Palaeozoic evolution of the Variscan Vosges Mountains

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Abstract: A geological synthesis of the Palaeozoic Vosges Mountains (NE France) is presented using existing observations and new data. The geodynamic evolution involves: (1) Early Palaeozoic sedimentation and magmatism; (2) Late Devonian subduction triggering back-arc spreading; (3) early Lower Carboniferous continental subduction, continent–continent collision and poly-phase deformation and metamorphism of the orogenic root; and (4) late Lower Carboniferous orogenic collapse driven by thermal weakening of the middle crust. The evolution is integrated within the framework of the European Variscan Belt. The Northern Vosges comprise sediments of Rhenohercynian affinity separated from Teplá-Barrandian metasediments by a Lower Carboniferous magmatic arc. The latter is correlated with the Mid-German Crystalline Rise, and is ascribed to the south-directed subduction of the Rhenohercynian Basin. The Saxothuringian–Moldanubian suture is thought to be obliterated by the magmatic arc, while the Lalaye–Lubine Fault is interpreted as the Teplá-Barrandian–Moldanubian boundary. The Central Vosges are paralleled with the Moldanubian domain of the Bohemian Massif where identical lithologies record the Devonian–Carboniferous SE-directed subduction of the Saxothuringian passive margin below the Moldanubian upper plate. The Southern Vosges represent the upper Moldanubian crust and are linked to the southern Black Forest. The presence of an oceanic domain to the south of the Vosges–Black Forest remains unclear.

Supplementary material: List of radiometric ages used for probability plots is available at http://www.geolsoc.org.uk/SUP18734.

The Variscan orogen is an 8000 km-long belt which formed as a result of Palaeozoic subduction and collision events (e.g. Matte 2001; Nance et al. 2010). In Europe, it has been divided into distinct litho-tectonic domains since the early works of Suess (1926) and Kossmat (1927). This subdivision into the major Rhenohercynian, Saxothuringian and Moldanubian domains is based on the assumption that the orogen represents a juxtaposition of different litho-tectonic units formed by continuous continental belts with their surrounding basinal sequences (e.g. Behr et al. 1984; Ziegler 1984; Matte et al. 1990; Franke 2000). However, a growing number of studies tends to reveal that the Variscan domains are neither lithologically homogeneous (e.g. Oncken 1997; Chopin et al. 2012) nor laterally continuous (Franke & Zelazniewicz 2000; Lardeaux et al. 2014). These works describe the litho-tectonic domains as a more complex juxtaposition of autochthonous and allochthonous material (e.g. Guy et al. 2011) that originally belonged to different plates. It is therefore in the light of these new studies and concepts that the Variscan Orogen should be examined today.

The Palaeozoic basement of the Vosges Mountains (NE France) illustrates the lack of continuity between the Variscan domains and the non-cylindricity of the orogenic belt (Fig. 1a). The Vosges Mountains are traditionally divided into a northern part of Saxothuringian affinity and a southern part correlated with the Moldanubian domain (Kossmat 1927). The boundary is traced along the Lalaye–Lubine and Baden–Baden fault zones located in the Vosges and Black Forest, respectively (Krohe & Eisbacher 1988; Fluck et al. 1991). However, Kossmat (1927) recognized that the...
characteristic thrust of the Moldanubian over the Saxothuringian was much less developed in the Vosges Mountains than towards the east. By comparison with the Bohemian Massif, Franke (2000) pointed out that the Tepla´-Barrandian domain was missing between the Saxothuringian....
and Moldanubian parts of the Vosges Mountains. The presence of the Bristol Channel–Bray Fault also renders difficult the correlations with the Variscan massifs located to the west (Fig. 1a).

The possible correlations with the neighbouring Variscan massifs leave a wealth of open questions. Although the northern Black Forest seems to be a prolongation of the Northern Vosges (e.g. Montenari & Servais 2000), safely linking the Central Schwarzwald Gneiss Complex with the Central Vosges metamorphic units remains difficult, despite their geochemical resemblance (Müller 1989). Similarly, the suture zone of a south-dipping oceanic domain recognized in the southern Black Forest (Loeschke et al. 1998) cannot be directly followed in the Southern Vosges, but may be located further to the south (Maass et al. 1990). It is also problematic to connect the Southern Vosges back-arc basin with the Brévenne unit in the NE French Massif Central (Faure et al. 2009; Skrzypek et al. 2012b). Finally, the classical litho-tectonic zonation is questioned by Edel & Schulmann (2009) who propose that both the Rhenohercynian and Saxothuringian sutures could lie to the north of the presently exposed Vosges basement.

The present contribution tries to review more than one century of geological observations of the Palaeozoic basement of the Vosges Mountains. It is complemented by new data to present a synthesis of the lithostratigraphic record, igneous activity, metamorphic conditions and structural evolution of the Vosges Mountains. The different datasets are combined in order to constrain the significance of the different litho-tectonic units of the Vosges Mountains, and discuss the position and geodynamic evolution of this segment in the framework of the European Variscan Belt.

**Lithostratigraphy**

The Palaeozoic basement of the Vosges Mountains is formed by a wide central zone of granitoids and metamorphic rocks surrounded by Early Palaeozoic–Carboniferous (meta-)sediments to the north and Upper Devonian–Carboniferous (volcano-)sedimentary rocks to the south (Fig. 1). The Permian clastic sediments are mostly found around the massif, but locally overlay the magmatic and metamorphic rocks in the central part. The Vosges Mountains are subdivided into three parts (Fig. 1 inset): the Northern Vosges are separated from the Central Vosges by the Lalaye–Lubine Fault Zone (LLFZ), while the Southern Vosges are defined by the dominant (volcano-)sedimentary rocks occurring to the south of the Central Vosges granitic rocks.

**Northern Vosges**

The Northern Vosges correspond to a succession of NE–SW-striking sedimentary belts intruded by a magmatic suite. The latter separates the younger sediments and volcanics of the Northern succession from the older and weakly metamorphosed sediments of the Southern succession (Fig. 1).

**Northern succession (Bruche unit).** The base of the Northern succession is represented by basaltic lava flows, acid-volcanic rocks and coarse-grained sediments of possible Lower Devonian age (e.g. Juteau 1971; Fig. 2). They are overlain by early Middle Devonian conglomerate and sandstone (Benecke & Bücking 1898) and Givetian greywacke-pelite alternating with bimodal volcanism (Firtion 1945, 1957). The volcanoclastic association is composed of mostly submarine altered basalt and rhyolite (‘spilite-keratophyre’) with pyroclastic breccias showing a tholeiitic affinity (Ikenne & Baroz 1985; Rizki & Baroz 1988). The Givetian age is also recognized in scarce carbonate lenses, which preserve evidence of a reef environment receiving abundant siliceous material from the neighbouring continent (Jaeckel 1888; Bücking 1918; Blanalt 1969), and in the surrounding polymictic conglomerate containing Late Cambrian granitic pebbles (Dörr et al. 1992). These observations indicate that the Middle Devonian is associated with the erosion of a Cambrian substratum, coastal sedimentation and the development of reef carbonates in a relatively shallow-marine siliciclastic basin (Fig. 2).

The sedimentary succession continuously passes to thick Frasnian and Famennian sandy-pelitic deposits with radiolarite intercalations and numerous samples of plant debris (Figge 1968; Blanalt & Lillié 1973; Braun et al. 1992; Aghai Soltani et al. 1996; Fig. 2). This record reflects a quiet sedimentation in a coastal environment receiving continental flora (Blanalt & Doubinger 1973). However, late Upper Devonian sedimentary breccias with clasts of the underlying lithologies indicate subsequent sedimentary instabilities. It is further supported by the lower Visean greywacke and pelite alternations which document a synsedimentary tectonic activity and preserve characters of flysch-type turbiditic deposits (Corsin & Dubois 1932; Dubois 1946; Corsin et al. 1960). The Early Carboniferous tectonic activity probably culminates during middle Visean time, as indicated by the sedimentary hiatus, contact metamorphism (Bonhomme & Prévôt 1968) and the contemporaneous magmatism occurring to the south.

Few upper Visean deposits are found in the axial part (‘Bande médiane’) of the magmatic suite (Fig. 1). They are juxtaposed with granitic rocks as a result of late normal faulting. They chiefly...
correspond to pyroclastic rocks and ignimbrite, but rare pelite and greywacke are also observed (Elsass & von Eller 2008). According to Rizki et al. (1992), this calc-alkaline to shoshonitic volcanism is related to the upper part of the magmatic suite and is indicative of an active margin setting in the late Lower Carboniferous.

Upper Carboniferous–Permian sediments and volcanics are present on both sides of the magmatic suite (Fig. 1). They are represented by Stephanian–Autunian coal-bearing coarse-grained sediments (Doubinger 1956, 1965), Saxonian rhylolitic volcanism (Mihara 1935; Lippolt & Hess 1983; Boutin et al. 1995) and Thuringian arkosic sandstone and conglomerate (Hollinger 1969; Fig. 2). In the Stephanian–Autunian deposits, numerous pebbles of magnesio-potassic (Mg–K) granite, gneiss and schist from the Central Vosges indicate that the deep crustal levels were already close to the surface at that time. It was followed by a widespread Middle Permian subaerial acid volcanism which is also documented in the neighbouring Black Forest or Saar regions (Lippolt et al. 1983; Schleicher et al. 1983) and by Upper Permian continental sedimentation.

Southern succession (Villé and Steige units). The Southern succession is represented by the two NE–SW-trending Villé and Steige units (Fig. 1). The structurally deeper Villé unit is formed by Cambrian–Ordovician pelite followed by quartzolitic sediments with quartzite and acid tuff. Cambrian–Ordovician pelite followed by quartzolitic volcanics are present on both sides of the magmatic suite and is indicative of an active margin setting in the late Lower Carboniferous.

Upper Carboniferous–Permian stratigraphy. Bruche unit: 1, Benecke & Bücking (1898); 2, Firtion (1945, 1957); 3, Jaeckel (1888), Bücking (1918), Blanalt (1969); 4, Blanalt & Doubinger (1973), Blanalt & Lillié (1973); 5, Figge (1968); 6, Braun et al. (1992), Aghai Soltani et al. (1996); 7, Corsin & Dubois (1932), Dubois (1946), Corsin et al. (1960). Upper Carboniferous–Permian stratigraphy: 8, Doubinger (1956, 1965); 9, Velain (1885), Benecke & von Verveke (1890), Choubert & Gardet (1935), Laubacher & von Eller (1966), Hollinger (1969). Northern Vosges, Southern succession. Villé unit: 10, Doubinger & von Eller (1963b), Ross (1964), Reitz & Wickert (1989). Steige unit: 11, Doubinger (1963), Doubinger & von Eller (1963a), Ross (1964), Tobschall (1974). Southern Vosges, Allochthonous units: 12, Doubinger & Ruhl (1963), Maas & Sioppel (1982); 13, Corsin & Mattauer (1957), Corsin & Ruhl (1959); 14, Markstein sedimentology after Krecher et al. (2007). Autochthonous units: 15, Chevillard (1866), Asselberghs (1926), Bain (1964); 16, Firtion (1845), Mathieu (1868), Corsin et al. (1956), Mattauer & Théobald (1957), Corsin & Mattauer (1957), Mattauer (1959), Coulon et al. (1978); 17, Hahn et al. (1981), Vogt (1981), Hammel (1996), Montenari et al. (2002); 18, Tornquist (1895, 1896, 1897, 1898), Delepine in Mattauer (1959), Doubinger & Rauscher (1966), Coulon & Lemoigne (1969), Corsin et al. (1973), Coulon et al. (1975a, b), Coulon et al. (1978), Hahn et al. (1981), Hammel (1996); 19, Mathieu (1968), Creuzot (1983). References for radiometric ages: Northern Vosges: a, Dör et al. (1992); b, Bonhomme & Prévôt (1968); c, Boutin et al. (1995), Hess et al. (1995), Reischmänn & Anthes (1996), Altherr et al. (2000), Edel et al. (2013); d, Edel et al. (2013); e, Lippolt & Hess (1983), Boutin et al. (1995); f, Bonhomme & Dunoyer de Ségonzac (1962); g, Cauer & Bonhomme (1970). Central Vosges: h, Skrzypek et al. (2012a); i, Boutin et al. (1995); j, Schaltegger et al. (1999); k, Schulmann et al. (2002); l, Kratinova et al. (2007). Southern Vosges: m, Skrzypek et al. (2012b); n, Schaltegger et al. (1996).
during the Late Cambrian–Early Ordovician (Fig. 2). The sediments were subsequently affected by medium-pressure–high-temperature (MP/HT) metamorphism. On the other hand, U–Pb zircon ages reveal that the felsic granulite protolith was probably emplaced during the Late Cambrian at c. 500 Ma. It was shortly followed by the sedimentation of the protoliths of the varied gneiss unit during Late Ordovician–(?)Early Silurian time (Fig. 2). Despite a strong tectono-metamorphic overprint, it is possible to recognize that the varied unit initially involved a thick basal layer of basic magmatic rocks overlain by pelitic sediments containing intercalations of limestone, quartzite and acid-volcanic rocks (Fluck 1980). The felsic granulite and varied gneiss units both underwent high-pressure–high-temperature (HP/HT) metamorphism (Fig. 2).

**Magmatic units.** The numerous magmatic rocks of the Central Vosges can be divided into two distinct groups. The oldest I-type magmatic event is associated with elongated bodies of biotite–amphibole-bearing porphyritic granitoid (CVMg – K granitoids) and occurred at 340–335 Ma across a large part of the Vosges (Figs 1 & 2). The CVMg – K granitoids are intrusive in the Central Vosges metamorphic units as well as in the Southern Vosges sediments where microgranite sills are developed. The younger S-type Central Vosges Granite (CVG) represents a second event of widespread anatexis in the Central Vosges at 330–325 Ma (Fig. 2). Detailed mapping of this voluminous biotite-bearing anatectic granite reveals the presence of numerous xenoliths of Mg – K granitoid, gneiss or sedimentary rocks (von Eller 1961). On the other hand, the associated biotite–muscovite-bearing leucogranites (‘Thannenkirch-Brézouard-Bisltein’) correspond to narrow and elongated plutons that occur along the major tectonic discontinuities (Fig. 1).

**Southern Vosges**

The Southern Vosges are dominantly composed of (volcano)-sedimentary successions that are divided into allochthonous and autochthonous units (Jung 1928). The boundary between the units lies close to the Klippen Belt which corresponds to discontinuous exposures of partly ophiolitic material. Towards the south, an east–west-trending Mg–K magmatic complex is intrusive in the autochthonous units (Fig. 1).

**Autochthonous units (Oderen and Thann units).** The oldest autochthonous sediments (‘Belfortais’) are found in the southernmost part of the Vosges (Fig. 1). There, limestones of probable Frasnian age are conformably overlain by a thin Fammenian pelitic sequence (Chevillard 1866; Asselberghs 1926; Bain 1964) which preserves a fauna indicating an Upper Devonian platform environment (Fig. 2). The pelites are in turn unconformably overlain by a Lower Carboniferous conglomeratic greywacke which is also observed in the northern part of the autochthonous units (Oderen unit). There, the autochthonous succession corresponds to thick Tournaisian–lower Visean pelite and greywacke with episodic conglomerate and carbonate deposits (Corsin et al. 1956; Corsin & Mattauer 1957; Mattauer & Théobald 1957; Mattauer 1959). The sediments are locally interlayered with submarine altered basalt and rhyolite (‘spilite-keratophyre’) showing a tholeiitic affinity (Lefèvre et al. 1994). Towards the top of the Oderen unit, acid volcanism is found together with more abundant carbonate intercalations indicating an early middle Visean age (Hammel 1996; Montenari et al. 2002), although Tournaisian fossils are also found (Hahn et al. 1981; Vogt 1981). The Oderen unit represents flysch-type turbiditic deposits (Gagny 1962; Krecher 2009) that were later affected by middle–upper Visean sedimentary instabilities as indicated by the resedimented fauna occurring at its top (Schneider et al. 1989). These instabilities are the only expression of the so-called ‘intra-Visean event’, and no significant deformation or sedimentary hiatus is documented in the Vosges Mountains at that time (Schneider et al. 1989).

The boundary with the younger autochthonous unit (Thann unit) is marked by the emplacement of abundant andesitic lavas (Fig. 2) that have a calc-alkaline potassic affinity (Lefèvre et al. 1994). They are overlain by upper Visean sandstone or conglomerate alternating with trachytic to rhyolitic volcanic rocks (Corsin et al. 1973; Coulon et al. 1975a, b, 1978). Up to the Namurian, the coarsening of sediments and the increasing amount of plant debris indicate the progressive filling of small basins associated with an ultimate episode of high-K rhyolitic volcanism (Lefèvre et al. 1994). The continental sedimentation is later characterized by Stephanian–Saxonian sandstone, conglomerate, pelite and rhyolitic tuff with some coal-bearing strata (Mathieu 1968; Creuzot 1983).

**Allochthonous units (Klippen Belt and Markstein units).** The allochthonous units are represented by the dominant Markstein unit and the Klippen Belt, which is regarded as the base of the allochthonous succession (Jung 1928; Schneider et al. 1990; Skrzypek et al. 2012b). The klippen preserve serpentinite, ophicalcite and Famennian gabbro overlain by a conglomeratic greywacke containing Neoproterozoic gneiss blocks. This block-in-matrix formation is capped by Famennian siliceous pelite (Maas & Stoppel 1982; Fig. 2). The Klippen Belt
is conformably overlain by thick lower Visean pelite and greywacke deposits (Markstein unit) with only minor conglomerate and carbonate material (Corsin & Mattauer 1957; Corsin & Ruhrland 1959). The sedimentation is thought to last up to the upper Visean (e.g. Krecher 2005), but middle Visean granitic intrusions in the already folded allochthonous units make this hypothesis unlikely. To summarize, the allochthonous lithologies indicate the presence of a deep Late Devonian basin subsequently filled by lower Visean flysch turbidites with characters of a prograding system of sandy submarine fans (Krecher et al. 2007).

Magmatism

Four major magmatic associations are recognized in the Variscan Vosges Mountains. From north to south, they include: the Northern Vosges magmatic suite, the Central Vosges Mg–K granitoids, the Central Vosges Granite and the Southern Vosges Mg–K complex.

Northern Vosges magmatic suite

The Northern Vosges magmatic suite (‘Champ du Feu’) corresponds to NE–SW-trending or circular-shaped magmatic bodies intruding the surrounding (meta-)sedimentary units (Fig. 1). It is a composite succession of I- to S-type plutons associated with subaerial to aerial volcanic rocks which were all emplaced during a short middle Visean event at 335–330 Ma (Fig. 2).

The oldest I-type magmatic rocks correspond to the narrow belts of diorite (‘Neuntelstein’) and the southern granodiorite body (‘Hohwald’). Al-in-hornblende barometry points to an intrusion depth of c. 10 km for the diorite (Altherr et al. 2000); the southern granodiorite was emplaced at a slightly shallower level as indicated by intrusive contacts with the low-grade Steige metasediments and by the presence of numerous metasedimentary xenoliths. I-type magmatic rocks show a clear enrichment in light rare earth elements (LREE) and large ion lithophile elements (LILE) and pronounced Nb and Ti anomalies (Altherr et al. 2000). The isotopic compositions lie at $^{143}\text{Nd}$ (330) = 2.9 to 1.8 and $^{87}\text{Sr}/^{86}\text{Sr}$ (330) = 0.70474–0.70612 for the diorite, and $^{143}\text{Nd}$ (330) = −0.5 to 0.4 and $^{87}\text{Sr}/^{86}\text{Sr}$ (330) = 0.70529–0.70534 for the granodiorite (recalculated after Altherr et al. 2000; Fig. 3). The volcanic rocks comprise pyroclastite, tuff and ignimbrite that range from a basaltic to rhyolitic composition. Trace elements reveal Nb and Ti anomalies, and support a genetic link with the I-type plutonic rocks (Elsass & von Eller 2008). It is proposed that the diorite is derived from an enriched lithospheric mantle source, while the granodiorite originated from the melting of a meta-igneous protolith (Altherr et al. 2000).

The calc-alkaline magmatic activity is followed by the intrusion of the S-type northern granite (‘Belmont’). This heterogeneous body hosts abundant xenoliths of sedimentary and volcanic rocks (Elsass & von Eller 2008) which suggest that its emplacement at a shallow depth was associated with magmatic stoping of the overlying Northern succession. The last magmatic episode is reflected by the intrusion of the circular-shaped, S-type younger granites (‘Andlau’, ‘Natzwiller’, ‘Senones’ and ‘Kagenfels’ granites) which cross-cut the NE–SW-trending bodies (Fig. 1). These high-K to shoshonitic granites are characterized by a granophytic texture towards their margins, and represent the shallowest intrusions of the magmatic suite. S-type magmatic rocks are enriched in LILE and show weak Nb, Ti anomalies compared to the I-type plutonic rocks (Altherr et al. 2000). The isotopic compositions are nearly similar for the northern and younger granites with $^{143}\text{Nd}$ (330) = −3.4 to −2 and $^{87}\text{Sr}/^{86}\text{Sr}$ (330) = 0.70535–0.70609 (recalculated after Altherr et al. 2000; Fig. 3). Both show geochemical features indicating melting of metasedimentary (metagreywacke for the northern granite) protoliths (Altherr et al. 2000). Previous works emphasize the calc-alkaline to high-K affinity of the Northern Vosges magmatic suite and interpret
it as arc-type magmatism related to an Early Carboniferous subduction event (Altherr et al. 2000; Tabaud 2012).

Central Vosges Mg–K association

The Central Vosges Mg–K association exhibits porphyritic plutonic rocks ranging from amphibole-biotite syenite (durbachite) to granite (‘Granite des Crêtes’) emplaced between 340 and 332 Ma. The prominent geochemical feature of these rocks is a constant total alkali content with increasing SiO₂ and a significant enrichment in Mg, Ni, Cr, K, U and Th. In addition, they show a decreasing REE content from the basic to the acid end-members. The isotopic data indicate nearly constant $e^{(^{87}Sr/^{86}Sr)}_{Nd} = -6.7$ to $-5.3$ values with $^{87}Sr/^{86}Sr^{(340)}$ increasing from 0.7096 to 0.7137 (Tabaud 2012; Fig. 3).

The rocks of the CVMg–K association are thought to reflect the partial melting of an enriched lithospheric mantle located above a subduction zone and the subsequent crustal contamination of the magma at a deep crustal level (Gagny 1968). It is proposed that they represent the mixing between mantle magmas and acid melts derived from the anatexis of the lower orogenic crust (Tabaud 2012).

Central Vosges Granite

The large Central Vosges Granite (‘Granite fondamental’), emplaced between 335 and 325 Ma, corresponds to different textural variants of biotite or muscovite-biotite granite that locally contain cordierite or andalusite (Hameurt 1967; Tabaud 2012). These are typical S-type peraluminous granites with a high LILE content. With respect to the average continental crust, the CVG is enriched in Ni, Cr, K, U and Th. In addition, they show a decreasing REE content from the basic to the acid end-members. By contrast, the isotopic compositions are more primitive (Fig. 3) with $e^{(^{87}Sr/^{86}Sr)}_{Nd}^{(340)} = -4.8$ to 1.4 and $^{87}Sr/^{86}Sr^{(340)} = 0.7048 – 0.7084$ (Tabaud 2012). Previous studies show that the SVMg–K association has a high-K signature and is probably derived from a basaltic source, either of tholeiitic (André & Bébien 1983) or shoshonitic affinity (Pagel & Leterrier 1980). André (1983) proposes that the basic rocks located at the margin of the SVMg–K complex are derived from fractional crystallization of a tholeiitic basaltic magma, while Pagel & Leterrier (1980) relate the SVMg–K complex to hyperpotassic or shoshonitic series where alkaline magma was contaminated by the continental crust. The mixed mantle and crustal affinities are also recognized in the volcanic rocks and could testify for a subduction setting (Lefèvre et al. 1994).

Metamorphic record

Contrasted metamorphic conditions are documented across the Vosges Mountains (Fig. 4). They range from limited contact metamorphism around the granitoids to ultra-high-pressure conditions in peridotite slices of the Central Vosges. Nevertheless, geochronological studies demonstrate that metamorphism was restricted to a relatively short Late Devonian–Early Carboniferous period.

Contact metamorphism

The various granitoid intrusions are commonly associated with metamorphic aureoles in the neighbouring sedimentary rocks. The polyphase intrusion of the Northern Vosges magmatic suite is responsible for contact metamorphism in both the Northern and Southern successions (Fig. 4a). The
sediments of the Bruche unit document a resetting of the Rb–Sr isotopic system (Bonhomme & Prévôt 1968), whereas a narrow aureole of hornfels and spotted slate was generated by the southern granodiorite and the younger Andlau granite in the Steige unit (Rosenbuch 1877; von Eller 1964).

In the Southern Vosges, the margin of the allochthonous Markstein unit and parts of the autochthonous Oderen unit are affected by contact metamorphism over a relatively large area (Fig. 4a). In the northern part, the Mg–K granitoids produce mostly hornfels while both the Mg–K and Central Vosges granites transform the southern sediments into spotted slates. Hornfels is additionally found in the autochthonous units around the SVMg–K magmatic complex.

**Low- to medium-grade metamorphism (Northern Vosges)**

In the Northern Vosges, metasedimentary and metavolcanic rocks exhibit a very low- to medium-grade overprint increasing towards the south (Fig. 4a). The volcanic rocks of the central magmatic suite preserve prehnite and actinolite (Reibel & Wurtz 1984) which indicate $P$–$T$ conditions of...
200–300 °C at pressures not exceeding 1–2 kbar. In the Steige unit, the assemblage paragonite–chlorite–illite together with the transition from kaolinite to dickite point to a temperature of 100–200 °C at c. 1 kbar (Fig. 4b), except along the contact with the Villé unit where pyrophyllite may indicate a slightly higher temperature (Clauer 1970). By contrast, pyrophyllite and illite with increasing crystallinity are common in schist and phyllite of the Villé unit (Clauer 1970), suggesting P–T conditions of 1–2 kbar and 250–350 °C (Fig. 4b). Towards the south, mica schist with a garnet–biotite assemblage pervasively replaced by muscovite–chlorite is found in a narrow zone along the LLFZ (Ighid 1985). Chemical analyses reveal a significant spessartine proportion in the garnet core (0.1–0.2), and point to peak metamorphic conditions reached the upper greenschist facies close to the Central Vosges metamorphic units.

Medium- to high-grade metamorphism (Central Vosges)

In the metamorphic units of the Central Vosges, the high-grade felsic granulite and varied gneiss are mantled by a large zone of medium-grade monotonous gneiss (Fig. 4a). Several studies recognize that an initial medium-to-high-pressure–high-temperature (MP–HP/HT) stage is pervasively overprinted by a low-to-medium-pressure–high-temperature (LP–MP/HT) metamorphic event. In the monotonous unit, a relictual garnet–staurolite–kyanite assemblage points to prograde metamorphism up to 6–7 kbar and 600–700 °C (Rey et al. 1989; Latouche et al. 1992). The subsequent development of abundant sillimanite, cordierite and biotite indicates a drop in pressure below 4–5 kbar at temperatures probably still above 550–600 °C (Fig. 4c). The metamorphic evolution of the varied gneiss and felsic granulite units is markedly different (Fig. 4c). In both units, the occurrence of garnet–kyanite–K-felspar is used to propose HP granulite-facies metamorphism with peak P–T estimates of 14–16 kbar at 820–880 °C for the varied gneiss (Rey et al. 1989; Skrzypek et al. 2012a) and 12–15 kbar at 700–900 °C for the felsic granulite (Pin & Vielzeuf 1988; Gayk & Kleinschrodt 2000; Skrzypek et al. 2012a). However, their retrograde evolution is nearly shared with that of the monotonous unit (Fig. 4c). In the varied gneiss, the assemblage biotite–sillimanite–cordierite with minor hercynite indicates a LP/HT stage at 2–5 kbar and 600–700 °C (Rey et al. 1989, 1992), while the felsic granulite is retrogressed at 2–3 kbar and 650–700 °C (Gayk & Kleinschrodt 2000). According to Altherr & Kalt (1996), the garnet peridotites initially equilibrated close to the graphite–diamond transition at 49 kbar and 1000 °C before being incorporated into the felsic granulite unit at 10 kbar/700–1000 °C (Fig. 4c).

Towards the south, partially molten gneiss bodies are entirely surrounded by the CVG (Fig. 4a). They correspond to orthogneiss with a relatively low melt fraction (10–30%), metasedimentary migmatite with a variable amount of former melt (10–80%) or nebulitic migmatite with scarcely oriented biotite (Schulmann et al. 2009a).

Geochronology

The compilation of geochronological data for the Palaeozoic basement of the Vosges Mountains emphasizes the Late Devonian–Early Carboniferous thermal events. They are related to medium- to high-grade metamorphism in the Central Vosges, but also to several magmatic events which occurred across the entire massif.

Timing of the igneous activity

The synthesis of existing ages for igneous rocks indicates distinct pulses of magmatic activity between 350 and 290 Ma (Fig. 5a). The oldest igneous rocks are related to the basic plutonism which occurred at the margin of the SVMg–K complex at c. 345 Ma, as indicated by U–Pb zircon data on diorite and monzodiorite samples (Schallegger et al. 1996; Tabaud 2012). It was shortly followed by more abundant magmatism with the intrusion of the larger SVMg–K granite at 339–336 Ma (Schallegger et al. 1996; Tabaud 2012) and the associated aerial rhyolitic volcanism at 340–335 Ma (Boutin et al. 1995; Schallegger et al. 1996). The SVMg–K magmatism is nearly coeval with the CVMg–K event recognized in the Central Vosges (Fig. 5a). There, durbachitic to granitic intrusions preserve U–Pb zircon ages between 340 and 332 Ma (Schallegger et al. 1996; Schulmann et al. 2002). Nevertheless, a few zircon cores yielding ages of c. 350 Ma suggest that this magmatic event could have started earlier (Tabaud 2012).

Following both Mg–K events, arc-type magmatism took place in the Northern Vosges (Fig. 5a). The successive intrusions of I- to S-type plutons are dated by various methods, and there is a general agreement to consider this episode to be relatively short-lived and lasting from 335 to 330 Ma (Boutin et al. 1995; Hess et al. 1995;
Reischmann & Anthes 1996; Altherr et al. 2000; Edel et al. 2013). However, recent U–Pb zircon and monazite data show inheritance at 360–345 Ma (Elsass & von Eller 2008; Edel et al. 2013), indicating that the igneous activity in the Northern Vosges could have started earlier. Conversely, several $^{40}$Ar/$^{39}$Ar ages of c. 320 Ma reported for the magmatic suite could represent partial resetting due to the younger and widespread Middle Permian acid volcanism estimated at 299–293 Ma in the northernmost part of the Vosges Mountains (Lippolt & Hess 1983; Boutin et al. 1995).

The latest Carboniferous magmatic event produced granitoids which cover the largest part of the Central Vosges (Fig. 1). It is associated with the emplacement of the Central Vosges Granite at 328–320 Ma (Schaltegger et al. 1999; Tabaud 2012) and leucogranites between 330 and 323 Ma (Boutin et al. 1995; Schulmann et al. 2002; Kratinnová et al. 2007). The CVG also preserves inherited zircon or monazite ages of c. 335 Ma, suggesting that the granite digested host rocks emplaced or metamorphosed during the Early Carboniferous, that is, most likely rocks belonging to the Central Vosges metamorphic units (Tabaud 2012).

Timing of metamorphism

Previous geochronological studies show that metamorphic ages cluster at 350–330 Ma (Fig. 5b). Few data document Early Carboniferous metamorphism in the Northern Vosges. Rb–Sr whole-rock analyses indicate contact metamorphism in the Northern succession at 339 ± 22 Ma due to the intrusion of the northern granite (recalculated age after Bonhomme & Prévôt 1968), while the southern granodiorite affects the Southern succession at 339 ± 38 Ma (recalculated pooled age after Claus & Bonhomme 1970). In the Central Vosges metamorphic units, U–Pb and $^{40}$Ar/$^{39}$Ar ages indicate a prominent event at 340–335 Ma (Fig. 5b). The monotonous unit seems to lack Early Carboniferous zircon ages (Fig. 5b), but preserves a $^{40}$Ar/$^{39}$Ar biotite cooling age of 330 ± 14 Ma (Boutin et al. 1995). Conversely, U–Pb zircon data in both the varied gneiss leucosomes and restites indicate that HT metamorphism and partial melting occurred from 340 to 335 Ma. In the felsic granulite unit, zircon grains similarly point to granulite-facies metamorphism at 345–335 Ma (Schaltegger et al. 1999; Skrzypek et al. 2012a), although the peak pressure event may have been slightly older. In the two high-grade units, $^{40}$Ar/$^{39}$Ar ages between 340 and 325 Ma lie close to U–Pb zircon estimates, indicating rapid cooling of this deep part of the crust. In the migmatite bodies, inherited zircon ages of c. 335 Ma indicate that this domain was also affected by Early Carboniferous metamorphism before being pervasively invaded by the Central Vosges Granite (Tabaud 2012).

Structure

The synthesis of new and existing data allows the structural succession for the different lithotectonic units of the Vosges Mountains to be constrained. The observations include the planar and linear structures in sedimentary or metamorphic
lithologies and the anisotropy of magnetic susceptibility data (AMS) in magmatic rocks (Fig. 6).

**Northern Vosges**

**Northern succession.** The dominant planar structure in the Bruche unit is the sedimentary bedding S₀. This bedding is initially affected by a gentle kilometre-scale north–south folding which generates S₀ planes variably dipping to the east or west (Fig. 7). The folded S₀ is subsequently affected by a moderate kilometre-scale NE–SW folding locally associated with a spaced cleavage S₁ (Fig. 7). The NE–SW-striking cleavage S₁ steeply dips to the SE and cross-cuts the S₀ bedding at a high angle. The second deformation is responsible for the main NE–SW trend of the Bruche synform (see also Blanalt & Lillie´ 1973; Wickert & Eisbacher 1988), but the final deformation pattern clearly results from two quasi-orthogonal compression events (Fig. 8a).

**Magmatic suite.** Following the results of Edel et al. (2013), the AMS record in the magmatic suite shows a clear distinction between the northern granitic domain and the southern dioritic-granodioritic domain (Fig. 7). In the northern granite, the magnetic foliation strikes NW–SE and dips moderately to the NE while the lineation trends north–south to NW–SE with a variable plunge (Fig. 7). Similar orientations are observed in the late granites intruding the northern part. Conversely, the belts of volcanic rocks, diorite and granodiorite preserve magnetic structures which are nearly perpendicular to those observed in the northern domain (Fig. 8a). These are east–west- to NE–SW-striking foliations steeply dipping to the north or SE, and NE–SW-trending lineations moderately plunging to the SW (Fig. 7). All structures were acquired at a magmatic state.

**Southern succession.** In the Steige unit, the original sedimentary bedding S₀ is rarely visible and is more commonly affected by upright east–west folds. The folding produces a subvertical east–west-schistosity S₁, which is the dominant structure in this unit (Fig. 7). In addition, a variably plunging intersection lineation L₀–1 is observed on S₁ surfaces. It suggests that S₀ was folded, most likely along a north–south axis, before the development of S₁. At the contact with the granodiorite, magmatic veins are found parallel to the subvertical S₁ in spotted slates (Fig. 8a). A later deformation event generates subhorizontal cleavage planes, and the superposition of orthogonal fabrics gives rise to a typical pencil cleavage.

In the Villé unit, the dominant metamorphic foliation S₁ is most likely developed parallel to the
Fig. 7. Structural map of the Palaeozoic Vosges basement. Own observations and data from Edel et al. (2013) in the magmatic suite, Kratinová et al. (2007) in the leucogranites, Kratinová et al. (2012) in the eastern anatectic granite, Rey et al. (1992) in the western anatectic granite, Blumenfeld (1986) in the western migmatite and Schulmann et al. (2009a) in the eastern migmatite. Rare fold axes in some units are omitted for clarity reasons. Lithologies as in Figure 1.
sedimentary bedding (Ruhland & Bronner 1965). The $S_1$ was probably originally subhorizontal, but is now commonly affected by east–west- to NE–SW-trending chevron-type folds. The folding generates east–west- to NE–SW-striking $S_{1-2}$ planes that dip moderately to the SE or steeply to the NW, and a NE–SW axial plane cleavage $S_2$ steeply dipping to the SE (Fig. 7). A later vertical shortening is locally observed close to the contact with the Steige unit.

At the southern margin of the Ville unit, a narrow zone of black schist with quartz augen surrounded by sigmoidal mica-rich bands occurs. The black schist preserves a subvertical NE–SW-striking schistosity cross-cut by subvertical east–west-striking shear planes that bear a subhorizontal lineation. This fabric superposition reflects a dextral sense of shear which is compatible with the latest kinematics of the LLFZ (e.g. Bouyalaoui 1992).

Central Vosges

Metamorphic units. The structural analysis of the Central Vosges metamorphic units reveals the superposition of three main structures. The oldest structure corresponds to the metamorphic foliation $S_1$ which is dominant on both sides of the Mg–K granitoid (Fig. 7). In all units, the $S_1$ consistently strikes north–south to NE–SW and dips steeply to the NW in the eastern part and to the SE in the western part, thereby defining a fan-like structure (Fig. 8b). In the varied gneiss, coarse-grained quartz–K-feldspar–garnet leucosomes are additionally found parallel to the $S_1$ fabric.

The $S_1$ foliation is subsequently affected by millimetre- to metre-scale recumbent folds that are open to isoclinal. This heterogeneous vertical shortening event produces the new subhorizontal foliation $S_2$ (Fig. 7). To the west of the granitoid, the $S_2$ foliation is shallowly dipping to the south or...
SW, and is associated with concordant anatetic veins. To the east of the granitoid, $S_2$ corresponds to the axial planar cleavage of north–south-trending folds or, more commonly, to a continuous foliation shallowly dipping to the west. There, the $S_2$ is dominantly present at the contact between the varied and monotonous gneiss units and gives to this contact an apparent thrust geometry; no kinematic indicators that could support the hypothesis of an east-directed transport are, however, observed (Fig. 8b).

To the east of the Mg–K granitoid, the monotonous and varied gneiss units are weakly affected by a subsequent metre- to kilometre-scale east–west upright folding (Fig. 7). This weak deformation produces east–west-striking $S_{2-3}$ planes variably dipping to the north or south, and an incipient east–west axial plane cleavage $S_3$ steeply dipping to the north (Fig. 8c).

**Leucogranites.** The structural record in the leucogranites intruding the Central Vosges metamorphic units was detailed by Kratinová et al. (2007). From north to south, the Thannenkirch and Brézouard bodies preserve a northern isotropic zone and a southern anisotropic margin with a magmatic to solid-state fabric, whereas the Bilstein granite only exhibits a pervasive solid-state deformation with S-C fabrics indicating sinistral shearing. Similarly, the AMS record highlights kilometre-scale domains of north–south- to NW–SE-trending lineations cross-cut by narrow zones of east–west-trending lineations and subvertical east–west magnetic foliations (Figs 7 & 8c).

**Western anatetic domain.** The NE–SW-trending Sainte-Marie-aux-Mines Fault Zone (SMMFZ) divides the Central Vosges into two distinct anatetic domains (Fig. 1). The western domain comprises a large migmatitic unit surrounded by the CVG. In the western part of the migmatitic unit, Blumenfeld (1986) documented a NE–SW-striking foliation steeply dipping to the NW, whereas in the eastern part the foliation shallowly dips to the north or NE (Fig. 7).

To the north of the migmatitic unit, the Central Vosges Granite preserves a magmatic fabric which gradually evolves to a dominant solid-state foliation towards the south (Rey et al. 1992). The foliation is in continuity with the subhorizontal $S_2$ fabric observed in the southwestern part of the metamorphic units (Fig. 7). It shallowly dips towards the migmatitic unit, that is, it is south- or SW-dipping in the northern part and east- or north-dipping along the eastern margin of the migmatite. Close to the migmatitic unit, fault striations and other shear indicators indicate a top-to-the-SW normal displacement (see also Rey et al. 1992).

To the south of the migmatitic unit, AMS data in the CVG reveal a dominant NE–SW-striking magnetic foliation moderately dipping towards the SE or NW (Fig. 7). Close to the migmatitic unit a few lineations moderately plunge towards the NW, while most lineations plunge at variable angles to the east or NE in the rest of the area.

**Eastern anatetic domain.** The eastern anatetic domain comprises relictual bodies of migmatitic orthogneiss and metagreywacke surrounded by the large CVG. The metamorphic and magmatic structures in the migmatitic units were detailed by Schumm et al. (2009a). In the larger orthogneiss body an east–west-striking foliation steeply dipping to the south or SW is preserved in the centre, but tends to have a NW–SE strike towards the margins (Fig. 7). The small orthogneiss body indicates a nearly complete reworking of the original east–west subvertical fabric into shallowly south- or SW-dipping planes.

The surrounding CVG preserves magmatic to subsolidus structures to the north, but is isotropic towards the south (Kratinová et al. 2012). To the north, the magnetic foliation dips shallowly to the south and is associated with a subhorizontal east–west lineation (Fig. 7). In the isotropic granite, moderately east-dipping or shallowly south-dipping magnetic foliations are observed. The magnetic lineation trends north–south and gently plunges to the south or SE (Fig. 7).

**Mg–K magmatism.** Three distinct CVMg–K granitoid bodies occur in the Central Vosges. The two largest intrusions are found in the metamorphic units and the CVG. They both preserve a subhorizontal K-feldspar fabric. The nearly orthogonal AMS structures define an axial zone of NE–SW subvertical magnetic foliations and NE–SW lineations cross-cut by east–west- to NW–SE-trending lineations associated with subhorizontal foliations (Fig. 7). Importantly, the NE–SW magnetic structures are concordant with the $S_1$ foliation in the metamorphic core.

A small body of CVMg–K granitoid crops out at the northern margin of the allochthonous sedimentary units. There, numerous biotite-rich xenoliths are found and point to a clear intrusive contact with the sediments (Fig. 8c). In the granite, Kratinová et al. (2012) showed that the magnetic foliation is moderately dipping to the SW and that the north–south-trending lineation gently plunges to the south or SE (Fig. 7).

**Southern Vosges**

**Autochthonous units.** The dominant structure of the autochthonous units is the sedimentary bedding $S_0$. 
It is mostly visible in sediments of the Oderen unit and only rarely in the dominantly volcanic Thann unit. According to new data and observations summarized by Krecher (2005), two distinct S0 trends can be recognized. In the central part, the bedding strikes NW–SE and variably dips to the NE or SW (Fig. 7). By contrast, narrow zones to the north and to the south show a north–south-striking S0. In the northern part the S0 is subhorizontal and parallel to the roof of the underlying granite, whereas it is moderately to steeply east-dipping near the SVMg–K complex (Fig. 7).

**Allocathous units.** The main structure in the allochthonous Markstein and Klippen Belt units is the sedimentary bedding S0 (see also Ruhland 1958; Petrini & Burg 1998). As in the autochthonous units, two orthogonal trends are recognized. A first upright folding event produces north–south-striking S0 planes that are mostly preserved along the margin of the allochthonous units. This domain of north–south-striking orientations coincides with the zone affected by contact metamorphism and points to an influence of the surrounding granitoids (Figs 4 & 7). Conversely, the central part exhibits kilometre-scale asymmetrical folds associated with NW–SE-striking S0 planes variably dipping to the NE or SW (Fig. 7). On both sides of the Klippen Belt, the consistently NE-dipping S0 suggests the presence of a thrust of the allochthonous units over the autochthonous units (Fig. 8d). The subvertical S0 planes additionally bear NW–SE-trending subhorizontal striations, indicating a mostly dextral sense of shear.

**Mg–K magmatic complex.** The SVMg–K complex is characterized by a juxtaposition of orthogonal structures. An earlier study of K-feldspar phenocrysts proposes that a dominant east–west to NW–SE subvertical foliation is cross-cut by narrow corridors exhibiting a north–south to NE–SW subvertical fabric (Blanchard 1978). Similarly, new AMS data reveal the occurrence of orthogonal fabrics. In the centre of the magmatic body a north–south-striking and steeply east- or west-dipping magnetic foliation is associated with a north–south lineation steeply plunging to the north or south (Fig. 7). By contrast, the eastern and western parts of the granite exhibit east–west foliations steeply dipping to the south and subhorizontal east–west-trending lineations (Fig. 7). All structures were acquired at the magmatic state.

**Geodynamic evolution**

**Early Palaeozoic: the pre-collisional history**

*The Vosges Mountains: a Gondwana-derived assemblage.* The record of the Neoproterozoic–Early Palaeozoic evolution is cryptic (Fig. 9). Only the metagranite found in the Klippen Belt testifies for the presence of a Neoproterozoic substratum (Skrzypek et al. 2012b). In addition, the Northern Vosges Villé unit preserves Cambro-Ordovician siliciclastic sediments with acid tuffs and quartzite indicative of a shallow-marine basin (Fig. 2). Together with the contemporaneous pelite and carbonate found in the northern Black Forest (Sittig 1965; Montenari & Servais 2000), they define a succession which partly resembles that of the margin of the Gondwana continent. Similar deposits are documented on other Late Proterozoic continental blocks which are commonly regarded as peri-Gondwana crustal fragments (e.g. Chlupač 1993; Doré 1994; Linnemann et al. 2000). The Cambro-Ordovician protolith ages for granitic pebbles in the Northern Vosges sediments (Dör et al. 1992) and for the felsic granulite (Skrzypek et al. 2012a) also point to acid magmatism at c. 500 Ma (Fig. 9). This magmatic activity is commonly interpreted as the incipient break-up of the northern Gondwana margin and the associated opening of oceanic basins bounded by microcontinental blocks (e.g. Pin & Marini 1993; Crowley et al. 2000; Schätz et al. 2002). All these arguments confirm the Gondwana derivation of the entire Vosges Mountains.

**The Central Vosges metasedimentary units: deposits of the Saxothuringian Basin?** The opening of an Early Palaeozoic basin is indicated by the thick monotonous and varied metasedimentary units. The monotonous unit comprises psammitic sediments derived from a Cadomian source, and was probably deposited in the Late Cambrian (Fig. 5b). The varied unit originates from the Late Ordovician–Early Silurian sedimentation of pelite-sandstone derived from a Cambro-Ordovician source, with scarce carbonate and basic magmatic rocks (Fig. 5b).

This Early Palaeozoic sedimentary record bears strong similarities to the lithostratigraphy of the Saxothuringian domain, and especially to the Thuringian facies. The Thuringian succession is characterized by Ordovician sandy-pelitic sediments, overlain by Silurian shales with intercalations of carbonates and basic lavas (Falk et al. 1995). At first glance, the monotonous unit can be seen as the base of the Thuringian facies while the varied unit resembles the overlying Silurian succession. Both units could therefore be interpreted as proximal deposits of a Saxothuringian passive margin sequence. Correlating such sediments from the Vosges up to eastern Germany is possible, since similar sedimentation ages are proposed for some medium- to high-grade metasediments of the central Black Forest (Kober et al. 2004).
Fig. 9. Synoptic view of the Palaeozoic sedimentation, magmatic, metamorphic and deformation events in the Variscan Vosges Mountains. N, Northern Vosges; C, Central Vosges; S, Southern Vosges.
However, the structural and petrological data demonstrate that the varied succession was not originally located above the monotonous sediments. The varied unit presently rests over the monotonous unit, but shows a higher metamorphic overprint (Fig. 8b). It argues for a separate evolution of the two units, which should originate from different sedimentation areas. The monotonous unit was deposited close to a Neoproterozoic and Cadomian substratum which is also known to underlie the monotonous unit in the Bohemian Massif (e.g. Fritz 1996; Friedl et al. 2004; Schulmann et al. 2005). Conversely, the varied unit is related to the erosion of a Cambro-Ordovician substratum which is more abundant in the northern part of the peri-Gondwanan continental blocks (e.g. Kröner et al. 2000b; Kemnitz et al. 2002). The varied unit is therefore interpreted as a sedimentary succession from the northern part of the Saxothuringian Basin. The monotonous unit was probably deposited further south, and its link with the Saxothuringian Basin is less clear (Fig. 10a).

The Northern succession (Northern Vosges): deposits of the Rhenohercynian Basin? In the Northern succession, the oldest sediments correspond to Middle Devonian coastal conglomerate and sandstone with a few reef limestones (Fig. 2). In addition, pebbles point to the erosion of a Cambro-Ordovician granitic substratum (Dörr et al. 1992) which is also found further to the north in the Saar Basin (Sommermann 1993). The substratum of the Saar Basin is overlain by thick Middle–Upper Devonian platform carbonate (Hering & Zimmerle 1976). These scarce data indicate the presence of a Devonian sedimentary basin in the northernmost part of the Vosges. The coarse-grained character of the first sediments suggests that a probable episode of Early Devonian emersion was followed by marine transgression (Fig. 9). The correlation with the Middle Devonian deposits in the Saar Basin additionally points to a relatively shallow-marine platform environment which may be slightly deepening towards the north (Fig. 10a, b).

Nearly similar Devonian siliciclastic and/or carbonated sediments are documented in the Rhenish Massif (Franke 1995) in SW England (Leveridge & Hartlieb 2006) or Moravia (Hladil et al. 1999). These successions are interpreted as the filling of the Rhenohercynian Basin which started to open in the Early Devonian (e.g. Clark et al. 1998). By contrast, Devonian black shales or shales in both the Thuringian and Bavarian facies of the Saxothuringian Basin indicate a deeper sedimentary environment (Falk et al. 1995). The Middle–Upper Devonian record of the Northern succession is therefore correlated with that of the Rhenohercynian Basin. In this view, the Northern succession could represent a proximal part of the southern margin of this basin (Fig. 10a–c).

Late Devonian: onset of collision

Across the European Variscan Belt, multiple arguments testify for the activity of subduction zones during the Late Devonian (e.g. Matte 1998). In the Vosges Mountains, evidence for a subduction setting is represented by HP granulite-facies rocks which were probably metamorphosed during Late Devonian–Early Carboniferous (Skrzypek et al. 2012a) time and by the remnants of a Late Devonian back-arc basin in the Southern Vosges (Skrzypek et al. 2012b).

Subduction of the northern Saxothuringian passive margin. In the Central Vosges metamorphic units, the contrasted sedimentological records and detrital zircon ages are used to propose that the monotonous and varied gneiss protoliths were deposited in different areas (Figs 2 & 5b). In addition, petrological data reveal that the monotonous gneiss only reached peak amphibolite-facies conditions, whereas the felsic granulite and varied gneiss units underwent HP granulite-facies metamorphism (Fig. 4c).

HP granulite-facies metamorphism is a peculiar feature of the European Variscides (e.g. Pin & Vielzeuf 1988) and its significance has been explored by various studies (e.g. Kröner et al. 2000a; O'Brien & Rötzer 2003; see also Kotokova 2007 for a review). Based on geochronological and geochemical arguments, Janoušek et al. (2004) proposed that the felsic granulites which are now found in the Moldanubian domain represent metamorphosed and partially molten equivalents of Ordovician granites located in the Saxothuringian domain (Fichtelgebirge). It was integrated in a tectonic model where the HP granulite-facies rocks are interpreted as a part of continental crust which was subducted below the Moldanubian crust (Guy et al. 2011; Chopin et al. 2012). Such a model additionally suggests that the Mg–K granitoids frequently associated with HP granulites are the products of mixing between melt lost from the felsic granulite and the overlying lithospheric mantle (Janoušek & Holub 2007; Lexa et al. 2011).

The striking lithological, petrological and geochemical similarities between the Central Vosges metamorphic units and rocks of the Bohemian Massif argue for an identical tectonic scenario for both regions. In the Bohemian Massif, the timing and polarity of the SE-directed Saxothuringian subduction is well constrained thanks to numerous ages reflecting HP metamorphism at c. 380 Ma (Gebauer & Grünenfelder 1979; Stosch & Lugmair 1990; Beard et al. 1995) and to Late Devonian flysch
Fig. 10. Schematic cross-sections illustrating the Palaeozoic evolution of the different parts forming the present-day Vosges Mountains. This view tries to integrate all lithological, structural, petrological and geochronological data. Reconstructions for: (a) Middle Devonian (c. 380 Ma); (b) Late Devonian (c. 360 Ma); (c) Tournaisian (c. 350 Ma); (d) lower Visean (c. 340 Ma); (e) middle Visean (335–330 Ma); and (f) late Lower Carboniferous (330–320 Ma). No horizontal scale.
sedimentation followed by the NW-directed emplacement of high-grade nappes in the Saxothuringian domain (e.g. Franke 1984). The genesis of the Central Vosges orogenic root is therefore explained by the SE-directed continental subduction of a Saxothuringian-type passive margin below the Moldanubian upper plate (Fig. 10).

In this view, the present-day Moldanubian domain is interpreted as a mixture of a Saxothuringian allochthonous continental portion and the autochthonous Moldanubian upper plate (see also Chopin et al. 2012). This leaves the question regarding the nature of the Moldanubian upper plate before continental subduction to be resolved. In the Bohemian Massif, the Moldanubian crust is thought to involve a Neoproterozoic substratum (e.g. Friedl et al. 2004) and Early Palaeozoic back-arc sediments separated from the Saxothuringian Basin by the Teplá-Barrandian domain (e.g. Schullmann et al. 2009b). In the case of the Vosges, the monotonous unit is considered as the upper-plate material and probably rests on a Neoproterozoic substratum similar to that found in the Klippen Belt (Fig. 10a). The parallel between both massifs indicates that the Moldanubian upper plate represents the southern margin of the Saxothuringian Basin (Fig. 10a), but contains a varying amount of Teplá-Barrandian-type material between the Saxothuringian Basin and the Neoproterozoic substratum.

The Saxothuringian–Moldanubian (Teplá) suture in the Vosges Mountains. Invoking the subduction of the northern Saxothuringian passive margin requires the continuation of the Saxothuringian–Moldanubian (Teplá) suture to be identified within the Vosges Mountains. This suture was classically defined along the east–west Lalaye–Lubine Fault Zone (Fluck et al. 1991), although it is devoid of any ophiolitic remnants in the Vosges Mountains as well as in the neighbouring Black Forest. Several arguments are presented here to challenge this earlier interpretation.

Placing a suture along the LLFZ implies that the Southern succession of the Northern Vosges (Steige and Villé units) represents material from the Saxothuringian lower plate. Sediments involved in oceanic or continental subduction are expected to record pressure-dominated metamorphism coeval with HP conditions in the deeply subducted material (e.g. Maruyama & Liou 1988). However, such features are incompatible with the P–T–deformation–time record in the Steige and Villé units. These units show a continuous Barroisian metamorphic gradient reaching garnet grade towards the south (Fig. 4b) and kyanite grade if mica schists occurring in the northern Black Forest are considered (Wickert et al. 1990). The peak metamorphic assemblages are developed in an originally subhorizontal foliation which was transposed much later into a subvertical cleavage during Early Carboniferous north–south shortening (Fig. 6). In addition, metamorphic ages of 345–340 Ma in phyllyte and mica schist (Clauer & Bonhomme 1970; unpublished electron microprobe monazite ages) are similar to those obtained in the deep orogenic root (Fig. 5b). All data indicate that the Southern succession represents a normal sequence metamorphosed along a MP/MT gradient during the Early Carboniferous.

From a structural point of view, the earliest fabrics observed in the Central Vosges strike NE–SW (Fig. 7) and are parallel to the c. 60 km-long Sainte-Marie-aux-Mines Fault Zone (Fig. 1). The consistent orientation of these structures over several tens of kilometres indicates a NW–SE bulk shortening direction, which is in contradiction with the east–west strike of the LLFZ. Several major Variscan suture zones are also characterized by a thrust of high-grade units over less-metamorphosed rocks, producing inverted metamorphic sequences (e.g. Pitra et al. 2010). For the Vosges Mountains, the structural observations do not support a thrust of the medium-grade monotonous gneiss unit over the Southern succession, as already emphasized by Kossmat (1927).

To summarize, the Saxothuringian–Moldanubian (Teplá) suture is not believed to lie along the LLFZ. The Southern succession should be regarded as autochthonous sediments resting on the Moldanubian upper plate. Given that the deposition age of the Southern succession is older than that of the more metamorphosed monotonous unit (although poorly constrained), the Southern succession could not conformably overlay the monotonous unit sediments. Instead, it should correspond to a thin piece of Teplá-Barrandian-type material located at the northern edge of the Moldanubian upper plate. This interpretation is supported by the lithological similarities between the Southern succession and the Teplá-Barrandian deposits of the Bohemian Massif (Fig. 2). The metamorphism of the Southern succession is explained by moderate crustal thickening during the early Lower Carboniferous (Fig. 10a–c). According to this interpretation, the Saxothuringian–Moldanubian suture should lie to the north of the LLFZ. Edel & Schullmann (2009) consider that the Northern succession (Bruche) also belongs to the Teplá-Barrandian domain and trace the suture to the north of the presently exposed Vosges basement. However, the present work prefers to link the Northern succession with deposits of the Rhenohercynian Basin. The Saxothuringian–Moldanubian suture is therefore thought to lie within the Northern Vosges, where it is presently obliterated by the magmatic suite (Figs 10 & 11).
Southern Vosges: back-arc basin opening. The Southern Vosges Klippen Belt testifies for the opening of a Late Devonian back-arc basin due to the subduction of an Early Palaeozoic oceanic domain (Fig. 10b). The origin of this back-arc spreading through the SE-directed closure of the Saxothuringian basin or the north-directed closure of the Palaeotethys Ocean is still unclear (Skrzypek et al. 2012b). The arguments in favour of the first hypothesis involve the coeval timing of the Saxothuringian (or Rheic) subduction (Stampfli et al. 2013) and the doubtful existence of an oceanic domain to the south according to palaeontological data (e.g. Paris & Robardet 1990). Arguments for the second hypothesis include the east–west-trending structures of the basin (Fig. 7), which could indicate inversion controlled by its initial shape (e.g. Oncken et al. 1999) acquired during north–south opening, and the correlation with the neighbouring southern Black Forest. There, the Badenweiler–Lenzkirch zone is thought to reflect the north-directed subduction of a southern oceanic domain (Loeschke et al. 1998).

A correlation with the Brévenne unit located in the NE French Massif Central faces the same dualistic view. There, the occurrence of HP metamorphic rocks (‘Monts du Lyonnais’) and relicts of a Late Devonian back-arc basin (‘Brévenne’) was interpreted as a result of the north-directed subduction of a southern oceanic domain (Lardeaux et al. 2001). However, this idea is seriously challenged by structural (Leloix et al. 1999) and

Fig. 11. Position of the Vosges Mountains in the European Variscan Belt. (a) Map of the Variscan litho-tectonic domains (after Edel & Schulmann 2009) and enlarged view of the proposed subdivisions in the Vosges Mountains (inset). Kr., Kraichgau; T-B., Teplá-Barrandian blocks. (b) Schematic view showing the proposed subdivisions in the Vosges Mountains and neighbouring massifs.
geochronological (Faure et al. 2008) data which indicate a general north-vergence of the inverted back-arc basin, and no temporal link between HP metamorphism and back-arc spreading. These observations alternatively support the origin of the Late Devonian Brévenne back-arc due to the south-directed subduction of the Rheic Ocean (e.g. Faure et al. 2005).

Early Lower Carboniferous: polyphase collisional tectonics

East–west shortening: Saxothuringian–Moldanubian collision. The earliest fabric observed in the Vosges metamorphic units is the NE–SW subvertical S1 foliation (Fig. 7). The S1 foliation is connected with sillimanite growth after kyanite in both the felsic granulite and varied gneiss (Fig. 4c). By contrast, the metamorphic conditions of S1 are not known for the monotonous unit, but garnet-staurolite relics point to a prograde evolution (Rey et al. 1992). The observations therefore indicate a vertical upwards flow of the lower crust and a possibly contemporaneous downwards flow of the middle crust. Because the NE–SW fabrics are shared by upper and lower plate rocks along a vertical section of at least 10 km (from 8 kbar to at least 12 kbar; Fig. 4c) and along a horizontal section of c. 60 km (Fig. 7), the associated NW–SE to east–west shortening is thought to be nearly parallel to the compression direction at that time, and is tentatively ascribed to the compression imposed by the SE-directed subduction of the Saxothuringian passive margin (Fig. 10a–c).

The subvertical S1 foliation is subsequently transposed into a subhorizontal S2 fabric (Fig. 6). The metamorphism associated with S2 corresponds to a pervasive LP/HT overprint affecting all units (Rey et al. 1989; Latouche et al. 1992). Due to its high-temperature character the metamorphic event is correlated with zircon ages of 340–335 Ma that are repeatedly obtained in metamorphic rocks (Fig. 5b), especially in leucosomes parallel to S2 in the varied gneiss (Schaltegger et al. 1999). The combined observations are interpreted as a widespread vertical shortening of the metamorphic units which were previously juxtaposed at a mid-crustal depth. This event is responsible for the fan-like structure of the root and the apparent thrust of the HP/HT units over the monotonous unit (Fig. 8b), formerly interpreted as a result of nappe tectonics (Fluck et al. 1991). The localized vertical shortening may be due to a continuous accumulation of allochthonous felsic material at the base of the crust, as is proposed for the ductile thinning mechanism developed in the Franciscan complex (Ring & Brandon 1999). This event still results from the collision between the Saxothuringian and Moldanubian continental margins (Fig. 10d).

North–south shortening: subduction of the Rheohercynian Basin and Gondwana indentation. The Vosges Mountains experienced a switch from east–west to north–south shortening (Fig. 6) at c. 340 Ma. The change in the shortening direction is probably best reflected by the structural record in the Mg–K granitoids. These bodies were emplaced between 340 and 332 Ma (Schaltegger et al. 1996; Schulmann et al. 2002), and systematically preserve two orthogonal fabric sets (Fig. 7). Bulk north–south shortening is also indicated by the east–west to NE–SW subvertical cleavage planes developed in the Northern Vosges, and by the NW–SE-trending upright folds in the Southern Vosges sedimentary units (Fig. 7). In addition, east–west upright folding of the subhorizontal S2 foliation is observed in the eastern part of the metamorphic units (Fig. 6). The south-vergent structures developed in the Lower Carboniferous turbiditic sediments of the southern Black Forest (Hann & Sawatzki 1998) also testify for a general north–south shortening (Fig. 6).

In the Northern Vosges, the Lower Carboniferous flysch-type sedimentation indicates tectonic instabilities in the basin. This deformation event culminates with the middle Visean sedimentary hiatus and the coeval emplacement during trans-tension of the NE–SW-trending magmatic arc at 335–330 Ma (Altherr et al. 2000; Edel et al. 2013). Evidence for a contemporaneous south-directed subduction of the Rheohercynian passive margin (Holder & Leveridge 1986) and associated arc magmatism in the Mid-German Crystalline Rise (MGCR; Anthes & Reischmann 2001) is described across the European Variscan Belt. Consequently, the magmatic suite of the Northern Vosges is interpreted as a prolongation of the MGCR and its emplacement is ascribed to the south-directed subduction of the Rheohercynian Basin (Fig. 10e). The Lower Carboniferous magmatic arc intrudes a sedimentary succession of Rheohercynian affinity to the north, and Early Palaeozoic metasediments of Teplá-Barrandian affinity to the south. This close juxtaposition of contrasted lithologies is an additional argument for tracing the former Teplá suture at the place of the magmatic suite. Such a discontinuity could have controlled the intrusion of the NE–SW-trending magmatic arc in the upper plate.

The observed tectonic switch could be explained by a rigid block rotation, since palaeomagnetic data document a c. 80° anticlockwise rotation of the Vosges Mountains during the Early Carboniferous (Edel et al. 2013). However, the structural data indicate a bulk north–south shortening in present-day
coordinates. In addition, deformation-age relationships reveal that the east–west structures are progressively younger towards the north (Fig. 6). These data are in good agreement with the idea of a northwards indentation of Gondwana which was already invoked to explain the north–south Carboniferous shortening in the European Variscan Belt (Vollbrecht et al. 1989). A similar north- to NW-directed shortening due to the indentation of the Brunovistulian microcontinent is also recorded in other parts of the Moldanubian domain (SE Bohemian Massif, Schulmann et al. 2005; Sudetes, Chopin et al. 2012). The north–south shortening accounts for the general south-verging structures observed in the southern part of the Variscan orogen, and especially in the Southern Vosges and Black Forest (Wickert & Eisbacher 1988; Eisbacher et al. 1989; Fig. 10e).

**Late Lower Carboniferous: orogenic collapse**

*Detachment systems in the Central Vosges*. The north–south shortening is followed by north–south extension at c. 330–320 Ma (Fig. 6). It is revealed by normal faulting in the uppermost crust, by the transtensional emplacement of the Northern Vosges magmatic suite (Edel et al. 2013) and by the development of detachment zones in the middle crust. The western part of the CVG preserves evidence for the activity of a late Lower Carboniferous SW- to south-directed detachment system (see also Rey et al. 1991). At the same time, the eastern CVG is emplaced along a SE- to south-directed detachment zone (Schulmann et al. 2009a) while the leucogranites are emplaced under a transtensional regime (Katinová et al. 2007). All these structural features point to symmigmatic south-directed extensional tectonics during the late Lower Carboniferous (Fig. 10f).

*Significance of the Lalaye–Lubine Fault: a prediction of the model*. The LLFZ is a subvertical shear zone separating greenschist- to amphibolite-facies phyllite from partly migmatitic paragneiss, and documents Upper Carboniferous (?) dextral strike-slip (Fig. 1). It was previously interpreted as a south-dipping suture zone (e.g. Fluck et al. 1991), but several arguments challenge this view. Alternatively, it is proposed that the LLFZ marks the boundary between metasediments of Teplá-Barrandian affinity (Southern succession) and metasediments originally deposited on the Moldanubian upper plate (monotonous gneiss unit). The Teplá-Barrandian–Moldanubian boundary in the central Bohemian Massif corresponds to a subvertical shear zone hosting sheared granitoids and documenting a significant normal movement of the Teplá-Barrandian relative to the Moldanubian domain (e.g. Scheunens & Zulauf 2000). In the NE Bohemian Massif, this presumed boundary corresponds to a dextral strike-slip zone separating greenschist- to amphibolite-facies rocks from migmatitic orthogneiss, but it is thought to have previously operated as a detachment fault (Mazur et al. 2005; Chopin et al. 2012).

The LLFZ has numerous features in common with the Teplá-Barrandian–Moldanubian boundary described in the Bohemian Massif. The presence of sheared granitoids along the eastern prolongation of the LLFZ in the Black Forest (Baden–Baden Fault Zone, Wickert et al. 1990) adds to this list of similarities. Moreover, rocks located to the north of the Lalaye–Lubine and Baden–Baden fault zones represent a continuous metamorphic section reaching kyanite grade, while the monotonous gneiss located to the south documents peak upper-amphibolite facies conditions (Fig. 4c). The relatively small metamorphic gap suggests that the Steige–Villé units could have been originally located above the monotonous gneiss unit. Consequently, it is speculated that the LLFZ represents a former north-directed detachment system (Fig. 10e). By analogy with the Bohemian Massif, the Steige–Villé units are regarded as the detached upper crust of Teplá-Barrandian affinity. This interpretation is a prediction of the present model, and further work should try to recognize the possible earlier detachment structures that did not suffer the later and pervasive strike-slip reactivation of the LLFZ (e.g. Bouyalaoui 1992).

*Driving mechanisms for orogenic collapse*. The late Lower Carboniferous tectonic evolution was dominated by the activity of detachment systems. They mostly developed in the upper to middle crust, but left the orogenic lower crust unaffected (Fig. 6). It indicates that lower crustal flow (e.g. Vanderhaeghe et al. 1999) was not a driving mechanism for orogenic collapse in the case of the Vosges Mountains.

The development of a detachment zone during the emplacement of the CVG points to a role of the thermal structure of the crust. During extension the zone of anatexis developed above deep crustal rocks which show no signs of melting (Fig. 10f), suggesting that the heat source was instead located at a mid-crustal level. Simulations of the geotherm relaxation show that the large and highly radioactive Central Vosges Mg–K granitoids (e.g. Rothe 1962) emplaced in the middle crust at c. 340 Ma (Schaltegger et al. 1996) can trigger partial melting of the surrounding rocks after a period of c. 10 Ma, that is, precisely when the CVG was emplaced (Tabaud 2012). Conversely, the shallower Southern Vosges Mg–K granitoids are not expected to generate a sufficient perturbation
of the geotherm, since radiogenic heat production is strongly dependent on the depth of radioactive rocks in the vertical column (e.g. McLaren et al. 1999). Such a contrast emphasizes the influence of radioactive heat production on the late-orogenic tectonic evolution. Accordingly, detachments in the Central Vosges are interpreted to be activated by a thermal weakening of the middle orogenic crust (Tabaud 2012).

The north–south extension can also be correlated with the larger-scale Variscan evolution. Arc-type magmatism at 335–330 Ma in the Northern Vosges is thought to reflect the climax of the Rhenohercynian subduction (Edel et al. 2013). Such a south-directed subduction is likely to drive extension in the back-arc region, that is, precisely in the Central Vosges (Fig. 10f). Different directions of post-thickening extension have been documented in the European Variscan Belt (Burg et al. 1994), but this event can be correlated with the Middle Carboniferous NE–SW extension and abundant plutonism which are recognized in the French Massif Central (Faure 1995). The analogy with a Cordilleran metamorphic core complex setting (e.g. Coney & Harms 1984) suggests that the late Lower Carboniferous extension reflects an interplay between extensive melting of the middle orogenic crust and far-field forces.

Conclusions

The zonation of the Palaeozoic Vosges Mountains is described considering that the major Variscan lithotectonic domains: (1) have a variable width along the orogenic belt, and (2) can be a heterogeneous mixture of units with different affinities.

- **Northern Vosges.** The Devonian–Carboniferous Northern succession shows a Rhenohercynian affinity and is considered as deposits from the southern margin of the Rhenohercynian basin. It behaved as a fore-arc region during the late Lower Carboniferous south-directed subduction of the Rhenohercynian basin. The Early Palaeozoic Southern succession is a thin piece of Teplá–Barrandian affinity which originally belonged to the northern edge of the Moldanubian upper plate. The contrasting Northern and Southern successions are intruded by a Lower Carboniferous magmatic arc correlated with the Mid-German Crystalline Rise. The magmatic arc is thought to exploit a former major discontinuity: the Saxothuringian–Moldanubian (Teplá) suture. A prediction of the model is that the Southern succession was detached from the Moldanubian upper plate along the Lalaye–Lubine Fault Zone before dextral strike-slip reactivation.

- **Central Vosges.** The similarities to the SE Bohemian Massif support the Moldanubian affinity of the Central Vosges. However, the orogenic root is described as a polydeformed and polymetamorphosed assemblage of autochthonous and allochthonous crustal fragments. The high-grade felsic granulite and varied units are considered as a portion of the northern Saxothuringian passive margin, whereas the medium-grade monotonous unit belongs to the Moldanubian crust. The juxtaposition of units is ascribed to the early Lower Carboniferous SE-directed continental subduction of the Saxothuringian passive margin below the Moldanubian upper plate. The inferred nappe structure of the central Black Forest needs to be reinvestigated to support the correlation between the Vosges and the Bohemian Massif.

- **Southern Vosges.** The Southern Vosges Klippen Belt testifies for the opening of a Late Devonian back-arc basin. It can be related to the north- or south-directed subduction of a surrounding oceanic domain, the neighbouring massifs provide arguments for both views. The Southern Vosges later evolved as a detached upper part of the Moldanubian crust. Correlations with similar Upper Devonian–Lower Carboniferous lithologies in the NE Massif Central and the southern Black Forest are manifest, but they leave unresolved questions regarding the nature of the basement towards the south.

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**References**

Aghai Soltani, L., Bender, P., Braun, A. & Schmidt-Effing, R. 1996. Oberdevonische Radiolarien aus Kieselgesteinen des Breuschtals (Vallée de la Bruche, Nord-Vogesen, Frankreich). Jahresbericht und Mitteilungen des oberrheinischen geologischen Vereins, 78, 183–208.

Altherr, R. & Kalt, A. 1996. Metamorphic evolution of ultrahigh-pressure garnet peridotites from the Variscan Vosges Mts (France). Chemical Geology, 134, 27–47.
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ALTHERR, R., HOLL, A., HEGNER, E., LANGER, C. & KREUZER, H. 2000. High-potassium, calc-alkaline I-type plutonism in the European Variscides: northern Vosges (France) and northern Schwarzwald (Germany). Lithos, 50, 51–73.

ANDRÉ, F. 1983. Pétrologie structurale et pétrogenèse des formations plutoniques septentrionales du Massif des Ballons (Vosges, France). PhD thesis, Université de Nancy.

ANDRÉ, F. & BÉBIEN, J. 1983. Minéralogie et pétrologie des cumulats gabbro-dioritiques situés en bordure septentrionale du massif des Ballons (Vosges méridionales, France): cristallisation d’un magma basique en domaine ‘orogénique’ intracontinental. Bulletin de Minéralogie, 106, 341–351.

ANTHE, G. & REICHHMANN, T. 2001. Timing of granitoid magmatism in the eastern mid-German crystalline rise. Journal of Geodynamics, 31, 119–143.

ASSELBERGHS, E. 1926. Sur l’existence du Famenien (Néodévonien) à Chagey (Belfort). Bulletin de la Société Géologique de France, 26, 67–74.

BAIN, A. 1964. Etude d’un microplancton (Acritarches) du Dévonien supérieur. Mémoire de DEA, Université Louis Pasteur, Strasbourg.

BEARD, B. L., MEDARIS, L. G., JOHNSON, C. M., JELINEK, E., TONIKA, J. & RICIPUTI, L. R. 1995. Geochemistry and geochemistry of eclogites from the Maria neske massif de la Bruche (Vosges du Nord). Mittheilungen der geologischen Landesanstalt von Elsass–Lothringen, 105, 341–351.

BENNEKE, E. W. & BÜCKING, H. 1898. Calceola sandalina im oberen Breuschtal. Mittheilungen der geologischen Landesanstalt von Elsass–Lothringen, 4, 105–111.

BENNEKE, E. W. & VON VERVEKE, L. 1890. Über das Rotliegende der Vosges. Mittheilungen der geologischen Landesanstalt von Elsass–Lothringen, 3, 45–103.

BLANALT, J. G. 1969. Contribution à l’étude du conglo-érat givéien de Russ (Vallée de la Bruche, Vosges). Essai de paléogéographie. Thèse de 3eme cycle, Université Louis Pasteur, Strasbourg.

BLANALT, J.-G. & DUBINGER, J. 1973. Contenu paléontologique du gisement frasnien de la carrière Wenger et Petit à Herschbach (vallée de la Bruche, Vosges). Sciences Géologiques, 26, 75–90.

BLANALT, J. G. & LILLIE, F. 1973. Données nouvelles sur la stratigraphie des terrains sédimentaires dévonien-dinantiens de la vallée de la Bruche (Vosges septentrionales). Sciences Géologiques, 26, 69–74.

BLANCHARD, J.-P. 1978. Dynamique magmatique du Granite porphyroide des Ballons (Vosges méridionales). ‘Fluidalités planaires imbriquées’ et ‘couloirs magmatiques’. Phénomènes de percolation. Bulletin de la Société Géologique de France, 20, 157–162.

BLUMENFELD, P. 1986. Déformation et fusion partielle dans la croûte continentale: migmatites et granites de l’unité occidentale des Vosges moyennes (France). PhD thesis, Université de Nancy.

BONHOMME, M. & DUNOYER DE SEGONZAC, G. 1962. Mesures d’âge par la méthode Rubidium-Strontium dans les schistes de Steige (Vosges septentrionales). Bulletin du Service de la Carte Géologique d’Alsace-Lorraine, 15, 129–137.

BONHOMME, M. & PRÉVÔT, L. 1968. Application de la méthode Rubidium-Strontium à l’étude de l’âge radio-métrique de quelques dépôts dévono-dinantiens du massif de la Bruche (Vosges du Nord). Bulletin du Service de la Carte Géologique d’Alsace-Lorraine, 21, 219–248.

BOUTIN, R., MONTGNY, R. & THUIZAT, R. 1995. Chronologie K-Ar et 40Ar/39Ar du métamorphisme et du magmatisme des Vosges. Comparaison avec les massifs varisques avoisinants. Géologie de la France, 1, 3–25.

BOYVALAOGI, J. 1992. Schistes de Steige. Phyllades de Ville et mylonites du Climont (Vosges du Nord). Le développement de la zone cisallée de Lalaye-Lubine. PhD thesis, Université de Brest.

BRAUN, A., MAASS, R. & SCHMIDT-EFFING, R. 1992. Oberdevonische Radiolarien aus dem Breuschtal (Nord-Vosges, Elsäß) und ihr regionaler und stratigraphischer Zusammenhang. Neues Jahrbuch für Geologie und Paläontologie. Abhandlungen, 185, 161–178.

BÜCKING, H. 1918. Beiträge zur Geologie des oberen Breuschtals in den Vosges. Mittheilungen der geologischen Landesanstalt von Elsass–Lothringen, 12, 1–368.

BÜRG, J. P., VAN DEN DRIESSCHE, J. & BRUN, J. P. 1994. Syn- to post-thickening extension in the Variscan Belt of Western Europe: Modes and structural consequences. Géologie de la France, 3, 33–51.

CHEVILLARD, M. J. L. 1866. Trilobites du Dévonien du Mont de la Revenue, commune de Chagey, près Héricourt (Haute-Saône). Bulletin de la Société Géologique de France, 24, 124–129.

CHILUPACI, I. 1993. Geology of the Barrandian. A field trip guide. Waldemar Kramer Verlag, Frankfurt-am-Main.

CHOPIN, F., SCHULMANN, K. ET AL. 2012. Crustal influx, indentation, ductile thinning and gravity redistribution in a continental wedge: building a Moldanubian mantled gneiss dome with underthrust Saxothuringian material (European Variscan belt). Tectonics, 31, 1–27.

CHOUBERT, G. & GARDET, G. 1935. Contribution à l’étude du Permien des Vosges. Revue de Géographie physique et de Géologie dynamique, 3, 325–362.

CLARK, A. H., SCOTT, D. J., SANDMAN, H. A., BROMLEY, A. V. & FARRAR, E. 1998. Siegenian generation of the Lizard ophiolite: U–Pb zircon age data for plagiograni- nite, Porthkerris, Cornwall. Journal of the Geological Society, London, 155, 595–598.

CLAUSER, N. 1970. Etude sédimentologique, géochimique et géochronologique des schistes de Steige et de la Série de Villé - Vosges. Thèse de 3ème cycle, Université Louis Pasteur, Strasbourg.

CLAUSER, N. & BONHOMME, M. 1970. Datations Rubidium–Strontium dans les schistes de Steige et la série de Villé (Vosges). Bulletin du Service de la Carte Géologique d’Alsace-Lorraine, 23, 191–208.

CONKEY, P. J. & HARRMS, T. A. 1984. Cordilleran metamorphic core complexes: Cenozoic extensional relics of Mesozoic compression. Geology, 12, 550–554.

CORSIN, P. & DUBOIS, G. 1932. Description de la flore dinantienne de Champeny. Bulletin du Service de la Carte Géologique d’Alsace-Lorraine, 2, 1–33.
CORSIN, P., & MATTAUER, M. 1957. Quelques nouveaux gisements fossilières du Massif des Ballons (Vosges méridionales). *Comptes rendus sommaires de la Société Géologique de France*, 5, 92–94.

CORSIN, P., & RUHLAND, M. 1959. Les gisements à plantes du Viséen dans les Vosges méridionales. *Comptes Rendus de l’Académie des Sciences*, 248, 2145–2149.

CORSIN, P., GAGNY, C., & MATTAUER, M. 1956. Découverte d’une florule d’âge viséen dans les schistes et grauwackes des environs de Fellinger (Haut-Rhin). *Comptes Rendus de l’Académie des Sciences*, 242, 1908–1909.

CORSIN, P., DANZE-CORSIN, MILLOT, G., & RUHLAND, M. 1960. Sur l’âge viséen inférieur des schistes de Schwarzbach (vallée de la Bruche) dans les Vosgex du Nord. *Bulletin du Service de la Carte Géologique d’Alsace-Lorraine*, 13, 163–164.

CORSIN, P., COULON, M., FOURQUIN, C., PAICHETER, J. C., & POINT, R. 1973. Étude de la flore de la série de Giroumagny (Viséen supérieur des Vosges méridionales). Comparaison avec les autres floras du Culm des Vosgex. *Sciences Géologiques*, 26, 43–68.

COULON, M. & LEMOIGNE, Y. 1969. Paleoxylon Bourbach-cheniss: nouvelle structure ligneuse du Viséen des Vosgex. *Comptes Rendus de l’Académie des Sciences*, 269, 1498–1501.

COULON, M., FOURQUIN, C., HEDDEBAUT, C., & PAICHETER, J. C. 1975a. Mise au point sur l’âge des faunes de Bourbach-le-Haut et sur la chronologie des différentes séries du Culm des Vosgex du Sud. *Sciences Géologiques*, 28, 141–148.

COULON, M., FOURQUIN, C., PAICHETER, J. C., & POINT, R. 1975b. Contribution à la connaissance du tectorogène varisque dans les Vosges méridionales. II - Le Culm de la région comprise entre Giroumagny et Bourbach-le-Bas. *Sciences Géologiques*, 28, 109–139.

COULON, M., FOURQUIN, C., PAICHETER, J. C., CONIL, R., & LYS, M. 1978. Stratigraphie du Viséen des Vosges méridionales et datations obtenues par l’étude de plusieurs niveaux à microfaunes et algues. *Sciences Géologiques*, 31, 77–93.

CREUZOT, G. 1983. *Étude géologique du bassin permien de Ronchamp-Giroumagny*. Thèse de 3ème cycle, Université de Besançon.

CROWLEY, Q. G., FLOYD, P. A., WINCHESTER, J. A., FRANKE, W. & HOLLAND, J. G. 2000. Early Palaeozoic rift-related magmatism in Variscan Europe: fragmentation of the Armorica Terrane Assemblage. *Terra Nova*, 12, 171–180.

DORÉ, F. 1994. Cambrian in the Armorican Massif. *In: KEPPIE, J. D. (ed.) Pre-Mesozoic Geology in France and Related Areas*. Springer, Berlin, 136–141.

DÖRR, W., PIQUE, A., FRANKE, W. & KRAMM, U. 1992. Les galets granioclu de la conglomérat de Russ (Dévono-Dinantien des Vosgex du Nord) sont les témoins d’un magmatisme acide orovien. La distension crustale et le rifting saxothuringien au Paléozoïque inférieur. *Comptes Rendus de l’Académie des Sciences*, 315, 587–594.

DOUBINGER, J. 1956. Contribution à l’étude des floras auto-néopranchiennes. *Mémoires de la Société Géologique de France*, 75, 1–180.

DOUBINGER, J. 1963. Chitinozoaires orovéniciens et siliens des schistes de Steige dans les Vosgex. *Bulletin du Service de la Carte Géologique d’Alsace-Lorraine*, 16, 125–136.

DOUBINGER, J. 1965. Sur l’âge des gisements houillers des Vosgex. *Bulletin du Service de la Carte Géologique d’Alsace-Lorraine*, 18, 49–64.

DOUBINGER, J. & RAUSCHER, R. 1966. Spores du Viséen marin de Bourbach-le-Haut dans les Vosgex du Sud. *Pollon et Spores*, 8, 361–405.

DOUBINGER, J. & RUHLAND, M. 1963. Découverte d’une faune de Chitinozoaires d’âge Dévonien au Treh (région du Markstein, Vosges méridionales). *Comptes Rendus de l’Académie des Sciences*, 256, 2894–2896.

DOUBINGER, J. & VON ELLER, J.-P. 1963a. Découverte de Chitinozoaires d’âge silurien dans les schistes de Steige (vallée de l’Andlau, Vosgex). *Comptes Rendus de l’Académie des Sciences*, 256, 469–471.

DOUBINGER, J. & VON ELLER, J.-P. 1963b. Présence de Spongioaires dans les schistes précambriens métamorphiques des Vosgex. *Bulletin du Service de la Carte Géologique d’Alsace-Lorraine*, 16, 111–123.

DUBOIS, G. 1946. Répartition des gisements certainement et vraisemblablement dans la région de la Bruche (Vosges moyennes). *Comptes rendus sommaires de la Société Géologique de France*, 12, 222–223.

EDEL, J.-B. & SCHULMANN, K. 2009. Geophysical constraints and model of the ‘Saxothuringian and Rheihercynian subductions – magmatic arc system’ in NE France and SW Germany. *Bulletin de la Société Géologique de France*, 180, 545–558.

EDEL, J.-B., SCHULMANN, K., SKRZYPEK, E. & COCHERIE, A. 2013. Tectonic evolution of the European Variscan belt constrained by palaeomagnetic, structural and anisotropy of magnetic susceptibility data from the Northern Vosges magmatic arc (eastern France). *Journal of the Geological Society, London*, 170, 785–804.

EHRENBerg, S. N., AAGAARD, P., WILSON, M. J., FRASER, A. R. & DUTHIE, D. M. L. 1993. Depth-dependent transformation of kaolinite to dickite in sandstones of the Norwegian continental shelf. *Clay Minerals*, 28, 325–352.

EISBACHER, G. H., LÜSCHEN, E. & WICKERT, F. 1989. Crustal-scale thrusting and extension in the Hercynian Schwarzwald and Vosgex, Central Europe. *Tectonics*, 8, 1–21.

ELSS, P. & VON ELLER, J.-P. 2008. *Géologie du massif du Champ du Feu et de ses abords*: Éléments de notice pour la feuille géologique 307 Sélestat. Rapport BRGM/ RP-56088-FR.

FALK, F., FRANKE, W. & KURZE, M. 1995. Saxothuringian basin: autochthon and nonmetamorphic nappe units – stratigraphy, structure, and igneous activity. *In: DALMAYER, D., FRANKE, W. & WEBER, K. (eds) Pre-Permian Geology of Central and Western Europe*. Springer, Berlin, 221–234.

FAURE, M. 1995. Late orogenic carboniferous extensions in the Variscan French Massif Central. *Tectonics*, 14, 132–153.

FAURE, M., BE MEZEME, E., DUGUET, M., CARTIER, C. & TALBOT, J.-Y. 2005. Paleozoic tectonic evolution of medio-europa from the example of the french Massif Central and Massif Armorican. *Journal of the Virtual Explorer*, 19, 1–26.
FLUCK, P. 1980. Métamorphisme et magmatisme dans les Vosges moyennes d’Alsace. Contribution à l’histoire de la chaîne Varisque. Mémoires des Sciences Géologiques, 62, 248.

FLUCK, P., PIQUÉ, A., SCHNEIDER, J.-L., & WHITECHURCH, H. 1991. Le socle vosgien. Sciences Géologiques Bulletin, 44, 207–235.

Fournet, J. 1847. Résultats sommaires d’une exploration des Vosges, Bulletin de la Société Géologique de France, 4, 220–254.

Franke, W. 1984. Variszischer Deckenbau im Raume der Münchberger Gneissmasse, abgeleitet aus der Fazies, Deformation und Metamorphose im umgebenden Paläozoikum. Geotektonische Forschungen, 68, 1–253.

Franke, W. 1995. Rheonlycyanian foldbelt: autochthon and nonmetamorphic nappe units – stratigraphy. In: Dallmeyer, D., Franke, W. & Weber, K. (eds) Pre-Permian Geology of Central and Western Europe. Springer, Berlin, 33–49.

Franke, W. 2000. The mid-European segment of the Variscides: tectonostrophic units, terrane boundaries and kinematic evolution. In: Franke, W., HAAK, V., ONCKEN, O. & TANNER, D. (eds) Orogenic Processes: Quantification and Modelling in the Variscan Belt. Geological Society, London, Special Publications, 179, 35–63.

Franke, W. & ŽELAŽNIEWSZ, A. 2000. The eastern termination of the Variscides: terrane correlation and kinematic evolution. In: Franke, W., HAAK, V., ONCKEN, O. & TANNER, D. (eds) Orogenic Processes: Quantification and Modelling in the Variscan Belt. Geological Society, London, Special Publications, 179, 63–86.

Frey, M. 1987. The reaction-isograd kaolinite + quartz = pyrophyllite + H2O, Helvetic Alps, Switzerland. Schweizerische Mineralogische und Petrographische Mitteilungen, 67, 1–11.

Friedl, G., Finger, F., Paquette, J., Quadt, A., McNaughton, N. & Fletcher, I. 2004. Pre-Variscan geological events in the Austrian part of the Bohemian Massif deduced from U–Pb zircon ages. International Journal of Earth Sciences, 93, 802–823.

Fritz, H. 1996. Geodynamic and tectonic evolution of the southeastern Bohemian Massif: the Thaya section (Austria). Mineralogy and Petrology, 58, 253–258.

Gagny, C. 1962. Caractères sédimentologiques et pétrographiques des schistes et gruéwackes du Culm dans les Vosges méridionales. Bulletin du Service de la Carte Géologique d’Alsace-Lorraine, 15, 139–160.

Gagny, C. 1968. Pétrogenèse du granite des Crêtes. Vosges méridionales. Thèse, Université de Nantes.

Gayk, T. & Kleinschrodt, R. 2000. Hot contacts of garnet peridotites in middle/upper crustal levels: new constraints on the nature of the late Variscan high-T/low-P event in the Moldanubian (Central Vosges/NE France). Journal of Metamorphic Geology, 18, 293–305.

Gebauer, D. & Grünenfelder, M. 1979. U–Pb zircon and Rb–Sr mineral dating of eclogites and their country rocks. Example: Münchberg Gneiss Massif, Northeast Bavaria. Earth and Planetary Science Letters, 42, 35–44.

Guy, A., Edel, J.-B., Schulmann, K., Tomek, C. & Lexa, O. 2011. A geophysical model of lower crustal structure of the Palaeozoic crustal root (Bohemian Massif): implications for modern collisional orogens. Lithos, 124, 144–157.

Hahn, G., Hahn, R. & Maass, R. 1981. Trilobites aus dem Unterkarbon der S-Vosges. Oberhessische geologische Abhandlungen, 30, 1–26.

Hameurt, J. 1967. Les terraines cristallins et cristophylliens du versant occidental des Vosges moyennes. Mémoires du Service de la Carte géologique d’Alsace-Lorraine, 26, 402.

Hammel, C. 1996. Une faune nouvelle de trilobites (Brachymetopus, Namuropyge) dans le Viséen des Vosges du Sud. Conséquences stratigraphiques et paléoséismologiques. Géobios, 29, 745–755.

Hann, H. P. & Sawatzki, G. 1998. Deckenbau und Sedimentationsalter im Grundgebirge des Südschwarzwalds/SW-Deutschland. Zeitschrift der deutschen geologischen Gesellschaft, 149, 183–195.

Herin, O. & Zimmerle, W. 1976. Petrographische Beschreibung und Deutung der erbohrten Schichten (Saar 1). Geologisches Jahrbuch, A-27, 91–106.

Hess, J. C., Lippolt, H. J. & Kobert, B. 1995. The age of the Kagenfels granite (northern Vosges) and its bearing on the intrusion schema of late Variscan granitoids. Geologische Rundschau, 84, 568–577.

Hladíl, J., Melichar, R. et al. 1999. The Devonian in the Easternmost Variscides, Moravia: a Holistic analysis directed towards comprehension of the original context. Abhandlungen der geologischen Bundesanstalt, 54, 27–47.

Holder, M. T. & Leveridge, B. E. 1986. A model for the tectonic evolution of South Cornwall. Journal of the Geological Society, London, 143, 125–134.

Hollinger, J. 1969. Beitrag zur Gliederung des Deckgebirges der Nordvogesen. Zeitschrift der deutschen geologischen Gesellschaft, 121, 79–91.

Ighid, L. 1985. Contribution à l’étude microstructurale des schistes de Steige et de la série de Villé - Vosges. Mémoire de DEA, Université Louis Pasteur, Strasbourg.

Ikenne, M. & Baroz, F. 1985. Mise en évidence des caractères orogénique, tholéitique et calco-alcalin du volcanisme dévono-dinantien dans le massif du Rabodeau (Vosges septentrionales): apport à la reconstitution
Krecher, M., Behrmann, J. H. & Müller-Sigmund, H. 2007. Sedimentology and tectonic setting of Devonian–Carboniferous turbidites and debris flow deposits in the Variscan Vosges Mountains (Markstein Group, NE-France). Zeitschrift der Deutschen Gesellschaft für Geowissenschaften, 158, 1063–1087.

Kretz, R. 1983. Symbols for rock-forming minerals. American Mineralogist, 68, 277–279.

Krohe, A. & Eisbacher, G. H. 1988. Oblique crustal detachment in the Variscan Schwarzwald, southwestern Germany. Geologische Rundschau, 77, 25–43.

Kröner, A., O'Brien, P. J., Nemchin, A. A. & Pidgeon, R. T. 2000a. Zircon ages for high pressure granulites from South Bohemia, Czech Republic, and their connection to Carboniferous high temperature processes. Contributions to Mineralogy and Petrology, 138, 127–142.

Kröner, A., Štípská, P., Schulmann, K. & Jäckel, P. 2000b. Chronological constraints on the pre-Variscan evolution of the northeastern margin of the Bohemian Massif, Czech Republic. In: Franke, W., Haak, V., Oncken, O. & Tanner, D. (eds) Orogenic Processes Quantification and Modelling in the Variscan Belt. Geological Society, London, Special Publications, 179, 175–197.

Lardeaux, J. M., Ledru, P., Daniel, I. & Duchene, S. 2001. The Variscan French Massif Central – a new addition to the ultrahigh pressure metamorphic ‘club’: exhumation processes and geodynamic consequences. Tectonophysics, 332, 143–167.

Lardeaux, J.-M., Schulmann, K. et al. 2014. The Moldanubian Zone in French Massif Central, Vosges/Schwarzwald and Bohemian Massif revisited: Differences and similarities. In: Schulmann, K., Martínez Catalán, J. R., Lardeaux, J. M., Janoušek, V. & Ogliano, G. (eds) The Variscan Orogeny: Extent, Timescale and the Formation of the European Crust. Geological Society, London, Special Publications, 405. First published online April 9, 2014, http://dx.doi.org/10.1144/SP405.14

Latouche, L., Fabries, J. & Guiraud, M. 1992. Retrograde evolution in the Central Vosgian mountains (north-eastern France): implications for the metamorphic history of high-grade rocks during the Variscan orogeny. Tectonophysics, 205, 387–407.

Laubacher, G. & von Eller, J.-P. 1966. Contribution à l’étude géologique des dépôts permien du bassin de Ville. Bulletin du Service de la Carte Géologique d’Alsace-Lorraine, 19, 163–186.

Lefèvre, C., Lakhrissi, M. & Schneider, J.-L. 1994. Les affinités magnétiques du volcanisme dinantien des Vosges méridionales (France); approche géochimique et interprétation. Comptes Rendus de l’Académie des Sciences, 319, 79–86.

Leloix, C., Faure, M. & Feybesse, J.-L. 1999. Hercynian polyphase tectonics in the northeast French Massif Central: the closure of the Brévenne Devonian–Dinantian rift. International Journal of Earth Sciences, 88, 409–421.

Leveridge, B. E. & Hartley, A. J. 2006. The Variscan Orogeny: the development and deformation of Devonian/Carboniferous basins in SW England and South Wales. In: Brenchley, P. J. & Rawson, P. F. (eds)
The Geology of England and Wales. Geological Society, London, 225–255.
LEXA, O., SCHULMANN, K., JANOUŠEK, V., ŠÍPSKÁ, P., GUY, A. & RACZEK, M. 2011. Heat sources and trigger mechanisms of exhumation of HP granulites in Variscan orogenic root. Journal of Metamorphic Geology, 29, 79–102.
LINNEMANN, U., GEHLMICH, M. ET AL. 2000. From Cadomian subduction to Early Paleozoic rifting: the evolution of Saxo-Thuringia at the margin of Gondwana in the light of single zircon geochronology and basin development (Central European Variscides, Germany). In: FRANKE, W., HAAK, V., O’NECKEN, O. & TANNER, D. (eds) Organogenic Processes: Quantification and Modelling in the Variscan Belt. Geological Society, London, Special Publications, 179, 131–153.
LIPPERT, H. J. & HESS, J. C. 1983. Isotopic evidence for the stratigraphic position of the Saar-Nahe Rottliegend volcanism I. 40Ar/40K and 40Ar/39Ar investigations. Neues Jahrbuch für Geologie und Paläontologie. Monatshefte, 12, 713–730.
LIPPERT, H. J., SCHLEICHER, H. & RACZEK, I. 1983. Rb–Sr systems of Permian granulites un the Schwarzwald (SW-Germany) Part I: space of time between plutonism and late orogenic volcanism. Neues Jahrbuch für Geologie und Paläontologie, 12, 272–280.
LOESCHKE, J., GÜLDENPFENNIG, M., HANN, H. P. & SAWATZKI, G. 1998. Die Zone von Badenweiler-Lenzkirch (Schwarzwald): Eine variszische Suturzone. Zeitschrift der deutschen geologischen Gesellschaft, 149, 971–972.
MAASS, R. & STOPPEL, D. 1982. Nachweis von Oberdevon bei Markstein (Bl. Münster, Südvogesen). Zeitschrift der Deutschen Geologischen Gesellschaft, 133, 403–408.
MAASS, R., PROSCH, T. & SCHULER, D. 1990. The zone of Badenweiler-Lenzkirch – a Carboniferous accretionary wedge? Neues Jahrbuch für Geologie und Paläontologie, Monatshefte, 12, 717–734.
MARUYAMA, S. & LIOU, J. G. 1988. Petrology of Franciscan metabasites along the jadeite-glaucophane type facies series, Cabadero, California. Journal of Petrology, 29, 1–37.
MATHEU, G. 1988. Observations stratigraphiques, sédimentologiques et structurales sur le bassin houiller de la Ronchamp-St-Germain-Momont. Mémoires de l’Institut géologique de France, 2, 13–23.
MATTE, P. 1998. Continental subduction and exhumation of HP rocks in Paleozoic orogenic belts: Uralides and Variscides. Geological Society of Sweden (GFF), 120, 209–222.
MATTE, P. 2001. The Variscan collage and orogeny (480–290 Ma) and the tectonic definition of the Armorica microplate: a review. Terra Nova, 13, 122–128.
MATTE, P., MALUSKI, H., RAULICH, P. & FRANKE, W. 1990. Terrane boundaries in the Bohemian Massif: result of large-scale Variscan shearing. Tectonophysics, 177, 151–170.
MAZUR, S., ALEKSANDROWSKI, P. & SZCZEPANSKI, J. 2005. The presumed Teplá–Barrandian/Moldanubian terrane boundary in the Orlica Mountains (Sudetes, Bohemian Massif): structural and petrological characteristics. Lithos, 82, 85–112.
MCNAREN, S., SANDIFORD, M. & HAND, M. 1999. High radiogenic heat–producing granites and metamorphism – An example from the western Mount Isa inlier, Australia. Geology, 27, 679–682.
MIHARA, S. 1935. Etude géologique et pétrographique de la région du Nideck. Mémoires du Service de la Carte géologique d’Alsace-Lorraine, 4, 134.
MONTENARI, M. & SERVAIS, T. 2000. Early Paleozoic (Late Cambrian-Early Ordovician) acritarchs from the metasedimentary Baden-Baden-Gaggenau zone (Schwarzwald, SW Germany). Review of Palaeobotany and Palynology, 113, 73–85.
MONTENARI, M., LEPPIG, U. & WEYER, D. 2002. Heterocorallia from the Early Carboniferous of the Moldanubian Southern Vosges Mountains (Alsace, France). Neues Jahrbuch für Geologie und Paläontologie. Abhandlungen, 224, 223–254.
MÜLLER, H. 1989. Geochemistry of metasediments in the Hercynian and pre-Hercynian crust of the Schwarzwald, the Vosges and Northern Switzerland. Tectonophysics, 157, 97–108.
NANCE, R. D., GUTIÉRREZ-ALONSO, G. ET AL. 2010. Evolution of the Rheic Ocean. Gondwana Research, 17, 194–222.
O’BRIEN, P. J. & RÖTZLER, J. 2003. High-pressure granulites: formation, recovery of peak conditions and implications for tectonics. Journal of Metamorphic Geology, 21, 3–20.
ONCKEN, O. 1997. Transformation of a magmatic arc and an orogenic root during oblique collision and its consequences for the evolution of the European Variscides (Mid-German Crystalline Rise). Geologische Rundschau, 86, 2–20.
ONCKEN, O., VON WINTERFELD, C. & DITTMAR, U. 1999. Accretion of a rifted passive margin: the Late Paleozoic. Rhenohercynian fold and thrust belt (Middle European Variscides). Tectonophysics, 18, 75–91.
PAGEL, M. & LETERRIER, J. 1980. The subalkaline potassic magmatism of the Ballons massif (Southern Vosges, France): shoshonitic affinity. Lithos, 13, 1–10.
PARIS, F. & ROBARDET, M. 1990. Early Paleozoic paleogeography of the Variscan regions. Tectonophysics, 177, 193–215.
PETRINI, K. & BURG, J. P. 1998. Relationships between deformation, plutonism and regional metamorphism in the Markstein area (southern Vosges). Géologie de la France, 2, 13–23.
PIN, C. & MARINI, F. 1993. Early Ordovician continental break-up in Variscan Europe: Nd–Sr isotope and trace element evidence from bimodal igneous associations of Southern Massif Central, France. Lithos, 29, 177–196.
PIN, C. & WIELZEF, D. 1988. Les granulites de haute-pression d’Europe moyenne témoins d’une subduction éo-hercynienne. Implications sur l’origine des groupes leptyno-amphiboliques. Bulletin de la Société Géologique de France, 4, 13–20.
1. Einleitung, Beschreibung der Brachiopoden-Fauna. Abhandlungen zur geologischen Spezialkarte von Elsass-Lothringen, 5, 379–528.

Tornquist, A. 1896. Das fossilführende Unterkarbon am östlichen Rossbergmassiv in den Südvogesen. 2. Beschreibung der Lamellibranchiaten-Fauna. Abhandlungen zur geologischen Spezialkarte Elsass-Lothringen, 5, 1–190.

Tornquist, A. 1897. Das fossilführende Unterkarbon am östlichen Rossbergmassiv in den Südvogesen. 3. Beschreibung der Echiniden-Fauna. 5, 1–81.

Tornquist, A. 1898. Vorläufige Mitteilungen über neue Fossilfunde im Unterkarbon des Ober-Elsass. Mitteilungen der geologischen Landesanstalt von Elsass-Lothringen, 4, 97–104.

Vanderhaeghe, O., Burg, J. P., & Teysseire, C. 1999. Exhumation of migmatites in two collapsed orogens Canadian Cordillera and French Variscides. In: Ring, U., Brandon, M. T., Lister, G. S. & Willett, S. D. (eds) Exhumation Processes: Normal Faulting, Ductile Flow and Erosion. Geological Society, London, Special Publications, 154, 181–204.

Velain, C. 1885. Le Permien dans la région des Vosges. Bulletin de la Société Géologique de France, 12, 536–564.

Vogt, C. 1981. Benthonische Klein-Foraminiferen aus dem Unter-Karbon der Südvogesen. Neues Jahrbuch für Geologie und Paläontologie, Monatshefte, 6, 363–384.

Vollbrecht, A., Weber, K. & Schmoll, J. 1989. Structural model for the Saxothuringian – Moldanubian suture in the Variscan basement of the Oberpfalz (NE Bavaria, FRG) interpreted from geophysical data. Tectonophysics, 157, 123–133.

von Eller, J.-P. 1961. Les gneiss de Sainte-Marie-aux-Mines et les séries voisines des Vosges moyennes. Mémoires du Service de la Carte géologique d’Alsace-Lorraine, 19, 160.

von Eller, J.-P. 1964. Dioritisation, granitisation et métamorphisme dans les Vosges cristallines du Nord. I Région comprise entre la plaine d’Alsace, d’Andlau à Saint-Nabor et le Champ du Feu. Bulletin du Service de la Carte Géologique d’Alsace-Lorraine, 17, 171–210.

Wickert, F. & Eibacher, H. 1988. Two-sided Variscan thrust tectonics in the Vosges Mountains, north-eastern France. Geodinamica Acta, 2, 101–120.

Wickert, F., Altherr, R. & Deutsch, M. 1990. Polyphase Variscan tectonics and metamorphism along a segment of the Saxo-Thuringian boundary: the Baden-Baden zone, northern Schwarzwald (F.R.G.). Geologische Rundschau, 79, 627–647.

Ziegler, P. A. 1984. Caledonian and Hercynian crustal consolidation of Western and Central Europe - a working hypothesis. Geologie en Mijnbouw, 63, 93–108.

fabrics and rheology of deforming migmatites, Central Vosges, France. Journal of Structural Geology, 31, 1223–1237.

Schulmann, K., Konopásek, J. et al. 2009b. An Andean type Palaeozoic convergence in the Bohemian Massif. Comptes Rendus Geoscience, 341, 266–286.

Sittig, E. 1965. Der geologische Bau des variszischen Sockels nordöstlich von Baden – Baden (Nordschwarzwald). Oberrheinische geologische Abhandlungen, 14, 167–207.

Skrzyypek, E., Štípská, P. & Cocherie, A. 2012a. The origin of zircon and the significance of U – Pb ages in high-grade metamorphic rocks: a case study from the Variscan orogenic root (Vosges Mountains, NE France). Contributions to Mineralogy and Petrology, 164, 935–957.

Skrzyypek, E., Tabaud, A.-S., Edel, J.-B., Schulmann, K., Cocherie, A., Guerrot, C. & Rossi, P. 2012b. The significance of Late Devonian ophiolites in the Variscan orogen: a record from the Vosges Klippen Belt. International Journal of Earth Sciences, 101, 951–972.

Sommerrman, A. E. 1993. Zirkonalter aus dem Granit der Bohrung Saar 1. Beihefte zur European Journal of Mineralogy, 5, 145.

Spear, F. S. & Cheney, J. T. 1989. A Petrogenetic Grid For Pelitic Schists in the System SiO₂-Al₂O₃-951–972. Variscan orogen: a record from the Vosges Klippen Massif, southern Germany. Earth and Planetary Science Letters, 99, 230–249.

Suess, F. E. 1926. Intrusionstektonik und Wandertektonik im variszischen Grundgebirge. Verlag Borntrager, Berlin.

Tabaud, A.-S. 2012. Le magmatisme des Vosges: conséquence des subductions paléozoïques (dataation, pétrologie, géochimie, ASM). PhD thesis, Université de Strasbourg.

Thompson, A. B. & Connolly, J. A. D. 1995. Melting of the continental crust: some thermal and petrological constraints on anatexis in continental collision zones and other tectonic settings. Journal of Geophysical Research, 100, 15 565–15 579.

Torschall, H. J. 1974. Geochemische Untersuchungen zum stofflichen Bestand und Sedimentationsmittel paläozoischer mariner Tone: Die Gehalte der Hauptidelemente und der Spurenelemente Ni, Co, Zn, Rh, Sr, Y, Zr, Nb und Ba in den Steiger Schiefern (Vogesen). Habilitation Thesis, Mainz.

Tornquist, A. 1895. Das fossilführende Unterkarbon am östlichen Rossbergmassiv in den Südvogesen.