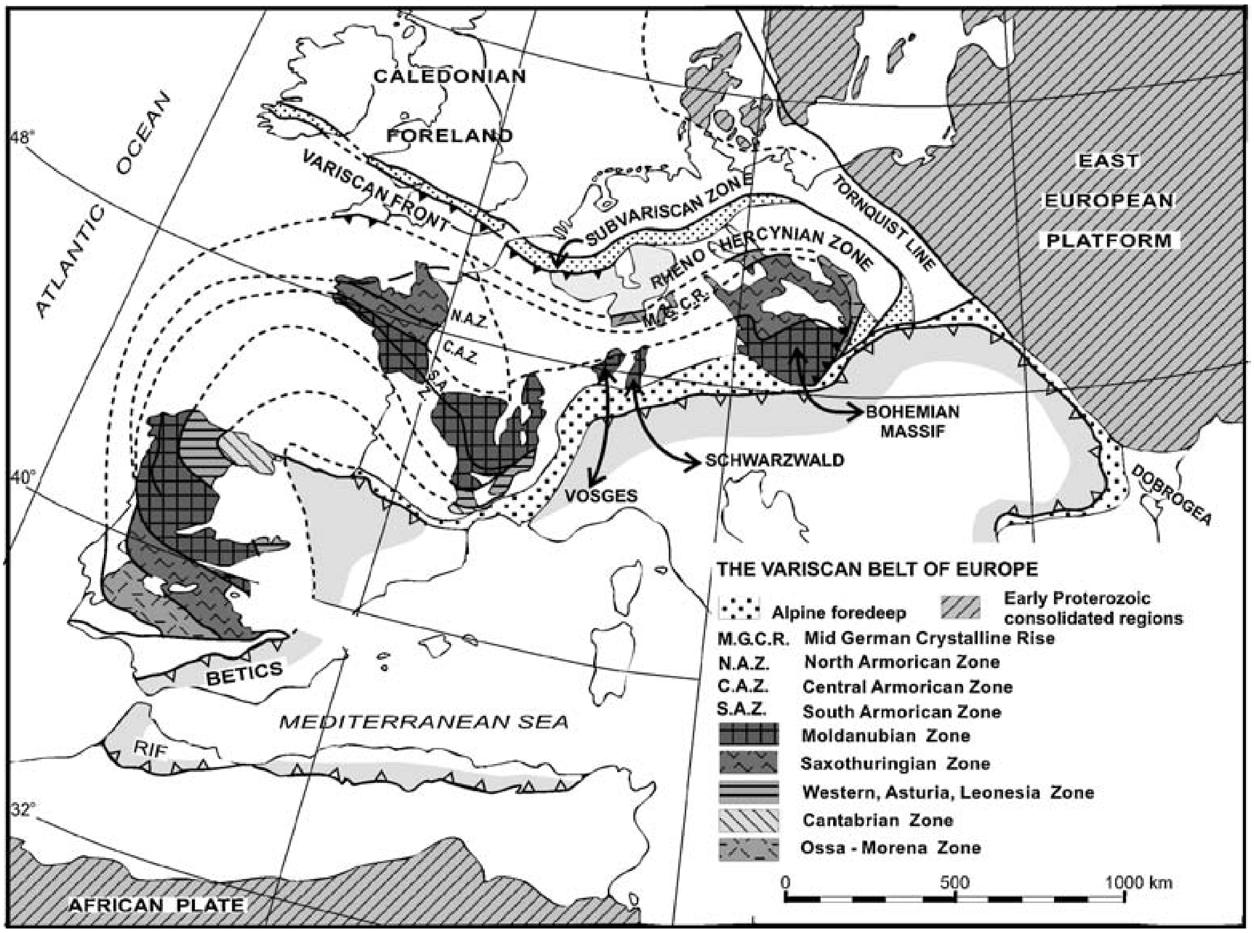

Figure 1. Position of Schwarzwald and Vosges Massifs in the Moldanubian Zone of the European Variscan Belt (modified after Schönenberg & Neugebauer, 1997).

for geodynamic reconstructions of the Variscides. However, protolith ages and the internal structure of the low-grade metamorphic sedimentary rocks, which are widespread in the Badenweiler–Lenzkirch Zone, are still insufficiently known. This paper aims to determine sedimentation ages of key lithologies from the Badenweiler–Lenzkirch Zone and adjoining areas of the South Schwarzwald Granite and Gneiss Complex. We consider this an important basis for the refinement of the geodynamic interpretation of the Central European Variscides.

It is also an attempt to refine the Palaeozoic biostratigraphy of the southern Schwarzwald terranes, with direct implications for their palaeocontinental reconstruction using palynological data. Being a good tool, palynomorphs, especially chitinozoans, have lately been used successfully to establish the palaeogeographical affinities of different areas (Cocks & Verniers, 1998).

2. Geological outline of the southern Schwarzwald and sample location

Samples were taken from both the Badenweiler–Lenzkirch Zone and the South Schwarzwald Granite and Gneiss Complex. A brief geological outline for these zones is given below.

2.a. Badenweiler–Lenzkirch Zone

The formations of the Badenweiler–Lenzkirch Zone (Fig. 3) have been imbricated and rotated into steeply inclined positions during continental collision and dextral transpression with anomalous contact (Krohe, 1996; Güldenpfenning, 1997). As a result, the Badenweiler–Lenzkirch Zone shows a complex internal structure. Based on detailed re-mapping, the Badenweiler–Lenzkirch Zone can be subdivided into three subunits (Hann & Sawatzki, 1998, 2002):

(1) The northern subunit comprises metagreywackes and metasiltstones containing lens-shaped bodies of polymictic, strongly deformed metaconglomerates, as well as phyllites, which had been thought to be devoid of fossils. The metaconglomerates were recently interpreted as Lower Palaeozoic glaciomarine diamictites (Ziegler & Wimmenauer, 2001) reflecting a heterogeneous continental source area, presumably a part of northern Gondwana. The metamorphic grade increases slightly from south to north from low- to

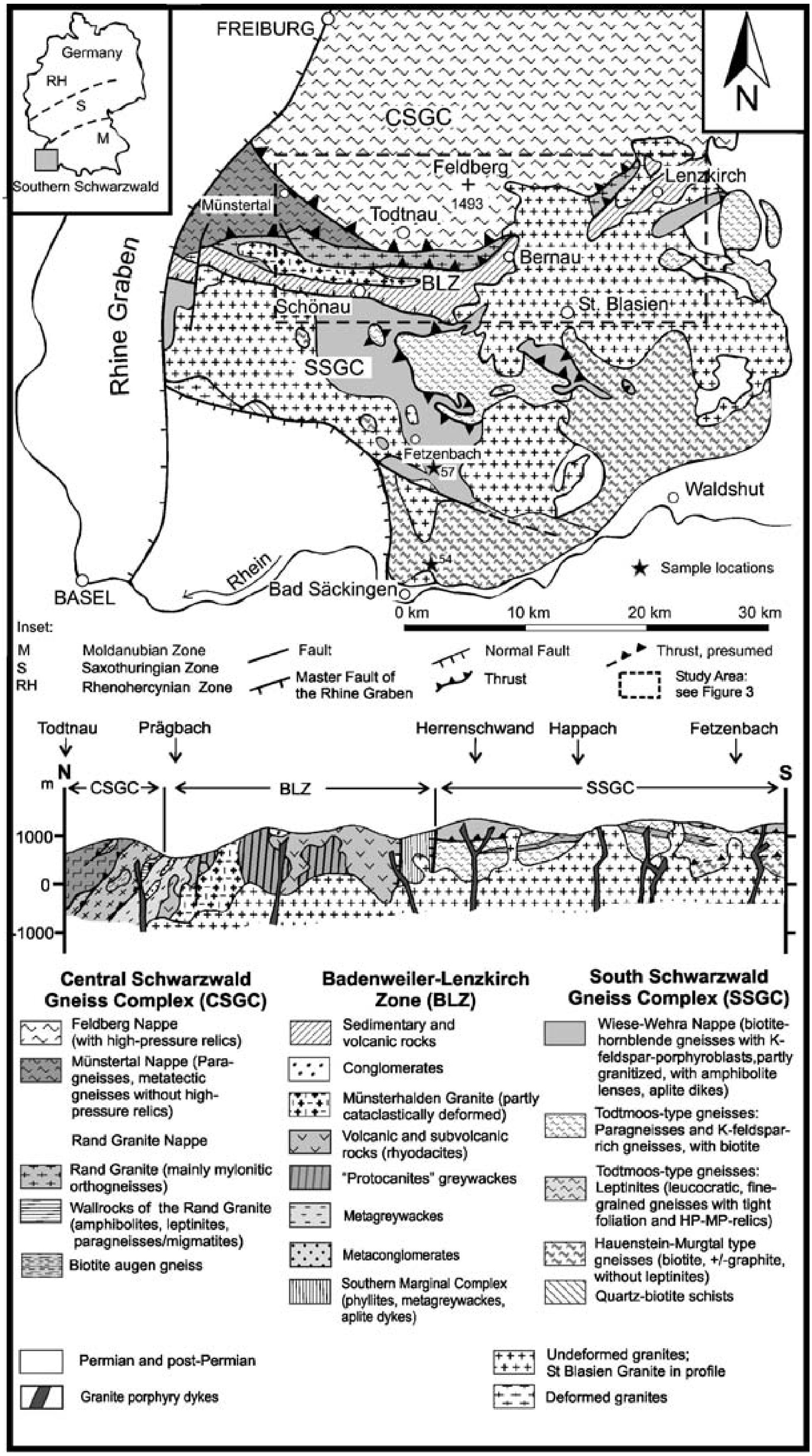

Figure 2. Geological sketch of the southern Schwarzwald (modified after Hann & Sawatzki, 2000) with a N–S cross-section. The Palaeozoic Badenweiler–Lenzkirch Zone (BLZ) is situated between the Central Schwarzwald Gneiss Complex (CSGC) and the South Schwarzwald Gneiss Complex (SSGC). The central and southern Schwarzwald represents a nappe stack cut by late-orogenic granite intrusions.

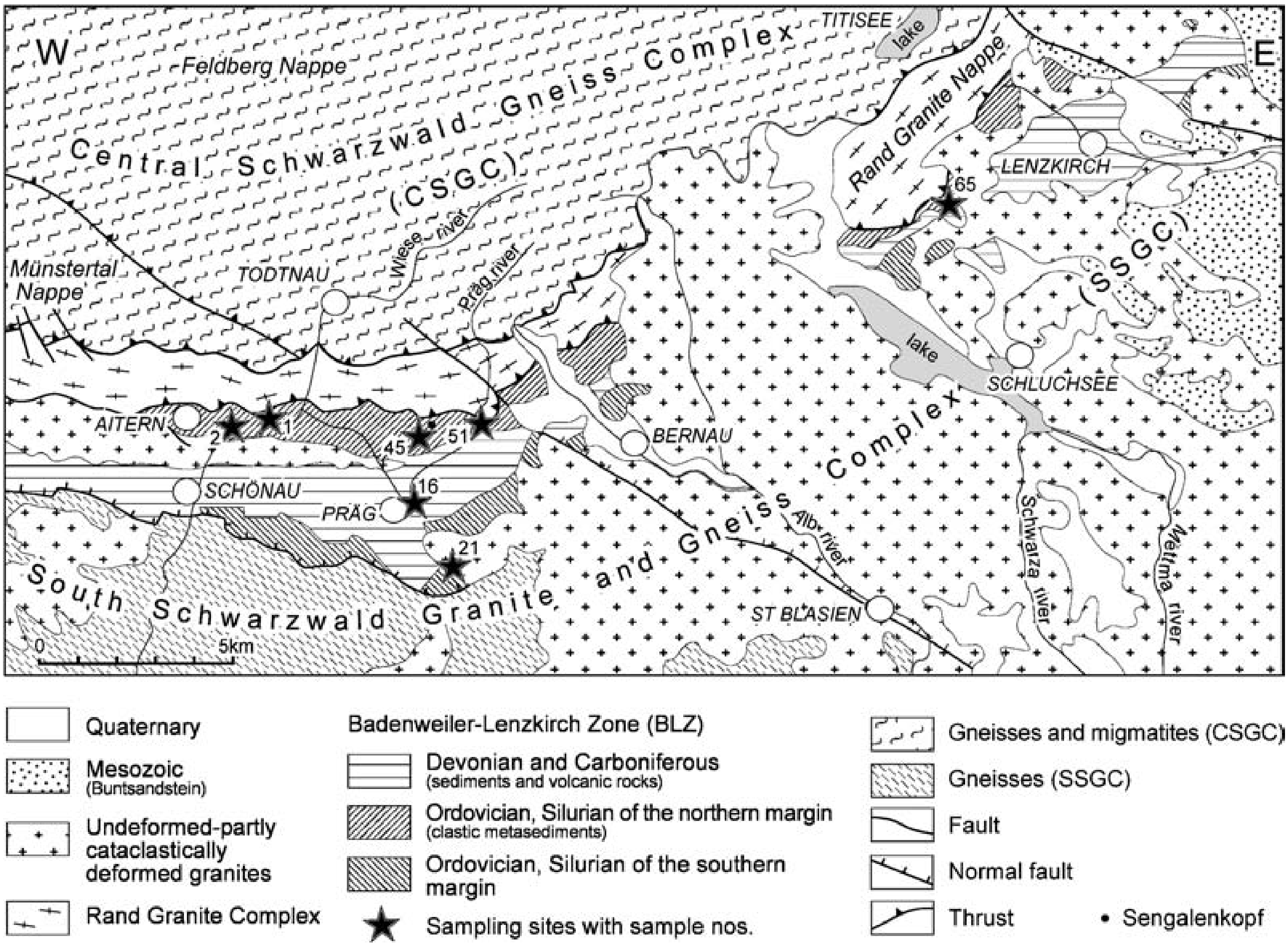

Figure 3. Geological map of the central and eastern part of the Badenweiler–Lenzkirch Zone (BLZ) with palynological sampling sites (modified after Hann & Sawatzki, 1998). See Figure 2 for location.

incipient medium-grade conditions (Altherr & Maass, 1977; Werling & Altherr, 1986).

(2) The central subunit consists of Upper Devonian to Lower Carboniferous clastic sediments (Sittig, 1967; Burgath & Maass, 1973) penetrated by Lower Carboniferous post-collisional rhyolithic to rhyodacitic subvolcanic and volcanic rocks (Fig. 3). The clastic rocks are mainly greywackes (‘Protocanites greywacke’: Wilser, 1933) and subordinate pelites. They experienced temperatures of high diagenesis to anchizonal metamorphism (Güldenpfennig, 1997). Weyer (1962) and Kneidl, Krebs & Maass (1982) described Upper Devonian conodonts from the pelitic layers. Molasse-type sediments, attributed to the late Visean (Sterzel, 1907; Frentzen, 1930; Vogellehner, 1968), represent the top of this sedimentation cycle.

(3) The southern subunit or Südrandkomplex (Southern Marginal Complex) is formed by weakly metamorphic formations (Sittig, 1969; Maass, Prosch & Schuler, 1990): cataclastically overprinted phyllites, metasiltstones and metagreywackes. They are penetrated by aplitic dykes (Hann & Sawatzki, 1997, 1998).

2.b. South Schwarzwald Granite and Gneiss Complex

The South Schwarzwald Granite and Gneiss Complex consists of the high-grade metamorphic gneisses of the Wiese-Wehra diatexites and the gneisses of the Todtmoos and Hauenstein-Murgal type (Hoenes, 1948; Metz & Rein, 1958; Sittig, 1969; Wimmenauer, 1984, 1988; Sawatzki, 1992). This assemblage experienced high-temperature low-pressure metamorphism around 335–330 Ma (Kalt, Grauert & Baumann, 1994; Lippolt, Hradetzky & Hautmann, 1994; Kalt, Altherr & Hanel, 2000, for overview). The Wiese-Wehra diatexites with metagabbros and meta-anorthosite fragments (Sebert & Wimmenauer, 1992) form a nappe structure (Hann & Sawatzki, 1998). Hegner, Chen & Hann (2001) constrained timing of thrusting, which occurred under ductile conditions, to between 342 and 333 Ma. The gneisses of the Todtmoos and Hauenstein-Murgtal type constitute the autochthonous unit. The Todtmoos gneisses contain leptynites with granulite-facies relics (Hann & Sawatzki, 1997; Kalt *et al.* 1999). The Hauenstein-Murgtal gneisses (Metz & Rein, 1958;

Table 1. Fossiliferous sample localities with number of map sheet

Fossiliferous sample no.	r*	h*	Top. map 1:25000	Locality	Unit
1	34 19 350	52 96 645	TK 8113	Utzenfeld	BLZ, northern subunit
2	341 8 460	52 96 395	TK 8113	Finstergrund	BLZ, northern subunit
65	34 37 120	53 01 970	TK 8115	Fischbacher Höhe	BLZ, northern subunit
45	34 23 150	52 96 080	TK 8113	Sengalenkopf	BLZ, northern subunit
51	34 24 200	52 96 050	TK 8113	Sägentobel	BLZ, northern subunit
16	34 23 360	52 94 260	TK 8213	Präg	BLZ, central subunit
21	34 24 140	52 92 830	TK 8213	N Hochkopf	BLZ, southern subunit
54	34 24 169	52 74 600	TK 8313	Wickartsmühle	SSGC
57	34 20 900	52 82 750	TK 8313	Wehratal, Pfeiferskopf	SSGC

* Gauss-Krüger coordinates.
TK – Topographical Map of Baden-Württemberg. BLZ – Badenweiler–Lenzkirch Zone; SSGC – South Schwarzwald Gneiss Complex. All samples except 54, 57, see Figure 3; for 54, 57 see Figure 2.

Mazurek, 1985), which are widely distributed in the southern and southeastern parts of South Schwarzwald Granite and Gneiss Complex (Fig. 2), predominantly consist of garnet, sillimanite and cordierite-bearing biotite gneisses containing graphite in places.

2.c. Sampling

Sixty-three samples were taken from different lithological units of the Badenweiler–Lenzkirch Zone and from the South Schwarzwald Granite and Gneiss Complex, however, only a few samples yielded identifiable microfossils (for localities, see Table 1, Figs 2, 3). The weakly metamorphic schists of the northern and southern subunits of the Badenweiler–Lenzkirch Zone were sampled throughout their entire exposure. Metagreywackes were sampled in the western and eastern parts of the northern subunit (Aitern and Lenzkirch, respectively: samples 1, 2, 65), and metasiltstones and phyllites in the central part (north of Präg: samples 45, 51). One sample from shales in the central subunit and another from phyllites in the southern subunit (samples 16, 21) were also taken.

Sampling was also carried out in the metapelitic layers of the gneisses of the South Schwarzwald Granite and Gneiss Complex (Wickartsmühle quarry, sample 54, Wehratal-Pfeiferskopf, sample 57; Fig. 2). Microfossils were contained in millimetre- to centimetre-thick layers or lenses of graphite-biotite schists within the gneiss anatexites of the Hauenstein-Murgtal type (sample 54), which are associated with marbles and calc-silicate rocks at this locality and in centimetre-thick layers of biotite-schists within the Wiese-Wehra diatexites (sample 57).

3. Palynological studies

3.a. Previous contributions

In recent years, attempts have been made to date the Schwarzwald metasedimentary rocks biostratigraphically using palynological methods. The first palynological dates were based on determinations made using an optical microscope. These were in part later confirmed by studies using a Scanning Electron Microscope (S.E.M.). Hann, Sawatzki & Vaida (1995) dated weakly metamorphic metagreywacke schists from the northern part of the Badenweiler–Lenzkirch Zone near Aitern; chitinozoans and acritarchs yielded a mid-Ordovician age. Montenari & Maass (1996) dated metagreywackes about 5 km further east (Sengalenkopf) as mid-Silurian. Hann & Sawatzki (1998) found Silurian to Early Devonian ages in samples of the same area. Montenari, Servais & Paris (2000) confirmed and further improved the chitinozoan ages from Sengalenkopf, for the first time with the aid of S.E.M. They were able to correct the originally proposed mid-Silurian age to Late Silurian. Although the samples came from a restricted area, the authors extrapolated their results to the weakly metamorphic schists of the entire Badenweiler–Lenzkirch Zone.

Montenari (M. Montenari, unpub. Ph.D. thesis, Freiburg, 1999), determined Late Proterozoic sedimentation ages in the highly metamorphic kinzigites of the Central Schwarzwald Gneiss Complex. Hanel, Montenari & Kalt (1999) described chitinozoans and acritarchs in paragneisses, interpreted as Palaeozoic marine deposits, from a drill hole in the northern part of Central Schwarzwald Gneiss Complex. They also discussed the metamorphic development of the gneisses of the central Schwarzwald, especially the fossiliferous gneisses, and made comparisons with palynological results from metamorphic rocks of the Bohemian Massif. Phyllites of the Baden Baden–Gaggenau zone, which separates the Moldanubian from the Saxothuringian Zone in the northern Schwarzwald, yielded Upper Cambrian to Lower Ordovician acritarchs (Montenari & Hanel, 1998; M. Montenari, unpub. Ph.D. thesis, Freiburg, 1999); Montenari, Servais & Paris, 2000). These authors also discussed possible correlations with the Vosges.

Sawatzki, Vaida & Hann (1997) investigated chitinozoans in metapelitic layers within gneisses of the Wiese-Wehra diatexites in the South Schwarzwald Granite and Gneiss Complex, which they interpreted as indicative of an Ordovician age, based on optical microscope determinations. Moreover, they suggested

Early Palaeozoic sedimentation ages for gneiss anatexites of the Hauenstein-Murgtal type. Vaida *et al.* (2000) proposed Early Palaeozoic sedimentation ages in different tectonic units of the southern Schwarzwald.

3.b. Chitinozoans

The group Chitinozoa Eisenack, 1931 is an enigmatic, extinct group of organic-walled microfossils; some are bottle-shaped, and others look like tubes, which occur individually or in chains. They are exclusively found in marine sediments (Paris, 1981; Sutherland, 1994, p. 2). Together with acritarchs, spores, cryptospores, pollen, and so forth, they are included under the general name of palynomorphs (Traverse, 1988, p. 1). The biological affinities of chitinozoans are uncertain (Taugourdeau & de Jekhowsky, 1960; Jansonius, 1967; Laufeld, 1974, p. 123; Paris, 1981, pp. 78–80; Sutherland, 1994, p. 23–24; Verniers *et al.* 1995), but most authors agree that they are metazoan eggs (e.g. Miller, 1996; Paris & Nõlvak, 1999). The vesicle walls consist of pseudochitin (Taugourdeau & de Jekhowsky, 1960; Eisenack, 1968; Traverse, 1988, p. 132) which gives them resistance against acids (e.g. Laufeld, 1974, p. 3; Taugourdeau, 1979, p. 4; Traverse, 1988, p. 132). This facilitates their extraction from different kinds of rocks. Due to the wide distribution and little dependence on sedimentary facies of the chitinozoans, their mode of life is interpreted to have been mostly planktonic (Verniers *et al.* 1995). However, benthic modes have also been proposed, and a nektic or planktonic mode cannot be excluded for these animals, which produced cysts, eggs or egg-capsules (e.g. Kozlowski, 1963).

Chitinozoans have a well-documented stratigraphic range from the Ordovician to the Devonian (Sutherland, 1994, p. 2; Verniers *et al.* 1995) or from the late Tremadoc to the topmost Devonian (Paris & Nõlvak, 1999). Rapid evolutionary change and widespread distribution make the chitinozoans an important biostratigraphic tool in the Ordovician–Devonian interval (Siesser *et al.* 1998). The group is also useful in palaeogeographical and palaeoenvironmental studies (Achab, Bertrand & van Grootel, 1992; Oulebsir & Paris, 1995; Paris *et al.* 1995; Al-Hajri & Paris, 1998; Mélou, Oulebsir & Paris, 1999; Paris, Al-Hajri & Verniers, 1999; Vecoli & Samuelsson, 2001). The chitinozoan group contains 1078 described species as of the end of 1997 (Paris & Nõlvak, 1999).

The Upper Ordovician glaciation coincides with a dramatic change of chitinozoan biodiversity (Paris & Nõlvak, 1999). Due to their resistance to alteration, chitinozoan biozonation is possible also in sediments that have undergone even greenschist facies metamorphism (Verniers & Van Grootel, 1991).

3.c. Preservation of palynomorphs under metamorphic conditions

For many years, preservation of microfossils in metamorphic rocks was considered controversial. Compared to unmetamorphosed units, palynomorphs in metasediments are less numerous because of destruction. Their state of preservation is affected by directed pressure, temperature, and recrystallization. A few studies have shown that organic microfossils survive metamorphism under favourable circumstances (Pacltová, 1986; Pflug & Reitz, 1987; Pflug & Prössl, 1991; Reitz, 1992). Grew (1974) noted fragmentary plant remains on the splitting surfaces of rocks of the garnet and staurolite zones. Priewalder & Schumacher (1976) recognized chitinozoans in rocks, which underwent low-grade metamorphism in the Eastern Alps. Downie *et al.* (1971) and Stapleton (1977) demonstrated that carbonized spores, organic tissues and cell structures can preserve morphologies so distinct as to be identifiable to the level of species. Stapleton (1977) noted that specimens in Devonian rocks from southern Africa are much smaller than is usual for Devonian spores. Most of the identified species were only one third to one half the size indicated in type descriptions, which may represent one of the reasons for their peculiar preservation.

The preservation of microfossils in high-grade metamorphic rocks can never be expected to be good (Muir, 1978). The possibility of recognizing taxonomically significant features decreases with the degree of thermal alteration and with the amount of shear strain that has affected the enclosing rock matrix (Vidal, 1981). Kalvacheva, Sassi & Zanferrari (1986) showed that palynomorphs may occur in a very large variety of clastic rocks, which are abundant in all low-grade metamorphic terrains. The same authors affirmed that a lack of fossils in most of the studied material is probably due to the metamorphic grade and penetrative deformation.

Specimens located in a protected position within the mineral matrix may escape destruction and remain morphologically intact. In such cases, preservation is frequently good enough to allow identification of the fossil at least to the genus level. If the fossil is graphitized, it can hardly be younger than the metamorphic event that has altered the rock (Pflug & Reitz, 1987).

Pflug & Prössl (1989, 1991) detected spores and acritarchs in gneiss samples. Reitz & Höll (1988) and Pflug & Reitz (1992) showed that palynomorphs can also be extracted from schists of amphibolite-facies grade, if special preparation procedures are used. Because of the destruction of large individuals, palynomorphs in metamorphosed sediments appear to be smaller than in unmetamorphosed rocks. Reitz (1987) observed that most of the palynomorphs are destroyed during recrystallization. The remains become graphitized during metamorphism (Pflug & Reitz, 1992; Hanel, Montenari & Kalt, 1999).

3.d. Sampling and techniques

The present study provides evidence that even under difficult metamorphic conditions, palynomorphs can be preserved. Our purpose is to present reliable palynological data from Schwarzwald metamorphic rocks. Samples were prepared using standard palynological acid maceration techniques described by Paris (1981). We present only the results obtained by S.E.M., which largely confirm the results obtained by optical microscopy (Hann, Sawatzki & Vaida, 1995; Sawatzki, Vaida & Hann, 1997). Scanning Electron Microscope study (S.E.M.) and conventional photography of palynomorphs were carried out at the Geological Institute, Tübingen University, Germany, with a Cambridge 250 scanning microscope at 15 kv.

4. Results

In the subunit represented by clastic metasediments of the northern margin of the Badenweiler–Lenzkirch Zone, mainly chitinozoans were identified, most of them badly preserved. The following species with their respective time ranges were found: *?Conochitina spp.* Eisenack, 1931, emend. Paris *et al.* 1999*a* (Ordovician–Silurian) (samples 1 and 65); *?Rhabdochitina spp.* Eisenack, 1931, Ordovician (Paris *et al.* 1999*a*) (samples 1, 2 and 65); *?Tanuchitina spp.* Jansonius, 1964 (Ordovician–Silurian) (Paris *et al.* 1999*a*) (sample 1); *?Rhabdochitina magna* Eisenack, 1931 (Fig. 4e) (Ordovician) (sample 2). The latter chitinozoan is a small specimen and has a cylindrical vesicle, and the slight flexure of the flanks near the oral pole is probably due to preservation effects. Its vesicle structure is smooth and presents a very small mucron at the aboral pole (Paris *et al.* 1999*a*).

Eremochitina baculata brevis Benoit & Taugourdeau, 1961 (Fig. 4l) (samples 1 and 65) was identified in the same metasediments from northern margin. *Eremochitina baculata brevis* Benoit & Taugourdeau, 1961 (sample 65) is an elongated chitinozoan, claviform and its vesicle is slightly thickened at about 1/3 of the length of the aboral pole. The surface is smooth. It presents a tubular prolongation in the direction of the aboral pole (copula), well enough preserved, slightly separated from the bottom of vesicle, this being characteristic for *E. baculata brevis* (Paris, 1981). The specimen described above is a very small one, having Early Ordovician as the interval of evolution. *Eremochitina brevis* (=*Eremochitina baculata brevis*) was defined as a biozone (Paris, 1990; Paris *et al.* 1999*b*) and the index species was described in the western Sahara. Outside the Algerian Sahara, *E. brevis* is well represented in Morocco, western Libya, central Portugal, in the northern part of the Armorican Massif, in southern France and in Montagne Noire (Paris, 1981), all areas belonging to the Northern Gondwana Domain (Paris, 1990).

?Cyathochitina protocalix Paris 1981 (Fig. 4g, j) (sample 2) is a chitinozoan characterized by a cylindrical vesicle and parallel flanks (the left one has a crack at 1/3 of the height to the oral pole). The neck is not differentiated from the body. At the aboral pole it presents a small mucron of conical shape. The surface is smooth. The chitinozoan has a carena at the aboral margin, which corresponds to the maximum diameter of the vesicle. Its biostratigraphic range is Early Ordovician (Late Arenig/Llanvirn) (Paris, 1981; Mélou, Oulebsir & Paris, 1999). *Cyathochitina protocalix* was used as the diagnostic species of the biozone with the same name (Paris, 1990) and corresponds to its total range. The main occurrences of *C. protocalix* are recorded from the northeastern part of the Armorican Massif. It is regarded as closely related to the Arenig–Llanvirn boundary in the Northern Gondwana chitinozoa zonation (Paris, 1990; Paris *et al.* 1999*b*).

We suggest that late Arenig/earliest Llanvirn is the age of the clastic metasediments from the western and eastern parts (Aitern and Lenzkirch) of the northern margin of the study area.

In samples from the metasiltstones from the central part of the northern subunit *Belonechitina lauensis* (Laufeld, 1974) (Fig. 4d, f) (sample 45) was described. It is a tri-dimensional chitinozoan, which has an operculum, and a granular ornament which covers most of the vesicle from the central portion of the base. Its range is Silurian (Ludlow (Late Gorstian–Early Ludfordian)) (Sutherland, 1994; Veniers *et al.* 1995). *Conochitina lauensis* Laufeld, 1974 was described as a new species by Laufeld (1974) in the late Llandovery through Ludlow of Gotland. In their global Chitinozoan biozonation for the Silurian, Verniers *et al.* (1995) considered it as an accompanying species of the *Angochitina elongata* biozone with a Ludlow (Late Gorstian–Early Ludfordian) age.

Conochitina proboscifera Eisenack, 1937 (Fig. 4k, n) (sample 51) was identified in the same metasiltstones mentioned above: a conical shaped chitinozoan, deformed and badly preserved. The surface of the vesicle is corroded; many gaps and cavities are observed. In the aboral part, there is a well preserved mucron (Llandovery (Telychian)–Wenlock (basal Homerian)). It is a characteristic chitinozoan for the *Angochitina longicollis* biozone, Llandovery (Telychian)–Wenlock (Upper Sheinwoodian) (Verniers *et al.* 1995). Next to *?Conochitina proboscifera* Eisenack, 1937 in the same sample, *Lagenochitina cylindrica* Eisenack, 1931 has been described (Fig. 4a) (sample 51). It is characterized by a cylindrical shape with a neck that is differentiated from the body by a slight flexure. The surface is smooth, without spines or other ornaments (Ordovician–Silurian).

Cryptospores were also identified (sample 51): *?Cymbohilates* Richardson 1996 (Fig. 5e, f) which has a sub-circular to circular amb, an almost circular hilum (contact area) with short spines and grana that is surrounded by a ‘sculptured’ zone consisting dominantly of grana, rarely short microbaculate coni (Silurian (Wenlock–Homerian)–Early Devonian (Lochkovian)). A second cryptospore species is *?Cryptospore A*

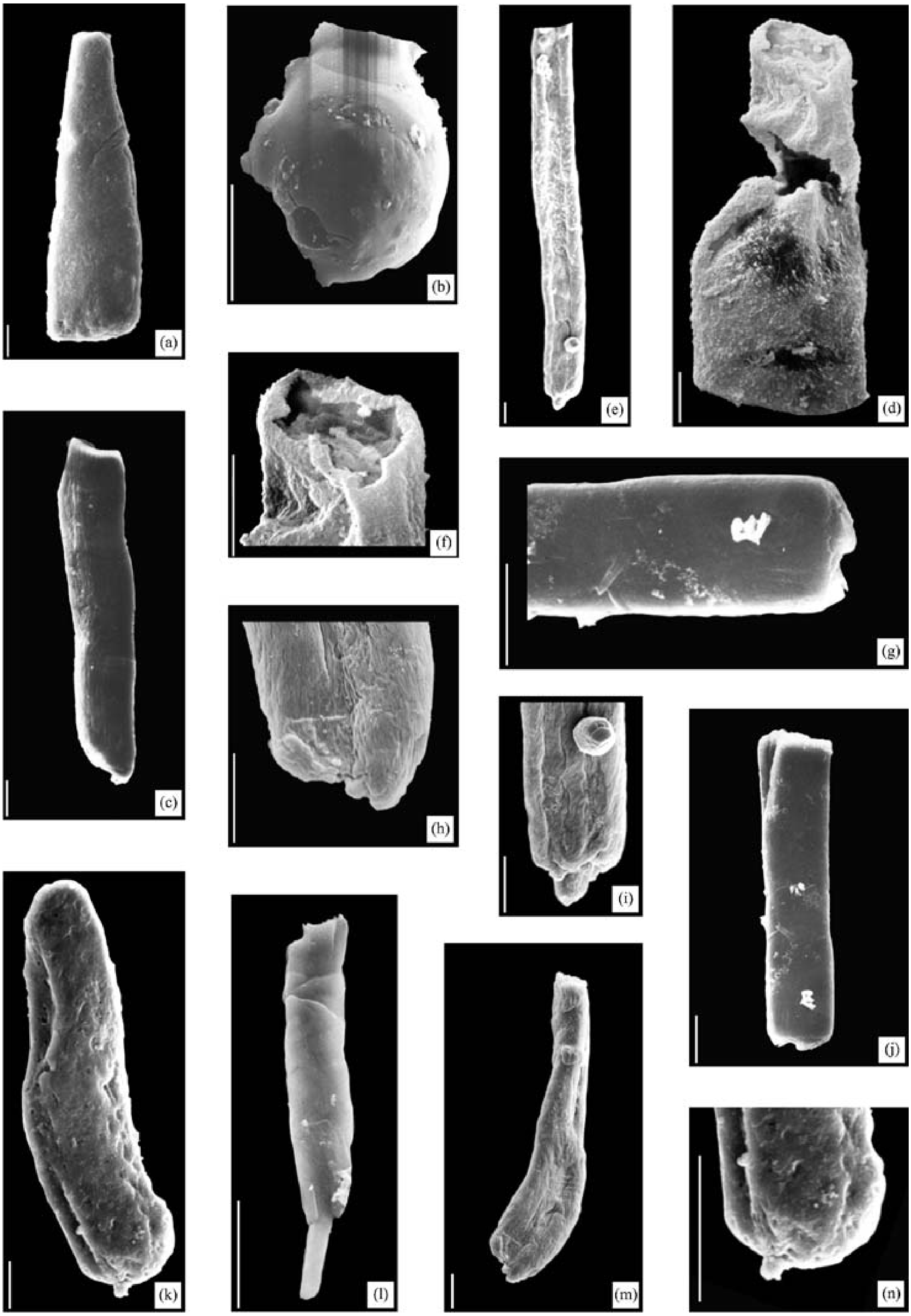

Figure 4. (a) ?*Lagenochitina cylindrica* Eisenack, 1931; (b) ?*Desmochitina sp*. Eisenack, 1931; (c) ?*Conochitina proboscifera* Eisenack, 1937; (d) *Belonechitina lauensis* (Laufeld 1974); (e) *Rhabdochitina magna* Eisenack, 1931; (f) Detail of oral part of (d); (g) Detail of aboral part of (j); (h) Detail of aboral part of (m); (i) Detail of aboral part of (c); (j) *?Cyathochitina protocalix* Paris, 1981; (k) *?Conochitina proboscifera* Eisenack, 1937; (l) *?Eremochitina baculata brevis* Benoit &Taugourdeau, 1961; (m) ?*Conochitina pachycephala* Eisenack, 1964; (n) Detail of aboral part of (k). Scale bar = 10 μm.

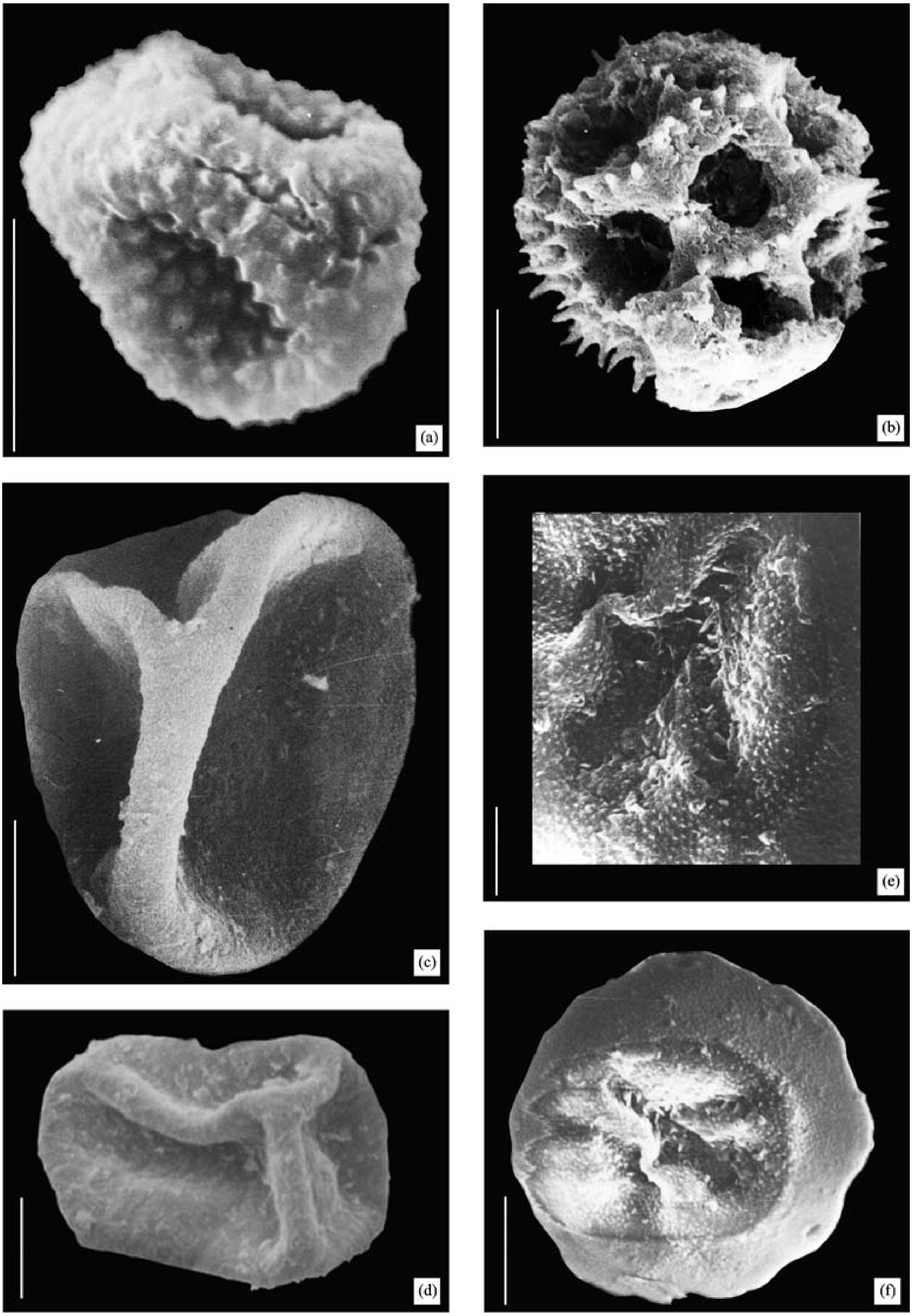

Figure 5. (a) *?Cryptospore A*; (b) ?*Cymatiosphaera sp*.; (c) ?*Cryptospore B*; (d) *?Retusotriletes sp*.; (e) Detail of structure of (f); (f) *?Cymbohilates sp*. Scale bar = 10 μm.

(Fig. 5a) (Silurian–Devonian) with 'permanent' tetrahedral tetrads composed of subtriangular to subcircular exine represented by a sculpture of grana and coni. A third form was also found: *?Cryptospore B* (Fig. 5c) (Silurian–Devonian).

Additionally, a poorly preserved acritarch was identified *?Cymatiosphaera sp*. O. Wetzel, 1933, emend. Deflandre, 1954 (Fig. 5b). The walls of the spherical vesicle form regular pentagons. Their outer edges are markedly tuberculate (Cambrian–Devonian).

The biostratigraphic range of palynomorphs which were yielded by samples 45 and 51, located in the central part of the northern subunit of the Badenweiler–Lenzkirch Zone, leads to the conclusion that its age is Silurian (Wenlock-basal Homerian–Ludlow–late Gorstian). The age of this assemblage is marked especially by the co-occurrence of *?Conochitina proboscifera* (Llandovery (Telychian)–Wenlock (basal Homerian)) and the cryptospore *?Cymbohilates sp.* ((Wenlock–Homerian)–Early Devonian (Lochkovian)), which indicates the Silurian (Wenlock–Homerian) age.

Trilete spores occur as well as chitinozoans in one sample (16) from the central subunit of the Badenweiler–Lenzkirch Zone. The presence of a trilete laevigate spore of the *Retusotriletes* type (Fig. 5d) is relevant because its biostratigraphic range is Silurian to Carboniferous, possibly even higher (E. Turnau, 2001, pers. comm.). As the *Retusotriletes* type does not appear before the Silurian (Llandovery–Telychian), the sediments cannot be older. Unfortunately, this spore cannot be identified at the species level, because the morphological features are not entirely preserved.

Chitinozoans (*?Conochitina spp., ?Ancyrochitina spp.*) (sample 21) in a poor state of preservation were recognized by S.E.M. techniques in metasiltstones and phyllites from the southern subunit (Fig. 3). Dark, opaque, flask-shaped palynomorphs were observed in the optical microscope. Poor preservation is the reason why only a general assumption for the depositional age of the rocks of the Südrandkomplex can be made: Ordovician or younger, considering Ordovician the beginning of the time-span of chitinozoans. It was possible to identify chitinozoans in the biotite and biotite-graphite schists (sample 54) from the South Schwarzwald Granite and Gneiss Complex (Fig. 2). One of them is a poorly preserved *?Conochitina proboscifera* Eisenack, 1937 (Fig. 4c, i), a conical-shaped chitinozoan with a mucron, indicating the Silurian (Llandovery (Telychian)–Wenlock (basal Sheinwoodian)) (Verniers *et al.* 1995). The other species is *?Conochitina pachycephala* Eisenack, 1964 (Fig. 4h, m), a claviform chitinozoan with the chamber differentiated from the neck. The flanks continue to the oral part. Although the specimen is flattened and deformed, it is possible to recognize that the structure of the tegument is smooth and that it contains a mucron at the aboral part, indicating a Silurian (Wenlock (Late Sheinwoodian)–Ludlow (Gorstian)) age. Additionally *?Ancyrochitina spp.* Eisenack, 1955 was identified (Late Ordovician–Late Devonian) (Paris *et al.* 1999*a*).

In the same complex (sample 57) *?Desmochitina sp.* Eisenack, 1931 was identified with a broken and small specimen (Fig. 4b) (Early Ordovician–Early Devonian; Paris *et al.* 1999*a*). In the gneisses of the South Schwarzwald Granite and Gneiss Complex (Wickartsmühle quarry, samples 54 and Wehratal–Pfeiferskopf, sample 57) the joint occurrence of the taxa mentioned above indicate the Silurian (Wenlock–Late Sheinwoodian/basal Homerian) as the depositional age of the pelitic protolith.

In the clastic metasedimentary rocks of the northern unit of the Badenweiler–Lenzkirch Zone (Fig. 3), two lithostratigraphical units can be discerned:

(1) The first unit is predominantly composed of metagreywackes and metapelites (Type Aitern: Güldenpfennig, 1997). An Early Ordovician (late Arenig/earliest Llanvirn) age is constrained by the biostratigraphic range of the chitinozoans identified in the clastic metasediments from the western and eastern parts (Aitern and Lenzkirch) of the northern subunit.

(2) The second lithostratigraphic unit, which is exposed in the central part of the northern subunit, is mainly composed of metasiltstones (Sengalenkopf–Prägbach zone). The biostratigraphic range of chitinozoans, cryptospores as well as acritarchs belonging to the palynological assemblage lead to a Silurian age (Wenlock (earliest Homerian)–Ludlow (Late Gorstian)).

Badly preserved chitinozoans were found by S.E.M. in metasiltstones and phyllites from the southern subunit (Fig. 3). Their poor preservation allows only a general indication of the depositional age of the rocks of the Südrandkomplex: Ordovician–Silurian–Devonian, which is the total range of the chitinozoans.

The biotite and biotite-graphite schists from the South Schwarzwald Granite and Gneiss Complex (Fig. 2) yielded chitinozoans, which indicate a Silurian (Wenlock–Late Sheinwoodian/basal Homerian) age.

5. Conclusions and geodynamic interpretation

For geodynamic reconstructions of the mostly highly metamorphic internal Variscides, it is essential to know the facies and ages of the protolithic sedimentary rocks. As discussed above, palynomorphs can be used for age determinations in even high-grade metamorphic rocks.

Scattered ages became known from the low-grade metamorphic rocks of the Badenweiler–Lenzkirch Zone. We strove for a systematic survey of age dating; however, poor preservation of the palynomorphs allowed determination of chitinozoans in a limited number of samples only.

(1) In the northern subunit of the Badenweiler–Lenzkirch Zone, age dating was most successful. On the basis of the new data, we were able to distinguish

two different lithostratigraphic units by their age: Lower Ordovician metagreywackes and metapelites were discerned from Silurian metasiltstones. In contrast to earlier interpretations, a wider stratigraphic range and a more complex internal structure of this subunit could be demonstrated.

(2) For the first time, new ages could be obtained using palynological methods for the central and southern subunits of the Badenweiler–Lenzkirch Zone, although poor preservation does not allow specification of the age in detail; the depositional age of the protolith is Silurian for the central subunit and Ordovician or younger for the southern subunit, where the sediments are very probably not younger than Devonian. This is in the same range as known sedimentation ages elsewhere in the Badenweiler–Lenzkirch Zone and thus conforms to earlier assumptions.

(3) In the highly metamorphic rocks of the South Schwarzwald Granite and Gneiss Complex, no protolith ages were previously known. Our age determination (mid-Silurian) from a biotite-graphite schist is important for the model reconstruction of the Ordovician–Silurian of the region. It shows that at least a considerable part of the high-grade rocks do not represent an older basement unit and that marine sedimentation took place during this period in the South Schwarzwald Granite and Gneiss Complex.

The ages of the metasediments of the Badenweiler–Lenzkirch Zone and of the South Schwarzwald Granite and Gneiss Complex could be constrained to the Early Palaeozoic. Until now the ages could not be specified more exactly than Palaeozic in general. The Ordovician–Silurian sedimentation ages represent a new basis for reconstructions in the geodynamic model, which was so far mainly based on hypotheses. Loeschke *et al.* (1998) developed a plate tectonic model in which the Badenweiler–Lenzkirch Zone was interpreted as an important suture zone within the Central European Variscides. Plate tectonic reconstructions show that continental blocks split off from the northern margin of Gondwana during Ordovician times, drifted towards Armorica and Laurussia and collided in the Early Carboniferous (Matte, 1986*a*,*b*; Matte, 1991; Ziegler, 1986, 1990; Bachtadse *et al.* 1995; Franke, Dallmeyer & Weber, 1995; von Raumer, 1998). The Central Schwarzwald Gneiss Complex and the South Schwarzwald Granite and Gneiss Complex are fragments of different microcontinents that were separated by an oceanic realm. The South Schwarzwald Granite and Gneiss Complex probably represents a separate terrane that may be correlated with the Drosendorf unit of the southern Bohemian Massif (Pharaoh, 1999). Chitinozoans are exclusively marine microfossils. This proves that the Ordovician to Silurian sediments of the Badenweiler–Lenzkirch Zone were deposited in an oceanic zone between these two microcontinents or along its margins. The existence of an oceanic basin and the simultaneous formation of oceanic crust are also documented by zircon age determinations in eclogites (486–445 Ma) from the Central Schwarzwald Gneiss Complex (Kalt, Hanel & Schleicher, 1994; Chen, Todt & Hann, 2003). The basaltic precursors of these eclogites and the marine sedimentation reflect the break-up of the northern margin of Gondwana.

The detrital material may have been derived from the northern rather than from the southern margin, as indicated by active sedimentation of pelitic material in the South Schwarzwald Granite and Gneiss Complex. This northern margin was transformed from a passive into an active continental margin in Silurian times or around the Silurian/Devonian boundary and, consequently, the sediments would have been scraped off from the subducting oceanic crust and imbricated in an accretionary wedge. Subduction-related magmatism was recently dated as probably Silurian to Early Carboniferous as is shown by a number of radiometric data by Hann *et al.* (2003). The first detritus of subduction-related magmatic rocks from a northern source, however, was supplied into the trench sediments above the subduction zone not before Middle Devonian time (Protocanites Greywackes: Güldenpfennig, 1997; Gruler *et al.* 1999), so that the timing of the formation of a volcanic arc above the subduction zone remains poorly constrained but bracketed between the Silurian and Middle Devonian.

Continued subduction through Devonian times led to collision, development of SE-directed shear zones, thrusting (Krohe & Eisbacher, 1988; Eisbacher, Lüschen & Wickert, 1989) and nappe stacking (Hann & Sawatzki, 2000; Hann *et al.* 2003). Deformation and metamorphism of the clastic sedimentary rocks took place in Visean times, which is well constrained by radiometric dating (Kalt, Grauert & Baumann, 1994; Lippolt, Hradetzky & Hautmann, 1994).

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