

Chapter 2

Pegmatitic Rocks and Their Geodynamic Setting in the Central European Variscides

Abstract Pegmatitic rocks are not randomly distributed across the Variscan/Hercynian basement in Central Europe. The evolution of pegmatites s.l. in the course of a complex orogeny of Meso-Europe took rather long, from the Devonian (419 Ma) through the Permian (252 Ma). In terms of structural geology and geodynamics, pegmatitic deposits primarily occur in ensialic Variscan-type orogens (calc-alkaline) with a thickened crust and a preponderance of thrusting and nappe stacking. In Rift-type settings (alkaline) a strong subcrustal impact is evident and as reactivated/reworked pseudopegmatites in Alpine-type orogens (calc-alkaline) these deposits developed during the initial stages when the crustal section was still rather thick. Both types pertain to the marginal ensimatic settings. They left their hallmarks to some extent also within the Central European Variscides and at its southern edge in the Alpine-Carpathian Orogen. The geodynamic units subjected to very-low-grade- to low-grade stage metamorphism at the margin of the Central European Variscides are barren with regard to pegmatites and aplites. Pegmatoids with minor B-(Li)-P-REE-U-Be mineralization occur along a suture zone extending across the present-day continents. It resulted from the late Variscan closure of the Rheic Ocean between Gondwana and Laurussia with remnants of an arc-related plutonism. Within allochthonous metamorphic complexes and nappes barren feldspar-quartz pegmatoids plus metapegmatites developed. Further south another part of this former coherent nappe also contains a small Be-Nb-P mineralization. Within the Subfluence zone, marked by continent-continent collision and thickening of the crust pegmatite, granite- pegmatite (miarolitic), pegmatite-aplite and pegmatoid abundant in B, Be, F, Li, Sn, U, P and As are encountered. Heading further to the core zone of the Variscan orogen, strong diaphoresis and shearing in the contact zone between the Saxothuringian and Moldanubian zones *sensu lato* favored the emplacement of pegmatite and aplite enriched in B, P, Be, Nb, As, Zr and F. High grade metamorphic rocks in an autochthonous position with a protolith mainly of Proterozoic age exist in the core zone. At the margin they are overthrust onto adjacent geodynamic units and penetrated by multiple intrusions. The Hagendorf-Pleystein Pegmatite Province is located near the root zone for the nappe complexes thrust onto the north-western geodynamic realms. Pegmatites and aplites with minor pegmatoids of the Hagendorf-Pleystein Pegmatite Province show the most varied concentration of rare elements in pegmatitic and aplitic rocks in this crustal section (B-P-REE-Nb-Ta-Li-Sc-Zn-Be). In some parts in core zone pegmatites can

also be observed associated with skarns. Variscan lithologies were incorporated into the Alpine orogen and reactivated during the Alpine orogeny at the southern edge of the Meso-Europe. They contain granitic pegmatites, meta-pegmatites, pegmatoids and pseudo-pegmatites (B-Be-P-Nb-U-F-As-Li-Sn-REE-U). By quality this element assemblage is not very much different from that of the neighboring Variscan parent rocks. The suite of pegmatitic and aplitic mineral deposits is associated with mineral deposits of non-pegmatitic origin. They include thrustbound deposits (Au-As-Sb-(Hg)-Fe-Cu-Pb-Zn), plutonic/granite-related deposits (Sn-W-Mo-Pb-Ag-Zn-(In)-Cu-U), and unconformity-related (U-Pb-Zn-F-Ba). While the deposits can at least in parts structurally and compositionally related to the various types of pegmatites and aplites, stratabound deposits are mainly marker deposits for geodynamic units prone to aplitic or pegmatitic rocks in an ensialic orogen (SMS >> VM FeS-Cu-Zn, SEDEX Fe deposits, black-shale –hosted U-Cu-Mo-Sb-Zn-REE (low-grade-large-tonnage) and graphite). As an exception from this rule, the two last-mentioned mineralization with organic compounds can be considered (see geophysical surveys).

Pegmatitic rocks are not randomly distributed across the Variscan basement in Central Europe. Everybody may find out by himself that they reveal a compositional and textural variation as a function of the geodynamic position within an ensialic orogen. Therefore it makes sense to look at these basement units in more detail shifting our view from the small-scale geodynamics to the large scale regional (economic) geology in order to facilitate a correlation between the study area in Germany and areas outside Europe hosting also pegmatites. Even if Precambrian Shields endowed with pegmatitic rocks are not exposed in Central Europe, which went through the orogenic phase during the Paleozoic, the results obtained in the present study might also contribute to a better understanding of the pseudopegmatites as they went through their incipient stages of emplacement.

2.1 The Geological and Metallogenetic Evolution of the Central European Variscides with Special Reference to Pegmatites

The Central European Variscides that gave host to the pegmatites of the HPPP and their adjacent pegmatoids/aplites and metapegmatites saw mining of metallic and non-metallic commodities during more than 2000 years. Compared to the mining period of 2000 years in the Central Europe, the evolution of pegmatites s.l. in the course of complex orogeny of Meso-Europe took rather long, from the Devonian (419 Ma) through the Permian (252 Ma), while some scientists even extend these orogenic processes into the Triassic (201 Ma) (Suess 1888). In the Anglo-Saxon literature the term Hercynian is a synonym for the German word “variszisch” or Variscan which is used in preference to the term Hercynian throughout this presentation.

To give scientists also interested in pegmatites in Northern America a chance for a comparative study and to geodynamically tie up the Variscan pegmatite provinces on both sides of the present Atlantic Ocean it is inevitable to have a closer look at the western prolongation of the European Variscides. It is the Alleghanian or Appalachian orogeny that formed the Appalachian and Allegheny Mountains (Bartholomew and Whitaker 2010). During the afore-mentioned mountain-building processes, North America which was part of the Euramerica super-continent collided with Gondwana resulting in the newly formed super-continent Pangaea. Taking a closer look at Central Europe, we find the African plate in the south which formed part of the afore-mentioned Gondwana continent and in the North Laurussia (Ziegler et al. 1977; Matte 2001) (Fig. 2.1a). Whatever name given above you might prefer for the northern continent, there is only one geodynamic event responsible for the emplacement of this supercontinent Laurussia or Euramerica. During the Silurian two continental blocks named Laurentia and Baltica amalgamated, closing the existing Iapetus Ocean in between the two during what is called the Caledonian Orogeny. Seafloor spreading and the closure of the resultant ocean was not anything but another of the same during the Variscan Orogeny as the Rheic Ocean between Laurussia and Gondwana was closed during the Carboniferous leading to the Variscides. It is imperative to keep an eye on this Late Paleozoic period of time

PEGMATITES ALONG THE BOUNDARY

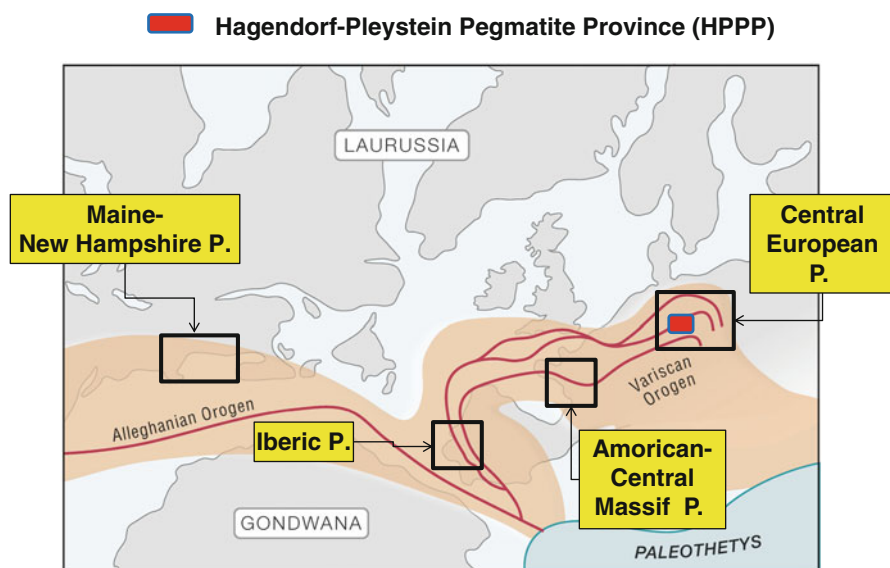


Fig. 2.1a Reconstruction of the mountain ridges produced in the course of the Alleghanian/Appalachian and Variscan/Hercynian orogenies during the Late Paleozoic on both sides of the present-day Atlantic Ocean amalgamating Laurussia and Gondwana and giving host to four pegmatite provinces

because it is the moment when the granites, pegmatites and aplites came into existence in the Central European Variscides. Pangea was the final result of this Variscan collision and originated from amalgamating of another large continent Siberia to the existing landmass during the Late Permian. Within this geodynamic framework our felsic intrusive rocks originated in what is called today Central Europe but was then the easternmost end of the Variscan mountain ridge (Fig. 2.1a).

The Central European Variscides rank among the most intensively studied crustal sections on Earth with a plethora of papers being available and part of them now stored in the various databases. These investigation starting off more than a century ago when the term Variscides was first coined by Suess (1888). The region experienced a tremendous increase in publications as the Continental Deep Drill Program of the Federal Republic of Germany (KTB) was in full swing and supplementary data derived from a deep-geophysical project, abbreviated to DEKORP were processes and interpreted to the full extent. These data sets were retrieved and made available for the deep-geology study of pegmatitic rocks. A brief retrospective of the data collection and goals of these ambitious programs is necessary.

At the very beginning, prior to the site selection, some held a continental drill hole down to 15,000 m in the midst of Europe feasible. During the late 1970s and early 1980 the motto was “Nothing but the very best will do”. The Russian engineers and scientists had raised the bar, or to be more precise, sunken the drill bit very deep into the upper crust, slowly but steadily. Whatever delicate excuses may have been put forward (I was a staff member of KTB Management Group, in charge of economic geology, mineralogy and geochemistry) and how many attempts made to adjust the goals, everything comes to light at the end (Emmermann and Lauterjung 1997). We were only fifth in the row, trailing by some considerable margin behind the other competitors. The Kola Superdeep Borehole SG-3, the physical expression of a scientific drilling project of the Soviet Union on the Kola Peninsula was for quite a long time second to none with a final depth of 12,262 m, and breaking the record of Bertha Rogers drill hole in Washita County, Oklahoma, at 9583 m. They were surpassed by oil well in Qatar (12,289 m) and offshore Sakhalin reaching a final depth of 12,345 m. In 1994, on October 12 after 1468 days the drilling bit stopped in the Oberpfalz at 9101 m. Even if we did not reached the goal, the scientific fallout was used as a basis for the present study.

Central Europe has seen a lot of ideas and models put forward by geophysicists, structural geologist and petrographers, alike, particularly throughout the heyday of geoscientific investigation in the wake of the superdeep hole which was sunken not far away from the HPPP. Not all of these ideas were solid-based and sometimes build at least in parts on shaky grounds, but one is still for sure. It is the geodynamic subdivision of the Central European Variscides, put forward by Kossmat in 1927 and still valid today without any restriction. Franz Kossmat was an Austro-German geologist but not a full-blown or full-time university staff member while heading the Geological Survey of Saxony in Germany for almost 20 years. In the succeeding paragraphs this classical subdivision is used as a basis to describe the various geodynamic units, placing particular emphasis on those units of interest for pegmatites.

Beforehand some of the major publications providing a comprehensive overview of this crustal section in Central Europe need to be cited so as to give those a chance

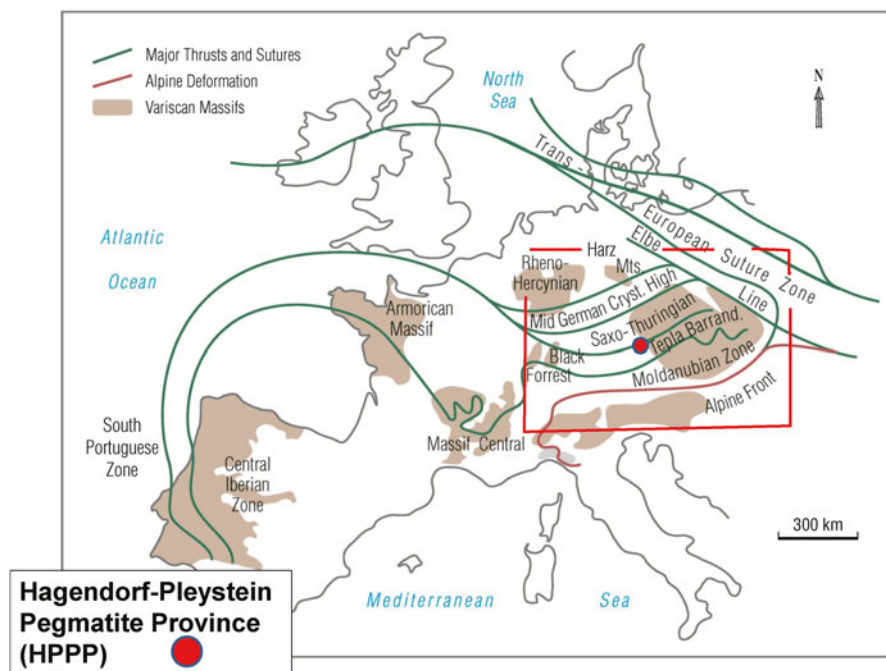


Fig. 2.1b Variscan massifs in Europe with sutures and lineamentary faults bounding the geodynamic units (Matte et al. 1990; Franke et al. 1995; McKerrow et al. 2000). The area framed by the red line demarcates the study area of the Central European pegmatites in this book (see Fig. 2.1d)

who want to immerse themselves in the geology of the Central European Variscides apart from the study of pegmatites (Walter 1992; Dallmeyer et al. 1995a, b; Winchester et al. 2002; Raumer von et al. 2003; McCann 2008a, b). In Fig. 2.1b the reader gets an idea what the geodynamic situation looks like in the Central and Western European Variscides while the diagrammatic N-S cross-section through the Central European Belt in Fig. 2.1c makes the reader familiar with the ideas of Behr et al. (1984), how to interpret the geodynamic evolution from the Moldanubian core zone through the northern passive margin along the western edge of the Bohemian Massif. The geodynamic units in Central Europe were discussed in the succeeding sections based upon the geodynamic map drafted by Dallmeyer et al. (1995a, b) (Fig. 2.1d).

2.1.1 The Subvariscan Foredeep

2.1.1.1 Lithology and Structural Geology

During the Upper Carboniferous, the Subvariscan Foredeep subsided along the north-western boundary of the Central European Variscides leading to a basin extending from the Ardennes, Belgium, in the West, through the Ruhr District, Germany, to

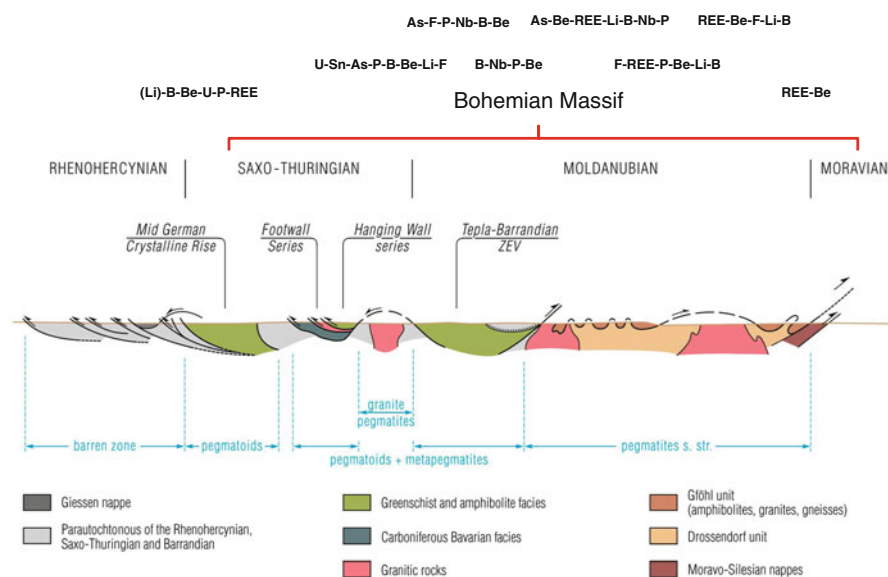


Fig. 2.1c Diagrammatic cross section through the allochthonous units and autochthonous units of the Central European Variscides (Behr et al. 1984). The types of pegmatitic rocks are given for each unit and their various element associations are shown on top

the Upper Silesian Coal Basin, Poland. Basin fill began in a flysch-type style and eventually faded out in what might be called a molasse-type sediment now being covered under the Mesozoic series of the North German Basin on the passive margin of Laurussia. The most striking feature of the basin is its cyclothems with more than 100 interbedded paralic coal seams that are still mined today in the Ruhr and in the Upper Silesian Basin for high volatile bituminous to anthracite-rank coal, but no longer in the Wallonian and Campine basins (Drozdowski 1993; Langenaier 2000; Gaschnitz 2001). The basin fill diminishes from approximately 5000 m in the South to 3000 in the North. The thickness of the Carboniferous molasse deposits in the eastern foreland of the Moravo-Silesian fold belt attains a much higher thickness of up to almost 9000 m (Jura et al. 2000). Igneous rocks are absent, excluding some tonstein horizons, in the Subvariscan Foredeep (Fig. 2.1d).

2.1.1.2 Mineral Deposits

Several Pb-Zn vein-type deposits perpendicular to the fold axes of the large anticlines crosscut the coal seams and are terminated by Cretaceous platform sediments resting upon an unconformity which truncates the Late Paleozoic sediments. Neither granitic mobilizates, nor pegmatites or aplites can be expected in this very-low grade metamorphosed to unmetamorphosed lithologies at the northwestern margin of the Central European Variscides.

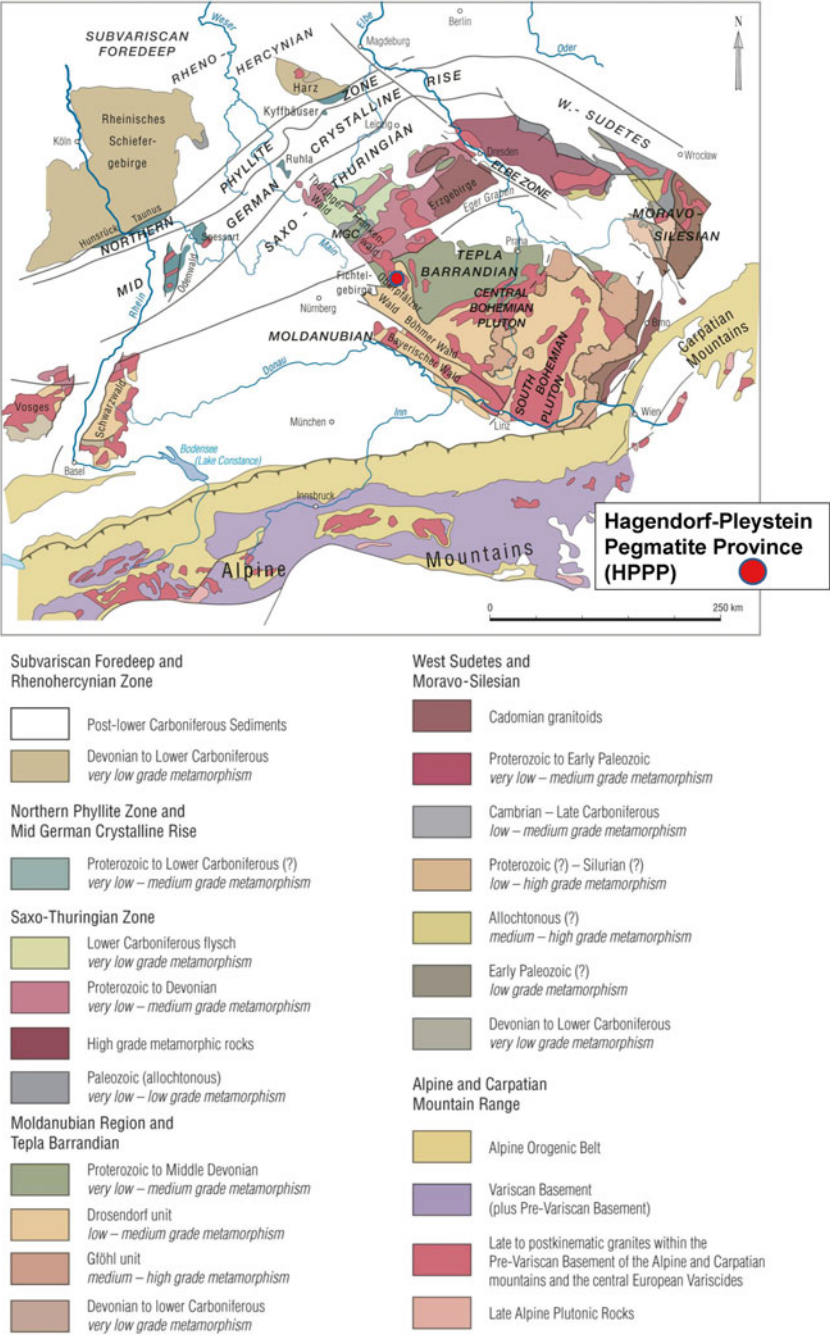


Fig. 2.1d The Hagendorf-Pleystein pegmatite Province the center of pegmatites among the geodynamic units and lithology of the Central European Variscides (Modified after Dallmeyer et al. 1995) and the Alpine-Carpathian Mountain ridges (Redrawn from Dill et al. 2008b) MGC Münchberg Gneiss Complex

2.1.2 *Rhenohercynian Zone*

2.1.2.1 Lithology and Structural Geology

The Rhenohercynian Zone follows immediately south of the Subvariscan Foredeep and forms the German low mountain ranges of the Rheinisches Schiefergebirge and the Harz, both of which are the source for the composite name Rhenohercynian used for this geodynamic zone (Fig. 2.1d). Towards the West, the clastic shelf sediments predominantly of Devonian age in the Ardennes, Belgium, Cornwall, Great Britain and the South Portuguese Zone, Portugal, pertain to the Rhenohercynian Zone (Franke 2000) (Fig. 2.1b). Basic submarine volcanic activity is widespread across this tectonostratigraphic unit, whereas felsic plutonic rocks are scarce. The seismic results of the DEKORP (Deutsches Kontinentales Reflexionsseismisches Programm=German Continental Seismic Reflection Program) indicate the presence of NW-vergent tectonics the effects of which can be traced down to the deepest parts of the crust (DEKORP Research Group 1990). Horizontal compression must have played a dominant role. The geodynamic position and geological results of the Rhenohercynian zones are controversially discussed and not unequivocal. The Rheic Ocean located between Avalonia and the American Terrane Assemblage was said to be closed, whereas the Saxo-Thuringian ocean was subducted to the S beneath the Teplá-Barrandian Zone during Early through Mid Devonian time (Winchester et al. 2002). This geodynamic zone is held to be a foreland fold-and thrust belt on a Devonian-Carboniferous passive margin (Oncken 1997). It developed from southward subduction and underthrusting underneath the Saxo-Thuringian Zone. The Northern Phyllite Zone stretching immediately south of the Rhenohercynian Zone contains relic of the Rheic suture zone of the former Rheic Ocean which persisted from the Early Ordovician through the Lower Devonian W. (McKerrow and Ziegler 1972; Linnemann et al. 2007). Weber (1978b) proposed a subfluence model which may be regarded as a plate tectonic model including the special features of an ensialic orogen. The superimposed uplift and tectonic shortening leads to horizontal overthrusts and nappe formation in places. Subfluence in the Rhenohercynian zone is interpreted in connection with the movement of larger lithospheric plates which transgress the limits of the Rhenohercynian zone and the Subvariscan Foredeep.

2.1.2.2 Mineral Deposits in the Rhenohercynian Zone

Many metallogenetic studies have been published by economic geologists on this geodynamic zone of the Variscides, highlighting prevalently the SEDEX or SMS-type mineralizations (“Rammelsberg-type”) during the syn-rift phase of the Rhenohercynian Basin, as metalliferous basin-dewatering brines conducted to these Pb-Zn-Cu-pyrite-barite deposits at Meggen, at Eisen, Lohrheim, in the Rohberg Mine near Wiesbaden and in the Hartz Mts. at Goslar and Elbingerode (more VMS)

(Werner and Walther 1995). The Lahn-Dill Fe deposits are another stratabound type of ore deposits closely related to the Devonian basic and keratophyric volcanic rocks (Bottke 1963). Apart from these stratabound deposits a variegated group of vein-type deposits developed synkinematically during the Variscan orogeny and postkinematically in its aftermaths, containing mainly Pb, Zn, Cu, Sb, Fe, Ag, and barite. The geodynamic and lithological settings were not favorable neither for the development of pegmatitic nor aplitic rocks, only deep-seated quartz veins formed along its southern margin and are still operated today near Usingen, Germany (Fig. 2.1e, f, g).

Quartz veins at Usingen are surrounded by Devonian slates and were emplaced during the Permian as a result of deep-seated lineamentary fault zones governing the circulation of hydrothermal fluids but without the mediating effect of felsic intrusive rocks which played a significant part at the same time further south within the Saxo-Thuringian and Moldanubian zones. The quartz veins formed near the SSE boundary of the Rheinisches Schiefergebirge and act as an intermediary between the ore-bearing vein-type deposits in the basement and the unconformity fault bound mineral veins in the platform sediments (Fig. 2.1d). To see how these vein-type deposits are related to the quartz bearing pegmatitic deposits geodynamically, the reader is referred to Fig. 2.2a. Among the domestic deposits relevant for the supply with industrial minerals, these high-purity quartz veins still play an important part. They are selectively worked so as to attain a grade of almost 100 wt% SiO_2 .



Fig. 2.1e Cross section through a massive quartz vein surrounded by Devonian slates and operated in an open pit near Usingen, Germany, for high-purity quartz

Fig. 2.1f Palisade quartz form the Usingen Quartz vein



2.1.3 Mid-German Crystalline Rise

2.1.3.1 Lithology and Structural Geology

The Mid German Crystalline High (Rise) does not show up geomorphologically as a coherent ridge, forming the central highland in Germany but is exposed only in isolated uplifted basement blocks, e.g., Odenwald, Spessart, Ruhla and Kyffhäuser massifs that are lined up in NE-SW direction and composed of metamorphic rocks very much different in their metamorphic grade which hits its peak with a series high-pressure eclogites and orthogneisses (Will and Schmädicke 2001) (Fig. 2.1d). It is often considered as part of the Saxo-Thuringian Zone, discussed subsequently, but in this study devoted to pegmatitic rocks it is treated as a separate entity for its rather different lithology and physical-chemical regime (Weber 1995). Lithologically the zone is characterized by a strong arc-related plutonism and Proterozoic (?) through Devonian medium to high grade metamorphic rocks (Anthes and Reischmann 1996). It is mainly late to post-kinematic felsic rocks of the granitic to dioritic suite that may be found in these isolated basement blocks. Detailed



Fig. 2.1g Open cavity fillings of quartz crystals (Bergkristall=rock crystals) in the Usingen quartz vein. See biro for scale

investigations about the lithology and geodynamic position have been performed by Will and Schmädicke (2001), Zeh et al. (2005), Zeh and Will (2010). The Cambrian to Ordovician rocks are metamorphosed attaining P-T conditions of the granulite-facies. Pre-Variscan granulites occur in the western Odenwald crystalline basement (Will et al. 2010). Medium-pressure metamorphic rocks formed during the Ordovician. The Silurian through early Devonian orthogneisses have calc-alkaline affinities. The Northern Phyllite Zone acting as the transition between the Rhenohercynian zone *sensu stricto* and the Mid German Crystalline High consists of low-grade stage regionally metamorphosed rocks of Ordovician through Devonian age.

The Mid-German Crystalline Rise forms part of a suture zone extending from Mexico to Turkey, resulting from the late Variscan closure of the Rheic Ocean opening up between Gondwana and Laurussia and taking a wide range of Paleozoic sediments sourced from Baltica and from Gondwana.

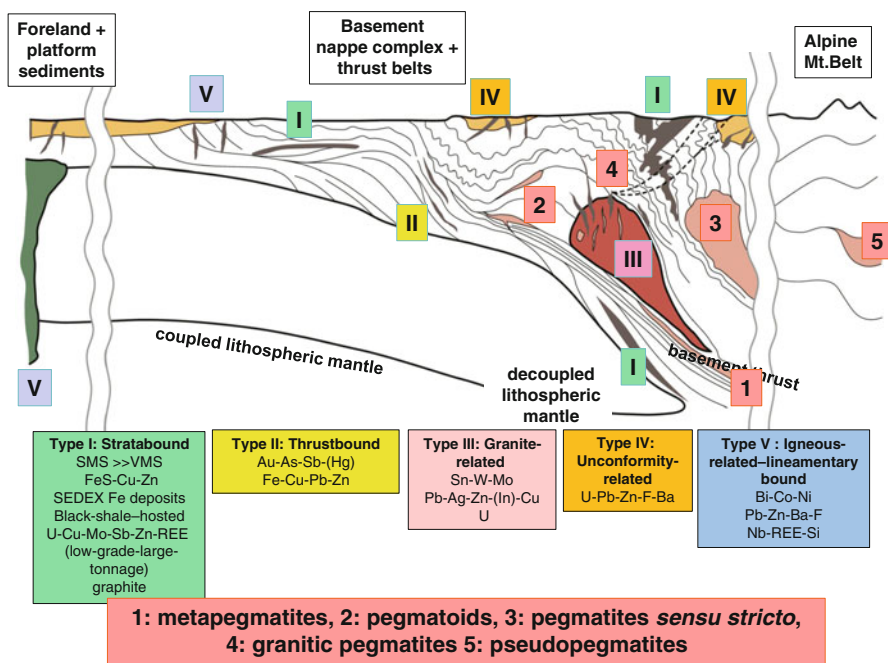


Fig. 2.2a An overview of mineral deposits typical of an ensialic orogen associated with pegmatitic rocks in time and space. As a consequence, non-pegmatitic mineral deposits are cast as marker deposits for pegmatite-prone or barren crustal sections and vice versa. *SMS* sedimentary massive sulfides deposits, *VMS* volcanic massive sulfide deposits, *SEDEX* sedimentary exhalative deposits

2.1.3.2 Mineral Deposits in the Mid-German Crystalline Rise

At the southern margin of the Rhenohercynian Zone, in the strongly metamorphosed Mid-German Crystalline Rise, pegmatitic mobilizates were mapped in the pre-Variscan gneisses of the Spessart Mts. as well as further SW, within the Odenwald Mts., where pegmatitic schlieren (pegmatoids) infiltrated magmatic rocks of granitic through gabbroic composition (Nickel and Fettel 1985). Compared with the pegmatitic rocks of the Bohemian Massif that form the gist of the matter in this book, the mineral assemblage of the Odenwald pegmatitic rocks is rather poor with quartz, feldspar and muscovite as the diagnostic rock-forming minerals and tourmaline and garnet forming only accessory minerals. Neither a temporal nor a spatial relationship can be established between felsic intrusive rocks and these alkaline mobilizates along the Mid-German Crystalline Rise. Pegmatoids developed in the environs of Aschaffenburg where a more elevated temperature provoked an intensive mobilization. The resultant pegmatitic schlieren contain quartz, K feldspar, plagioclase (albite-oligoclase), muscovite and biotite, arranged in order of decreasing abundance. Graphic intergrowth of feldspar and quartz is locally common, but rare elements typical of highly fractionated granitic pegmatites

are missing. Spessartite, magnetite and titaniferous magnetite formed instead. From the northern Kyffhäuser Crystalline Complex, only pegmatitic granites are known, yielding an K/Ar cooling age of 333 Ma (Neuroth 1997).

To get an impression, what a physical-chemical regime these pegmatites were faced with during their emplacement, the metamorphic conditions for the Odenwald Mts. are briefly depicted. In the Heppenheim Complex the metamorphic rocks experienced a P-T history of 8–9 kb at a temperature of around 580 °C, yielding maximum conditions of 650 °C at a more moderate pressure between 4 and 5 kb. (Willner et al. 1995). The retrograde pathway passed through the muscovite-quartz breakdown at 630 °C and about 3 kb. To allow for a better chronological correlation the minimum and maximum ages are reported for units I through III, yielding cooling ages for hornblende at 360 Ma (Kirsch et al. 1988) and concordant zircon ages of 335 Ma in migmatitic rocks (Todt 1979). An exceptionally high temperature of formation achieving 550 °C through 800 °C between 8 and 9 kb has reported by Willner et al. (1995). The age of formation span the range 380 Ma to 325 Ma (Kreuzer and Harre 1975; Todt 1979; Lippolt 1986). While the physical-chemical conditions are within the limits of what has been given for the Odenwald Mts., the age data of the Spessart are significantly younger with K/Ar and Ar/Ar mineral data ranging from 326 to 318 Ma (Lippolt 1986; Dombrowski et al. 1994).

With regard to the pegmatitic rocks, the Mid-German Crystalline Rise marks the passage from the barren zone into the zone of pegmatoids (Fig. 2.1c).

2.1.4 Saxo-Thuringian Zone

Lithology and structure of the Saxo-Thuringian Zone are representative of a Cambro-Ordovician rift basin separated from the afore-mentioned Mid-German Crystalline Rise by a south-facing reverse fault, which some geologists also call a strike-slip fault (Franke et al. 1995; Franke and Stein 2000; Linnemann 2003; Kroner and Hahn 2004). A great variety of sedimentary and volcanic rocks formed in this basin from the Precambrian through the Lower Carboniferous, when the Visean tectonic disturbances once and for all put an end to the basin development. In the south this geodynamic unit is bordered by Pre-Variscan basement blocks, stretching from the Vosges Mts., France, into the Bohemian Massif covered to a large extent by Czech Republic, which is eponymous to the Bohemian Massif (Fig. 2.1d). Separated by a pronounced NW-SE-striking Lineament named after the river Elbe (in Czech Labe) the Lugicum and the West Sudetes form the eastern prolongation of the Saxo-Thuringian Zone (Sect. 2.1.6.2). The crustal section of Saxo-Thuringian Zone in the Central European Variscides was named after Thüringen (Thuringia) and Sachsen (Saxonia), two German states which have a large share in this geodynamic real, the first one through the Thüringer Wald and the second one through the Erzgebirge, straddling the border with the Czech Republic where the Erzgebirge is called Krušné Hory in the Czech language. In the Free State of Bavaria

the Frankenwald, which is the southern prolongation of the Thüringer Wald is also attributed to this zone. Those who are accustomed to work in Precambrian terrains in ancient cratons where the lithology does not significantly vary over hundreds of kilometers may feel bewildered because of the variegated lithology in Central Europe and the great number of facies and site names, that sometimes change within a distance measuring only a few tens of kilometers.

2.1.4.1 Lithology and Structural Geology of the Fränkisch-Thüringisches Schiefergebirge

The Thuringian Facies in the Franconian-Thuringian Slate Mountains, or in German Fränkisch-Thüringisches Schiefergebirge, is composed of neritic clastic sediments of Cambrian through Ordovician age resting upon greywacke-dominated Proterozoic units (Falk et al. 1995) (Fig. 2.1c – see parautochthonous of the Saxo-Thuringian). The Silurian succession is dominated by black-shales and cherts and the younger sediments up to the Early Carboniferous encompass shales, calcareous rocks and turbidities (Wignall 1991). Volcanic rocks of bimodal character are known to occur during the Ordovician and late Devonian at a large extent in this geodynamic zone.

The Bavarian Facies is closely related tectonic units which have an allochthonous character at least in parts and may be found also further south near the heartland where the pegmatites crop out. Olistholiths and gravitational nappes are unique in this region made up of a wide range of rocks from shales, greywackes and tuffs of Ordovician and Cambrian age (Fig. 2.1c -see Bavarian Facies). The Silurian and Devonian units lithologically resemble largely those of the Thuringian Facies with cherts, black shales, calcareous and volcanic rocks. During the Tournasian and Viséan wild-flysch and mass flow deposits are common. The sedimentary rocks of the Bavarian Facies are a deeper-marine equivalent of the Thuringian Facies which was laid down originally further to the South-East and subsequently displaced towards the North-West by thrustal movements (Fig. 2.1c). The most striking example of tectonic mass movement in the Saxo-Thuringian Zone, the Münchberg Gneiss Complex can also make a significant contribution to the understanding of these feldspar-quartz mobilizates but prior to their discussion it needs a more detailed description as to the lithology and geodynamic setting of this tectonic klippen (Fig. 2.1c)

2.1.4.2 Lithology and Structural Geology of the Münchberg Gneiss Complex

Passing through the Münchberg Gneiss Complex from North to South by car along the “Autobahn” (motor highway) may provide the driver with an outline of the geomorphology that is anything but exciting. Neither eye-catching mountain ridges nor prominent bluffs or rock exposures are lined up along the route in this morphological depression between the deeply dissected plateau of the Frankenwald in the

North and the high-rising granitic domes of the Fichtelgebirge Anticline at its southern border (Fig. 2.1d). By contrast, the lithology and the structural geology of the Münchberg Gneiss Complex together with the other klippens at Wildenfels and Frankenberg both being located North-East of the Münchberg Gneiss Complex are far from dull and rather extraordinary from the petrographic point of view.

Recalling the regional metamorphism of the central Saxo-Thuringian Zone, the Early Carboniferous flysch sediments of the Bavarian Facies in the Frankenwald on top of the Berga Anticline are of low-grade stage to very low grade stage which is the case with most rocks of the Thuringian Facies of the in the remaining parts of the Saxo-Thuringian Zone. Heading further South-East and approaching the Münchberg Gneiss Complex, we will enter a succession with an increasingly higher metamorphic grade that has been overthrust by the Münchberg Gneiss Complex *sensu stricto* (Fig. 2.1c). The afore-mentioned succession is subdivided into the “Phyllit-Prasinit-Series” (phyllite-prasinite series [prasinite=fine-grained metabasalt bearing actinolite, chlorite, albite, epidote subjected green schist facies conditions]) and the “Rand-Amphibolit” (rim amphibolite) which contains minerals of the epidote-amphibolite facies and has been derived from a basic magmatic protolith (Fig. 2.1d – Paleozoic allochthonous of the Saxo-Thuringian Zone). Schüssler et al. (1986) found out that the mafic volcanic rocks exhibit a calc-alkaline affinity. Passing into the Münchberg Gneiss Complex *sensu stricto*, we are faced within this allochthonous synform with another dual subdivision into the so-called “Liegend-Serie” (footwall series) and the “Hangend-Serie” (hanging-wall series) (Fig. 2.1c). The “Liegend-Serie” is composed of meta-pelites and meta-greywackes, intercalated with orthogneisses/augengneisses and lenses of metagabbro and metagranodiorites. The orthogneiss yielded a Rb/Sr whole rock age of 499 ± 20 Ma (Söllner et al. 1981). U/Pb age dating using zircon and monazite from metagabbros and metagranites gave an age of intrusion around 500 Ma for both intrusive rocks (Gebauer and Grünenfelder 1979). Other than in the “Liegend-Serie”, in the “Hangend-Serie”, amphibolites, hornblende gneisses and eclogites prevail over metasedimentary rocks. The eclogites are of MORB affinity and the original basalt which they derived from were vented at 525 Ma based upon U/Pb zircon ages (Gebauer and Grünenfelder 1979). They derived from gabbros and tholeiites which underwent metamorphic pressure of 13 kb. The “Hangend-Serie” gave host to the albite-bearing pegmatoids which almost all are confined to the south-eastern part of the this allochthonous gneiss complex and bound to the hornblende gneisses (Figs. 1.5a and 2.1c). A rather strange type of pegmatoids, called zoisite pegmatite on account of its diagnostic accessory mineral, is closely-related to the eclogite and the eclogite amphibolite. Their emplacement and origin are discussed later in the book in context with the remaining felsic mobilizates from the Moldanubian Zone (Sect. 6.3)

Deformation and metamorphism of the Münchberg Gneiss Complex are of polyphase type. Both are treated in this paper only to the extent to understand the development of the pegmatoids and aploids in this allochthonous nappe complex.

An initial high- to medium-pressure regime was succeeded by a reequilibration when the entire nappe was thrust towards the Northwest. Metapelites formed under a physical-chemical regime of 8.2 kb and 607 ± 50 °C, while the eclogites saw

a pressure of 13 kb and a temperature of 600 °C (Blümel 1986). The HP metamorphism occurred during the Silurian. Cooling ages of 394 ± 14 Ma derived from a Rb/Sr isochrone and 395 Ma from a Sm/Nd isochrone refer to the Early Devonian (Stochs and Lugmair 1986, 1987). Kreuzer et al. (1989) provided K/Ar mineral ages for hornblende and mica in the range between 340 and 410 Ma. The large number of age date reported here for the various minerals point to a thrust movement between the Early Devonian and Early Carboniferous. As early as 1912, Suess postulated a nappe tectonic based on field geology which was only 70 years later proven by a painstaking investigation, involving geophysics, petrology, structural geology and geochemistry.

2.1.4.3 Lithology and Structural Geology of the Fichtelgebirge-Erzgebirge Anticline

The Fichtelgebirge-Erzgebirge Anticline strikes ENE–WSW and is characterized in the geophysical maps by a significant gravity minimum of less than 100 mgal that may be traced southward into the Moldanubian Zone, discussed in the following section (Behr et al. 1989). Several granitic complexes are accountable for this gravity low typical of the Fichtelgebirge-Erzgebirge Anticline. Two main intrusive complexes have been distinguished in the eastern part of this Variscan anticline, in the Erzgebirge (Tischendorf and Förster 1990; Sebastian 2013). The entire intrusive suite began with an older series, coded OIC and aged 330 through 310 Ma, that is of monzogranitic composition and of a mixed I/S type affiliation. Separated by a period of igneous quiescence, a younger series coded YIC followed with ages of intrusion in the range 305–290 Ma. It is mostly of I-type with some A-type affinities. These monzo- to syenogranites are strongly fractionated, in parts autometasomatically altered and enriched in Li and F (Tischendorf et al. 1987). Förster et al. (1999) put forward a chemical subdivision of the granitic intrusive rocks into (1) medium-F and low-P biotite granites (A-type), (2) high-F- and low -P lithium mica granites (A-type), (3) high-F- and high -P lithium mica granites (S-type), (4) low-F- two-mica granites (S/I-type). A peculiarity as to the chemical specialization in the Mid-European Variscides warrants mentioning; it is the abundance of Li mica- and topaz-bearing granites. Although very much different with respect to their chemical composition, the granites were emplaced in a small time window immediately after the collisional phase when the crust attained its maximum thickness of more than 60 km. A high-heat-producing process as a result of the radioactive decay within the time span of roughly 20 million years has been held accountable for the evolution of the late-collisional granites (Förster et al. 1999). The same authors envisioned as an additional heat source to generate these granites an intrusion or underplating of mafic magmas from the mantle (see also Sects. 5.1.1, 5.1.2, and 5.1.3). However, the first-mentioned process on its own is already sufficient to provide the heat necessary to create these granites.

In the western part of the anticline, geomorphologically termed Fichtelgebirge, the felsic intrusive rocks have some basic to intermediate predecessors, ranging in their chemical composition from gabbroic, through dioritic into granodioritic which were given the collective term “redwitzite” after the town of Marktredwitz located in the region (Richter and Stettner 1979). Their origin and emplacement is rather complex, and supposed to involve differentiation of a basaltic magma and/or mixing with a granitic melt (see also Sects. 5.1.1, 5.1.2, and 5.1.3).

Because of their outstanding part in terms of the origin, of what was denominated as “granitic pegmatites” in Table 1.1, the role they play among the magmatic evolution and their importance for the metallogenesis in the Saxo-Thuringian Zone, these granitic rocks deserve a particular treatment in a study like that. This is true especially in the western part of the anticline where their emplacement overlaps with that of pegmatites and aplites and on account of the cross border extension of these granites into the southern Moldanubian Zone which suggests a common process to have been responsible for their evolution in both geodynamic zones. Chemical composition and petrological description of these granites are based upon the study conducted by Richter and Stettner (1979) (Table 2.1). Similar to the equivalent intrusive rocks further NE, in the Fichtelgebirge also two intrusive suites can be distinguished. An older group of granites is coded G 1 and occurs together with its differentiates around Weißenstadt, Marktleuthen, Reuth and Selb. An account of its central position within the Fichtelgebirge Anticline it was named Central Granite. The Central Granite complex is prevalently made up of monzogranites grading towards the edge into what might be categorized as a granodiorite or taken to the extreme in its most basic facies as a diorite, when its chemically data points overlap with the felsic end members of the redwitzites. The older granites which are correlative to the OIC granites of the Erzgebirge formed throughout multiple intrusions between 330 Ma and 315 Ma (Lenz 1986; Carl and Wendt 1993). The oldest granite shows a porphyritic texture in a coarse groundmass and takes an overall tabular shape, dipping gently towards the south. Based upon its almost identical cooling ages of mica its magma consolidation was very fast around 319 ± 3 Ma.

The remaining granites G 2 (Marginal Granite), G 3 (Core Granite) and G 4 (Tin Granite) have been placed in order of their intrusion on geological grounds. Using radiometric age dating, however, does not allow a precise age of formation to be attributed to the individual granite bodies and proves these granite intrusions to be more or less coeval in the range 301–295 Ma. The G-2 granite is a fine-grained porphyritic monzogranite. Its texture attests to an intrusion of the granitic magma in an environment unbalanced as to the temperature. Approximately 20 million years after the intrusion of the G 1, the temperature had significantly dropped.

The coarse-grained G-3 granite is a syenogranite, whereas the youngest member of this series of granite straddles the boundary into monzogranite. The latter is a fine-grained granite that already by its name reveals a strong chemical fractionation leading to U and Sn mineral assemblages. While the granite-hosted uranium mineralization was only investigated by underground trial mining operations, the

Table 2.1 Chemical composition of the four major granite types in the Fichtelgebirge

Site	Unit	Granite G 1	Granite G 2	Granite G 3	Granite G 4
SiO ₂	wt%	67.9	74.2	75.5	74.80
TiO ₂	wt%	0.68	0.23	0.17	0.05
Al ₂ O ₃	wt%	15.00	13.40	13.00	14.10
Fe ₂ O ₃	wt%	0.74	0.32	0.23	0.10
FeO	wt%	2.90	1.60	1.50	1.20
MnO	wt%	0.06	0.04	0.03	0.03
MgO	wt%	1.22	0.30	0.21	0.06
CaO	wt%	2.30	0.75	0.57	0.37
Na ₂ O	wt%	3.30	3.00	3.00	3.70
K ₂ O	wt%	4.52	5.25	5.00	4.74
P ₂ O ₅	wt%	0.32	0.21	0.19	0.24
H ₂ O/LOI	wt%	0.80	0.60	0.50	0.30
Li	ppm	60	129	153	306
Be	ppm	4.6	7.7	9.9	17.6
B	ppm	2	2	2	17
F	ppm	602	1665	1243	2315
S	ppm	166	69	74	50≤
Cl	ppm	76	96	88	67
Sc	ppm	13	5	4	3
V	ppm	61	12	7	≤3
Cr	ppm	11	9	6	6
Ni	ppm	4	5	4	4
Cu	ppm	7	3	6	4
Zn	ppm	62	44	43	43
Ga	ppm	20	22	21	41
Rb	ppm	211	404	427	805
Sr	ppm	251	44	29	5
Y	ppm	18	26	25	14
Zr	ppm	267	112	80	25
Nb	ppm	15	12	11	15
Mo	ppm	≤2	2	2	2
Sn	ppm	8	12	15	24
Cs	ppm	9	24	33	59
Ba	ppm	930	283	129	13
La	ppm	73	46	33	39
Ce	ppm	99	56	29	22
Pb	ppm	35	31	34	19
Th	ppm	34	21	12	7
U	ppm	4	6	10	17



Fig. 2.3a Tin Granite (Granite No 4), the most strongly fractionated granite shown in its normal or un-mineralized facies. Kugler Quarry near Tröstau, Fichtelgebirge-Germany. Lens-protection for scale

abundance of cassiterite, present mainly as greisen-type or in alluvial-fluvial placer deposits in the clastic apron around the G 4, also sparked some mining operation in the past (Fig. 2.3a, b, c).

The peraluminous granites are of intracrustal and comagmatic origin based upon their trace element differentiation (Richter and Stettner 1979) and $^{87}\text{Sr}/^{86}\text{Sr}$ isotope ratios (Besang et al. 1976; Wendt et al. 1986). The granite suite reveals a textbook-style fractionation with a steady increase of elements such as Li, Be, Sn, Cs, and U with time (Table 2.1). The younger granites G 2 through G 4 can thus be grouped among the so-called fertile granites as to the elements Li, Be, Sn, W, U, and Nb. As to the P/T regime, the G 1 granite in the area of Weißenstadt and Marktleuthen formed around 660 °C at a pressure of 7 kb to be equal to a depth of between 20 and 25 km (Richter and Stettner 1979). The granite at Selb, belonging to the same intrusive stage formed at a depth of 7 km, equivalent to 2 kb and at a temperature of between 700 and 720 °C. The older granite has been derived from a migmatitic shear zone penetrating the upper crust at the afore-mentioned depth.

Applying the same parameters of the albite-anorthite ratios to the younger suite of granites yielded a pressure of between 0.5 and 2 kb which equals to a depth of formation of between 2 and 7 km at a temperature of 650–700 °C. The temperature can only be approximated owing to the abundance of fluorine in the range 1665–2370 ppm F which has a lowering affect on the temperature of formation. The younger granites in the Saxo-Thuringian Zone came into existence when the Asturian Orogeny deformed the sediments in the westernmost part of the Rhenohercynian Zone (Fig. 2.1c, d). The



Fig. 2.3b Tin Granite (Granite No 4). Specimen has been taken from the mineralized facies or greisen facies with cassiterite (*black*) and corroded arsenopyrite. Rudolfstein, Fichtelgebirge-Germany



Fig. 2.3c Tailings dumped in the softwood-tree forests around the Tin Granite. The dumps are relics of the mining operations targeting upon the cassiterite placers in the clastic apron around the Granite No 4

abnormally high rare element contents of, e.g., Sn and U may have derived from remobilization of Carboniferous and Devonian sediments. A preferred orientation of phenocrysts frequently observed in the younger granites may be interpreted as representative or a relic of the pre-existing cleavage and stratification in the surrounding country rocks. Metasomatic processes are more likely to have been caused these texture than a mechanically intrusive emplacement which might lead to flow banding in the magma similar in its outward appearance to such alignments of minerals. Willner et al. (1995) made an attempt to account for the complex geodynamic evolution of the Fichtelgebirge-Erzgebirge Anticline and put forward a four-step model involving (1) oceanic crust to be subducted and converted under eclogite-grade conditions, (2) continent-continent collision and thickening of the crust, (3) attenuation of the thickened crust with simultaneous and continuous under thrusting of continental crust, (4) exhumation of the existing stacked crustal section in the course of another thinning.

The Paleozoic country rocks of the Fichtelgebirge granites not only form part of the Saxo-Thuringian but also an integral part of the LP-metamorphic zone characteristic for the western edge of the Bohemian Massif (Stein 1988). It is the low-grade equivalent of the LP unit being present also further south.

2.1.4.4 Mineral Deposits

From the Cambrian through the upper Devonian a wide range of stratabound ore deposits evolved in the autochthonous part of the Saxo-Thuringian Zone (Baumann 1979; Baumann et al. 2000; Bernard 1980; Dill 1989; Pertold et al. 1994; Tischendorf et al. 1995b)- see also Fig. 2.2a. During the early Paleozoic several massive sulfide deposits evolved and were mined on both sides of the Czech-German border. They are abundant in pyrite and pyrrhotite with little Zn and Cu. During the early phases of rifting submarine hydrothermal fluids gave rise to these polymetallic deposits such as at Waldsassen in Germany and Tisova in the Czech Republic. The ironstone deposits of the Thuringite-/Wabana-Type have been reported from different parts of the world throughout the Ordovician, among others from the Saxo-Thuringian Zone of the Middle European Variscides (Van Houten and Hou 1990). The oolitic Fe ores, containing siderite, thuringite, chamosite and magnetite were formed during transgressions in a shallow-marine environment (Thuringian Facies). Similar to the afore-mentioned ironstones of worldwide occurrence, the Silurian and Lower Devonian alum shales of the Lower and Upper Graptolite Shales have also a share in the Saxo-Thuringian metallogenesis, yet only as low-grade-large tonnage deposits enriched in U, Au, Mo, Cu, Sb, Zn and REE. Passing vertically upward in the stratigraphic column, the exhalative magnetite-hematite iron ore deposits in the Saxo-Thuringian Zone show mineralogically and geological similarities to the Lahn-Dill deposits from the Rhenohercynian Zone where these iron deposits are

closely linked in time and space to the metabasalts (diabase) and keratophyres vented on the sea floor.

Another group of deposits common to both geodynamic zones, the Rhenohercynian and the Saxo-Thuringian Zones, are denominated as metamorphogenic, thrust bound and fold-related cleavage veins that are common to during the Devonian and Early Carboniferous. Activation of the continental margin of the Mid-German Crystalline Rise resulted in the initiation of southward subduction during which Rhenohercynian and Saxo-Thuringian crust was consumed. Without any doubt, these synkinematic fault-related deposits are more widespread in the Rhenohercynian than the Saxo-Thuringian zone, where only some mesothermal gold, mercury and antimony vein-type deposits along the Schwarzburg-, Berga and Fichtelgebirge-Erzgebirge Anticlines may be attributed to this stage of the Variscan metallogenesis. In the northwestern geodynamic zone, structurally equivalent vein-type deposits can be subdivided into two major groups, Ag-enriched Pb-Zn vein-type deposits and siderite-Cu-Pb-Zn vein-type deposits named as Siegerland-Type (Werner and Walther 1995; Wagner and Boyce 2001, 2003). Hein (1993) suggested that the Siegerland siderite veins, which extend down to a depth of 1000 m, formed from low salinity CO₂-undersaturated fluids at temperatures between 180 and 320 °C following the peak of metamorphism and prior to the postkinematic magmatism.

Postkinematic magmatism which is intensive in the Saxo-Thuringian zone marks the late stages of Variscan convergence in mid-to late Carboniferous times resulting in the emplacement of abundant synorogenic granites and genetically related Sn-, W-, Pb-, Zn-, and U deposits (Seltmann and Faragher 1994; Štemprok and Seltmann 1994; Henk et al. 2000). The highly fractionated S- and I-type granites are the most likely source for the fluids to create these mineralizations, present as vein-type, greisen and skarn deposits in the Erzgebirge Mts. Particular attention should be drawn to the Poehla-Haemmerlein deposit at Gottesberg, Germany, which is a large, low-grade, refractory tin skarn with its reserves standing at 12.3 Mt @ 0.42 % Sn (Buder et al. 1993). Wolframite occurs in quartz veins (Krásno, Czech Republic, Ehrenfriedersdorf, Germany, Altenberg, Germany, Zinnwald-Cínovec, Germany/Czech Republic), Pechtelsgrün, Germany. In the Altenberg Sn deposit, Germany, the missing link between the true pegmatite bodies and the granites exists. The afore-mentioned Sn deposit is characterized as “greisen” and “stockscheider”, both technical terms coined by the ancient miners in search of Sn. Greisen may be described as a pervasively altered lithium-albite granite in which feldspar and biotite are converted to a disseminated assemblage of quartz, topaz, muscovite, zinnwaldite and protolithionite (both Li-micas), cassiterite, sericite, fluorite, dickite, kaolinite, wolframite and scheelite. Stockscheider is an altered granite of pegmatitic texture abundant in topaz (pyknite), zinnwaldite, and quartz with cassiterite, wolframite, and molybdenite as the main ore minerals (Baumann et al. 1986). Both terms describe alteration zones within the host granite caused by the fluids that were concen-

trated in the apical parts of the granites during their consolidation. In the classical German literature these peculiar alteration zones were classified as “pegmatitic-pneumatolitic” alteration, a term which has become a bit obsolete in present-day literature and rather replaced by supercritical with some description of the mineralizing processes in more detail. Although occurring in an environment strongly enriched in highly volatile chemical compounds no individual pegmatite bodies resembling those from the core zone of the Central European Variscides have been encountered in the Erzgebirge. Host structures are mainly druses and cavities in the felsic intrusive rocks filled with pegmatite-type minerals, present on a collector’s rather than on a miner’s scale. Quite the same scenario may be reported from the Fichtelgebirge in the western part of the anticline. The so-called “pegmatitic-pneumatolitic” mineral assemblages mainly with schorl as diagnostic mineral may be observed in the apical parts of the G-3- and G-4 granite of the younger suite. They did neither spawn large individual pegmatitic bodies that were self –intrusive into the surrounding country rocks nor did they give rise to aplitic veinlets as it is the case with the older granite G-1, the “Central Granite”. The south-eastward dip of the tabular granite is marked by swarm of aplitic and pegmatitic veins in the roof of the Central Granite. Richter and Stettner (1979) reported aplite granites and aplitic through pegmatitic veins prevalently from those areas where meta-carbonates and calcsilicate rocks make up a great deal of the metamorphic country rocks. Aplitic veins prevailing over pegmatitic veins intersect not only meta-carbonate and calcsilicate rocks but also mica schists. Far away from the variegated mineral assemblage which we will see later in the pegmatites located farther south, these fault-related aplites and pegmatites in the vicinity of the G-1 granite have only a poor assemblage of schorl and beryl together with some apatite and sphene.

The majority of minerals which are listed in Table 1.2 for this zone is bound to druses and miaroles. Although well endowed with ample supplies and a variety of metallic, non-metallic and energy deposits, mining has peaked in the Erzgebirge-Fichtelgebirge Anticline on account of a long-lasting mining activity mainly focused on Sn, W, U, Pb, Zn and Ag. Only those commodities which our ancestors exempted from their mining operations, because they had no use for them, such as fluorite and barite are still worked from vein-type deposits at Niederschlag near Bärenstein. When the European countries realized their dependency on a few supply countries outside Europe, particularly in raw materials for future technologies such as lithium and indium, but also more traditional ones, e.g., tin and tungsten, mining companies mainly from outside Germany revisited this crustal section of the Central European Variscides and started drill on sites well known for ages for its Sn-W accumulations such as Geyer-Ehrenfriedersdorf and Gottesberg, in the western Erzgebirge (Dill et al. 2008a). As these deposits do no longer play in the champions league of extractive geology or called deposits by world standards neither as to size nor as to grade, their fate hangs by a silk thread in terms of exploration and exploitation. As being viewed realistically, a glimpse of hope is there but anything else.

2.1.5 The Moldanubian Zone

2.1.5.1 Lithology and Structural Geology

The rivers Moldau (Vltava in Czech) and Donau (Danube) drain the southern part of the Bohemian Massif and, logically sound and comprehensible for the audience, they lend their names to designate the central geodynamic or core zone of the Mid-European Variscides, the Moldanubian Zone. The southern half of the Bohemian Massif, which is identical to this geodynamic zone, includes two tectonostratigraphic units, one called the Moldanubicum *sensu stricto*, the other allochthonous unit is named the Teplá-Barrandian zone or Bohemicum (Malkovsky 1979; Tollmann 1982; Weber and Behr 1983). An overview of this geodynamic zone has been given by Franke (2000), Matte (2001) and Raumer et al. (2003). The Moldanubian zone represents a stacked pattern of nappes which were superimposed onto each other during the late Variscan (Fig. 2.1c, d).

The southern part of the Oberpfälzer Wald, Bayerischer and Böhmer Wald (Český les in Czech) are underlain by clastic and magmatic rocks in the Moldanubicum s.s., which were converted into high-grade gneisses granulites and orthogneisses, summarized under the lithostratigraphic term “Monotonous Group” or Ostrong unit. It is the lowermost part of the Moldanubicum *sensu stricto*.

In contrast to these lithologies, the “Varied Group” or Drosendorf unit consists of Proterozoic and early Paleozoic meta-greywackes, metapelites, marbles, calcsilicates, quartzites and graphite schists which reflect rather mobile dynamic processes in the original environment of deposition, an impression strengthened by the great variety of metabasic igneous rocks intercalated into these sedimentary rocks. In the map presented by Mazur et al. (2005), the majority of the Drosendorf encompass the Moldanubian zone.

The Drosendorf units was thrust over onto the Gföhl unit which was metamorphosed under amphibolite and granulite facies conditions. Its HP granulites are accompanied by pyrope- and spinel-bearing peridotites, pyroxenites, eclogites, migmatites, as well as orthogneisses and paragneisses (Fuchs and Matura 1976; Tollmann 1982). The source rocks were both sedimentary and igneous in origin. The protolith of the Gföhl Gneiss was an Ordovician granitic rock.

First records of detrital material in paragneisses on zircons showed an event around 2600–2400 Ma (Hansen et al. 1989). Metafelsic and metabasic igneous rocks yielded SHRIMP age of 555 ± 12 Ma, 549 ± 7 Ma and 549 ± 6 Ma (Teipel et al. 2002). Another event that brought about felsic metamagmatic rocks occurred at the Cambrian-Ordovician boundary, based on SHRIMP ages of 486 ± 7 Ma and 480 ± 6 Ma (Teipel et al. 2002). There is an indistinct sign referring to a medium-pressure metamorphic event at about 380 Ma (Hansen et al. 1989). A strong low-pressure-high-temperature regional metamorphic event about 320 Ma overprinted inherited metamorphic material (Hansen et al. 1989). A lower intercept age of 530 Ma can be recognized. The major metamorphic events include HT-LP (periplutonic) regional metamorphism with cordierite and andalusite ensued by the late Variscan felsic intrusions.

The Teplá-Barrandian zone is composed of volcano-sedimentary sequences affected by synsedimentary faulting and continental clastic rocks laid down in grabens subsequently to the Cadomian subduction and collision (Dallmeyer and Urban 1998; Zulauf et al. 1999; Dörr et al. 2002). Typical of the Teplá-Barrandian zone and its analogue in NE Bavarian Basement, the Zone of Erbendorf-Vohenstrauß (ZEV), their metamorphosed mafic igneous rocks revealed chemical affinities to suboceanic mantle, ocean-ridge, calc-alkaline and within-plate settings (Kastl and Tonika 1984; Schüssler et al. 1986; Jakes and Waldhauserova 1987). Similar to the Moldanubian s.s. the first zircon ages can be recorded from the interval 2500 Ma through 2400 Ma. Rubidium-strontium age dating of paragneisses from the ZEV were dated as Lower Cambrian (530 Ma) (Weger et al. 1998). A more detailed picture has been drawn by Drost et al. (2004) who claimed the Teplá-Barrandian unit to be part of the Avalonian-Cadomian belt at the northern margin of Gondwana during Proterozoic and Early Cambrian times- see also Fig. 2.1a. Its volcano-sedimentary series developed in a back-arc basin. Around 2500 m of Lower Cambrian continental siliciclastics were deposited in a basin-and-range-type setting accompanied by magmatism, which shows within-plate features in a few cases, but is predominantly derived from anatectic melts. The geochemistry of clastic sediments suggests a deposition in a rift or strike-slip-related basin, respectively. Upper Cambrian magmatism is represented by 1500 m of subaerial andesites and rhyolites demonstrating geochemical characteristics of an intra-plate setting. Zircons from a rhyolite give a U-Pb-SHRIMP age of 499 ± 4 Ma (Drost et al. 2004).

Metamorphic monazite from the Teplá-Barrandian zone indicated a Barrovian-type isograd in the Domažlice Crystalline Complex around 551–540 Ma (Zulauf et al. 1999; Timmermann et al. 2002). A magmatic event can be identified in the rock record between 530 and 460 Ma. The climax of metamorphic overprinting was reached around 390 Ma under medium-pressure conditions, with a rapid cooling until 360 Ma (Hansen et al. 1989). The final nappe emplacement took place around 330 Ma.

According to Holub et al. (1995) magmatic rocks of granitic composition in the Moldanubian zone may be attributed to the South Bohemian and Central Bohemian Plutonic Complexes with some of their satellite batholiths being also exposed along the western edge of the Bohemian Massif, in the NE Bavarian Crystalline Basement. As in this part the interrelationship between granites and pegmatitic rocks is crucial for the understanding of the origin of the latter felsic rocks they will be discussed later in more detail and only a general overview will be given in this chapter. The granitic rocks are subdivided into three successive suites each being directly correlated with the evolution of the Variscan Orogen in this geodynamic unit. During the early Carboniferous, synorogenic granitic rocks evolved as the Variscan orogeny went through its thermal climax around 350 through 335 Ma. The older suite of the synorogenic granitic rocks of the

South Bohemian Pluton developed during this period of time, starting off with minor gabbros, diorites and quartz monzonites and ending with the large coarse-grained Weinsberg Granite (Koller 1996). Today this suite of granitic rocks has a representative in the “Kristallgranite I”, as it is denominated in SE Germany (crystal granite I) by regional geologist. It is a coarse-grained biotite granite to granodiorite of I and I/S affiliation rife with mega crystals of K feldspar, that account for its regional name “Kristallgranite I” (crystal granite I). The subsequent suite of granite formed between 329 ± 7 Ma and 303 ± 6 Ma. The oldest intrusions of this suite of the South Bohemian Pluton in Germany may be traced into neighboring Austria where among others the Eisgarn (318 ± 7) and Mauthausen Granites are held to be contemporaneous with them (Scharbert and Vesela 1990). They are classified as slightly deformed S- and I-type granites. The youngest representatives of this group yielded Ar/Ar muscovite ages of between 312 and 308 Ma (Dallmeyer et al. 1995b). It is a suite of very shallow intrusions which very rapidly cooled down to less than 400 °C.

The third suite was emplaced between 300 ± 41 Ma and 295 ± 5 Ma (Holub et al. 1995). It is a group of anorogenic granites related to an extensional regime. Pegmatites and aplites are very rare, excluding the extraordinary phosphorus Homolka granite (Breiter 1998c).

More prominent than the South Bohemian Pluton in size and outstanding for its chemical variation, the Central Bohemian Pluton covers about 3200 km² and extends along the Central Bohemian Suture in NE-SW direction along the contact between the Tepla Barrandian and the Moldanubian *sensu stricto* (Kodym 1966). It shows the full blown succession of plutonic rocks with gabbros at the beginning and granites at the end. A peculiar type, in many places related to pegmatite is called durbachite, what is synonymous with potassium-enriched melanocratic syenites (Holub 1997). Numerous age data obtained by Pb/Pb single-grain dating of zircon and field evidence attest to a late Devonian to early Carboniferous age of formation of the Central Bohemian Pluton (Janoušek et al. 1995; Holub et al. 1997): Sázava (349 ± 12 Ma), Požáry (351 ± 11 Ma), Blatná (346 ± 10 Ma), Čertovo břemeno (343 ± 6 Ma). According to Janoušek et al. (1995) the Sázava unit is the most primitive one. It is supposed to be generated either by melting of metabasic igneous rocks as they were found as roof pendants on the Central Bohemian Pluton, by partial melting of mantle material or magma mixing, involving both source mentioned before. The remaining intrusive units give a similar very diverse picture as far as the source and magma generating processes are concerned, invoking mantle material being contaminated with crustal material from paragneisses (Blatná unit), or leucogranites, e.g. at Čertovo břemeno.

A comparison of the characteristic features of the Teplá-Barrandian and Moldanubian terranes, as they were called by Mazur et al. (2005) is given below since both terranes are host to a wide variety of pegmatitic rocks, yet very unevenly distributed across the Moldanubian Zone.

	Teplá-Barrandian terrane	Moldanubian terrane
sedimentation	Neoproterozoic and Early Palaeozoic to Middle Devonian	Proterozoic and poorly constrained Early Palaeozoic; in the Orlica-Šnieżnik unit — pre-Ordovician
plutonism	Cambrian; Carboniferous at the contact with Moldanubian terrane	Ordovician, Carboniferous
metamorphic age	close to the Proterozoic/Cambrian boundary, Early Carboniferous overprint at the contact with the Moldanubian terrane	intense Early Carboniferous HT/M-LP overprint
HP metamorphism	lacking	bodies of eclogites and granulites ranging in age from 360 to 330 Ma
metamorphic grade	low-grade to unmetamorphosed	medium- to high-grade
uplift/exhumation	Late Devonian	Early Carboniferous

2.1.5.2 Mineral Deposits

Evidently, not only the lithology but also the metallogenic evolution in the Moldanubian Zone is very much diverse, giving rise to a large number of stratabound and vein-type ore deposits besides the common granite-related and pegmatite deposits (Dill et al. 2008a). Volcanic-hosted massive sulfides, sedimentary massive sulfides and kieselager-type ore deposits were mined in the past and investigated in great detail by Czech and German geoscientists on both sides of the border.

Silver-, lead-, zinc and copper accumulations in the Příbram ore district, Czech Republic, were also attributed to the thrust-bound and fold-related metamorphogenic ore mineralization (Dill et al. 2008a). Several base metal veins were emplaced around the Central Bohemian Pluton where underground mines reached an operational

depth of more than 1500 m. The ore veins are feather structures accompanied by diabase dykes of similar shape (Pouba and Ilavský 1986). Important Ag carriers besides galena in this deposit are pyrargyrite, stephanite and diaphorite.

Several studies have been published by Boiron et al. (2001), Zachariáš and Stein (2001), Zachariáš and Pudilová (2002) about the gold deposits located in paragneisses and migmatites with intercalated quartzites, calc-silicate rocks, felsic volcanic rocks, amphibolites, and marbles of the Central Bohemian Metallogenetic Zone. The majority of these gold deposits is low in sulfur, enriched in siliceous gangue and shows a prevalence of metamorphic aqueous low-salinity fluids. The fluids belong to a fluid system enriched in C, N, O and H and probably resulted from fluid–rock interactions within the metamorphic series at high P–T conditions ($T \approx 450\text{--}550\text{ }^{\circ}\text{C}$ and $P \approx 250\text{--}400\text{ MPa}$) (Boiron et al. 2001). The Mokrsko deposit, Czech Republic, is one of the largest Au resources in Central Europe.

For the central part of the Bohemian Massif, Mrázek (1986) compiled the mineral deposits pertaining to the Late Proterozoic metallogeny and related them to volcanic and post-volcanic thermal activity. Pyrite and pyrrhotite mineralization with subordinate amounts of Cu and Zn sulfides occur in low-grade regionally metamorphosed basic and intermediate metavolcanic rocks. Representatives of this type of ore deposits are located near Struhadlo/Klatovy, Czech Republic, at the SW edge of the Teplá-Barrandian Zone, where Fe sulfide-Cu-Zn deposits are held equivalent to the modern Cyprus-type ore deposits, and in the Jílové Belt, where Cu-Zn sulfide mineralization occurs in basic and acidic metavolcanites near the boundary between the Teplá-Barrandian and Moldanubian *sensu stricto*, closely resembling those mineralizations known from the Achaean greenstone belts (Morávek and Pouba 1990). A unique lithological series silicites bearing uranium and vanadium in amounts of up to 0.2 wt% and with Fe contents attaining as much as 35 wt% cover large areas in the southeastern and western parts of the Teplá-Barrandian Zone (Mrázek and Pouba 1995). In terms of geochemistry and geodynamic setting, this stratabound mineralization is similar to the Siluro-Devonian black shale mineralization in the Graptolite Shales elsewhere in Central Europe. The role of organic material in the formation of these metal-rich shales in the late Precambrian Bohemian Massif has been noted by Pašava et al. (1996).

Along the south-western part of the Moldanubian *sensu stricto*, the Lam-Bodenmais Kieslager Belt extends from the Northwest through the Southeast, parallel to the shear zone of the “Pfahl” (“Great Bavarian Quartz Lode”) and runs through the middle of the area hosting the majority of pegmatites of the Bayerischer-Böhmer Wald, which were mined for feldspar and quartz for several decades (Dill 1985a). The afore-mentioned sediment-hosted Fe-Zn-Cu-Pb sulfides located in the Drosendorf Unit show a zonation into a proximal Fe-Zn-Cu association with Fe-enriched sphalerite, argentiferous galena, pyrite and pyrrhotite and a distal Pb-Ba mineralization. Elevated barium contents were found genetically associated with these massive sulfide deposits and their Pb and S isotopes are well in accordance with those sediment-hosted deposits classified as Sullivan-type/Meggen-type deposits *sensu* Jiang et al. (1998) and Taylor and Beaudoin (2000).

Sedimentation, diagenesis and thermal activity contributed very much to the concentration of metals in this stratabound ore deposits throughout the Late Proterozoic, but these processes tell us little about the evolution of physical-chemical regime in the immediate surroundings and as such they are of minor relevance for the emplacement of adjacent pegmatites. Argentiferous galena and the pyrite-pyrrhotite association agree well with the maximum temperature of 700 °C achieved at the climax of low-pressure regional metamorphism (Dill 1990). The variation of the activity a_{FeS} in pyrite coexisting with sphalerite was determined to be between 15.8 and 16.5 mol% and used to calculate $\log a_{\text{S}_2}$ as 1.27 and $\log a_{\text{O}_2}$ as 14.2 for the metamorphic country rocks pierced by the granites and pegmatites in the period of time from 340 through 280 Ma. After the heyday of metamorphism was hit the sulfur fugacity decreased whereas the salinity of mineralizing fluids increased. Silver-bearing tetrahedrite, zincian spinel and the study of fluid inclusion are appropriated tools to the temperature path of the retrograde metamorphism. Quartz mobilization became very widespread during temperature drop. Along with desulfurization, at about 410 °C zincian spinel appeared and around 390 °C quartz mobilization began. The physical-chemical regime observed in the retrograde pathway displays many similarities with that reported from the vein-type gold deposits of the Central Bohemian Metallogenetic zone mentioned earlier in this chapter.

The Czech part of the Moldanubian zone, that is synonymous with the core of the Moldanubian Bohemian Massif and dominated by the two large igneous complexes of the Central and South Bohemian Plutons, deserves a special treatment on account of its numerous pegmatites which have been mined for feldspar for decades but now almost all have been closed. Although of subeconomic grade, considerable amounts of rare elements were determined in these mineralogically and structurally very much different pegmatites resultant in a wealth of uncommon minerals which render these felsic rocks highly attractive for mineral collectors and mineralogists and economic geologists to conduct genetic investigations (Novák 2005). Given the large outcrops of the Central and South Bohemian Plutons in the Moldanubian Zone, the pegmatitic rocks' preference of metamorphic host rocks to granitic host rocks comes as an unexpected surprise: Třebíč Pluton at Oslavice near Velké Meziříčí resides in syenogranite "durbachite" (shoshonitic association) and gneisses (Škoda et al. 2006; Škoda and Novák 2007; Novák et al. 1999), the Horní Bory pegmatite near Velké Meziříčí in granulites, cordierite migmatites, biotite-sillimanite migmatitic gneisses (Povondra et al. 1992; Novák et al. 1992), the Příbyslavice pegmatite near Čáslav in orthogneiss and two-mica and biotite paragneisses (Němec 1973, 1978; Čech et al. 1978; Prachař et al. 1983; Povondra et al. 1987, 1998), The pegmatite at Vlastějovice near Zruč nad Sázavou has Fe-skarns as host rocks besides the common migmatized biotite-sillimanite gneisses amphibolite, pyroxene gneiss, quartzite, marbles, two- mica and tourmaline-bearing orthogneisses (Novák and Hyršl 1992; Žáček et al. 2003; Ackerman et al. 2007). Some of them are also emplaced within serpentinized lherzolite such as the Věžná I pegmatite and the pegmatite at Ruda nad Moravou (Novák and Gadas 2010; Dosbaba and Novák 2012). The pegmatite dikes Bližná I cut through calcite-dolomite marble, while its neighbor Bližná II intersects graphite-bearing biotite (Novák et al. 1999b, 2012).

Almost each district mineralized with pegmatites shows its peculiar host rock lithology. Metapegmatites have been recorded from Maršškov I and III by Černý et al. (1992).

Lithium-bearing pegmatites make up a great deal of the pegmatites, mainly scattered in the southern part of the Moldanubian zone *sensu stricto* (Novák 2005). It is prevalently lepidolite-bearing pegmatites which prevail over elbaite-bearing ones in that region (Novák and Povondra 1995). Moreover other Li hosts such as petalite or Li phosphates are also present in the pegmatites of Moldanubian region, all of which are situated in metamorphic country rocks omitting the large batholiths of the Bohemian plutons and their offshoots (Novák 2005).

As a reference type of these lithium-bearing pegmatites, the Rožná pegmatite, where rossmanite $[\text{LiAl}_8\text{Si}_6\text{O}_{18}(\text{BO}_3)_3(\text{OH})_4]$ and lepidolite $[\text{KLi}_2\text{AlSi}_4\text{O}_{10}\text{F}(\text{OH})]$ have been found for the first time, is described in more detail because of its intensive mineralogical studies through time by numerous geologists (Němec 1998; Selway et al. 1998, 1999; Novák and Černý 2001; Čempírek and Novák 2006a). The pegmatitic dike extends over a length of about 1000 m and is about 35 m wide. It is oriented parallel to the NWN-trending strike of the foliation and runs along the boundary between the Strážek Moldanubicum and the Svratka Unit (Novák 1992) (Fig. 2.4a, b). The country rocks consist of biotite gneisses with minor hornblende gneisses, serpentinites, lenses of amphibolites and leucocratic gneisses. The various minerals at Rožna are listed below (Pezzotta and Guastoni 1998; Selway et al. 1998):

Albite, amblygonite, apatite, bertrandite, beryl, brazilianite, columbite-(Mn), cookeite, dravite, elbaite (“rubellite, indigolite, verdelite”), feldspar, foitite, mica, hydroxylherderite, cassiterite, lepidolite, montebrasite, muscovite, quartz, rossmanite, schorl, topaz, triplite, zircon

The mineralogical and chemical setting observed in this part of the Moldanubian Zone or in other words along the SE boundary of the Bohemian Massif looks like a mirror image of what we have already observed along its NW boundary near the

Fig. 2.4a Slender crystals of albitic feldspar in a matrix of lepidolite. Rožna pegmatite, Czech Republic



Fig. 2.4b Massive milky quartz with nests filled with cassiterite (*black*) and amblygonite (*pinkish*). Rožna pegmatite, Czech Republic

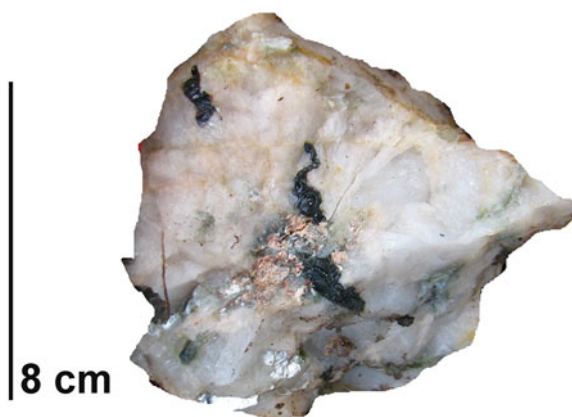


Fig. 2.4c Porous episyenite at the rim of the Rožna pegmatite. The mineral replacing quartz is a minerals of the smectite group (pers. com. M. Novák, Brno)



Saxo-Thuringian subfluence zone. A closer look at the cross section of Fig. 2.1c provides us with an explanation. Both boundaries are marked by deep-seated fault and trust zones dipping towards the core zone of this uplifted basement block (Fig. 2.1c, d).

In a later stage episyenitization has affected this pegmatite along fault zones causing a porous desilicified rock with smectitic phyllosilicates (pers. com. M. Novák) (Fig. 2.4c). The most conspicuous group of minerals identified in this

pegmatite vein is mica, being composed of biotite, muscovite, lepidolite (trilithionite to polyolithionite) and illite (Černý et al. 1995). They are replaced by phyllosilicates such as kaolinite and chlorite. The tourmaline-bearing mineral assemblages made up of schorl-foitite, elbaite and rossmanite were investigated by Novák and Selway (1997) and by Novák et al. (1998). Further diagnostic minerals are cassiterite and Nb-Ta-oxide minerals, e.g., columbite-(Fe) and columbite-(Mn). Lithium also entered together with aluminum the structure of phosphates resulting in the formation of the amblygonite–montebrasite s.s.s. There are a few Li-free phosphates such as iacroixite, brazilianite, goyazite, eosphorite, and fluorapatite in this pegmatite (Němec 1998). One of the few pegmatites hosted by granites is the euxenite-type pegmatite of Kožichovice II attributed to the NYF series (Novák and Filip 2010). It stands out predominantly by its beryllium contents causing the precipitation of a great variety of primary and secondary Be minerals disseminated among the rock-forming minerals of the ultrapotassic orogenic Třebíč syenogranite (beryl, bavenite, bazzite). A representative of the peraluminous P-rich tourmaline-bearing pegmatite is situated at Příbyslavice near Čáslav within a host rock series of orthogneisses and two-mica and biotite paragneisses (Čech et al. 1978; Němec 1973, 1978; Prachař et al. 1983; Povondra et al. 1987, 1998). The pegmatitic schlieren and dikes are abundant in phosphates and Al-enriched silicates. An overview of the central parts of the Moldanubian Zone as to the pegmatites and their mineralogy is given in Table 2.2.

2.1.6 Geodynamic Zones Along the Northeastern and the Southeastern Margin of the Bohemian Massif

Dealing with the pegmatitic rocks in central Europe from a geodynamic point of view while claiming that the HPPP is the center of pegmatites and to ignore the Sudetes along the northeastern margin and the Moravo-Silesicum along the southeastern margin of the Bohemian Massif would simply be only half the story (Fig. 2.1d). Therefore a brief overview of the lithologies, structural features and the mineral assemblages of both units is presented to thwart any possible accusations that these Variscan pegmatites and their geodynamic setting had been cast aside in this pegmatitic regional overview for whatever reasons.

2.1.6.1 The Sudetes

Lithology and Structural Geology

The Sudetes (West Sudetes=Lugicum, East Sudetes=Silesicum), was once considered by Kossmat (1927), the father behind the idea of geodynamic subdivision in the Central European Variscides, as the eastern prolongation of the Saxo-Thuringian Zone, and while doing so made an object for a lively debate among geoscientists lasting until today (Żelaźniewicz 1995). Its geotectonic position as part of one of the

Table 2.2 Host rocks, mineral assemblage and morphology of pegmatitic rocks from the central zone of the Bohemian Massif (Czech Republic)

Locality	Host rock		Morphology	Reference
Oslavice near Velké Mezířčí Třebíč Pluton	Syenogranite shoshonitic association	Quartz, oligoclase, phlogopite±amphibole, microcline, quartz, tourmaline, ilmenite, titanite, allanite-(Ce)	Dikes	Škoda et al. (2006) and Škoda and Novák (2007)
Oslavice near Velké Mezířčí Třebíč Pluton	Syenogranite shoshonitic association	K feldspar, quartz, oligoclase, phlogopite±amphibole, albite, titanite, phenakite, beryl, euxenite, green amazonite, Mg-rich biotite, allanite-(Ce), aeschynite, ilmenite, niobian rutile, actinolite, zircon, monazite-(Ce), bavenite, bazzite, milarite, bertrandite, chlorite, pyrochlore pseudorutile	Dikes, pockets	Škoda et al. (2006) and Škoda and Novák (2007)
Oslavice near Velké Mezířčí Třebíč Pluton	Gneiss	Quartz, albite, K-feldspar (locally amazonite), cleavelandite, muscovite, zinnwaldite, lepidolite to masutomilite, schorl (elbaite), topaz, spessartine, F-rich hambergite, monazite-(Ce), xenotime-(Y), zircon, columbite, wolframioiolite, cassiterite, fergusonite-(Y), samarskite and pyrochlore group, beryl, bertrandite, bavenite, fluorite	Dikes	Novák et al. (1999)
Horní Bory near Velké Mezířčí	Granulites, cordierite migmatites, biotite-sillimanite migmatitic gneisses	Cordierite, schorl, oxy-schorl, grandidierite-onnelite, boralsilite, dumortierite (locally Sb-enriched), ferberite, rutile – niobian, W-rutile, wolframioiolite, ilmenite, monazite-(Ce)	Pockets, veinlets, dikes	Povondra et al. (1992) and Novák et al. (1992)
Starkoč near Čáslav, Kutná Hora Unit –	Granulites, garnet peridotites, eclogites, garnet-biotite gneiss to migmatite biotite gneiss	Tourmaline, dumortierite, garnet (Alm 80–62 Sps 30–10 Prp 8–3 Grs 3–2), chrysoberyl, plagioclase, K-feldspar, kyanite, staurolite, fluorapatite, monazite-(Ce), xenotime-(Y), löllingite	Discordant pegmatite veins, zoned pegmatite	Cempírek and Novák (2006a, b)

(continued)

Table 2.2 (continued)

Locality	Host rock	Albite, K-feldspar, muscovite, biotite (annite), trillithionite, oxy-schorl, schorl, elbaite, garnet, staurolite, dumortierite, sillimanite, nigerite, fluorapatite, triphylite, sarcopside, grafitonite, ferrisicklerite, heterosite, ferroalluaudite, lipscombite, ludlamite, melonjosephite, messelite, mitridatite, phosphophyllite, rockbridgeite, strunzite, vivianite, niobian rutile, cassiterite, ferrocolumbite, manganocolumbite, tungstenite, tantalum rutile, zircon	Morphology	Reference
Přibyslavice near Čáslav	Orthogneiss in two-mica and biotite paragneisses	Albite, K-feldspar, muscovite, biotite (annite), trillithionite, oxy-schorl, schorl, elbaite, garnet, staurolite, dumortierite, sillimanite, nigerite, fluorapatite, triphylite, sarcopside, grafitonite, ferrisicklerite, heterosite, ferroalluaudite, lipscombite, ludlamite, melonjosephite, messelite, mitridatite, phosphophyllite, rockbridgeite, strunzite, vivianite, niobian rutile, cassiterite, ferrocolumbite, manganocolumbite, tungstenite, tantalum rutile, zircon	Lenticular schlieren-like pegmatite, dike	Čech et al. (1978), Němec (1973, 1978), Prachař et al. (1983), and Povondra et al. (1987, 1998)
Vlastějovice near Zruč nad Sázavou	Migmatized biotite- sillimanite gneisses amphibolite, pyroxene gneiss, quartzite, marbles, two- mica tourmaline-bearing orthogneisses, Fe-skarns	Amphibole (hastingsite + edenite), fluorite, biotite, hedenbergite, andradite-grossular, epidote, titanite, calcite, magnetite, bastnaesite, fluorapatite, zircon, rutile, monazite-(Ce), xenotime-(Y), allanite-(Ce), arsenopyrite, pyrite, uraninite, cassiterite, niobian rutile, Sn-rich titanite, gadolinite-hingannite minasgeraisite, Y-rich milarite, pyrochlore-group minerals, manganocolumbite, datolite, bavenite, tourmaline (schorl, dravite, elbaite), garnet	Veins, layers	Novák and Hyršl, (1992), Žáček et al. (2003), and Ackerman et al. (2007)
Myšec near Protivín, Písek region	Amphibole-biotite syenite (durbachite)	Tourmaline, inclusions of chromite in tourmaline, beryl, phenakite, danalite, biotite, ilmenite, muscovite, schorl-dravite, dravite	Veins, zoned	Novák et al. (1997)
Podlesi Stock (see also Lázní Kynžvart and HPPPP for gradual changes along a N-S lineamentary fault zone)	Isotite granite, phyllites,	Alkali feldspar, zinnwaldite, protolithionites, quartz, topaz, apatite, childrenite-eosphorite, zwieselite, triphylite, monazite, Nb-Ta rutile, columbite, cassiterite, ilmenorutile, U-tantalite, U-microlite, ixiolite, wolframite, huebnerite, scheelite, rutile, ilmenite, haematite, pyrite, bismuthinite, powellite, roosveltite	Stock + dyke granite apical veins	Breiter et al. (1997)

Lázni Kynžvart		K feldspar, albite, muscovite, biotite, quartz, opaline, tridymite, topaz, schorl, chlorite, beryl, euclase, bertrandite, zircon, helvigne, coffinite, thorite, triplite, montebrasite, lacroixite, brazilianite, fluorapatite, greifensteinite, rockbridgeite, lipscomite, crandallite, perhamite, monazite, brabantite, fluellite, hurlbutite, hydroxylherderite, herderite, chemikovite, torbernite, autunite, xenotime, vivianite, wolframate, fluorite, hematite, ilmenite, ixiolite, columbite, magnetite, pseudorutile, rutile, uraninite, arsenopyrite, bismutite, emplectite, galena, greenockite-hawleyite, galenobismutite (?), chalcopyrite, cassiterite, maldrlite, molybdenite, pyrite, sphalerite, stannite, tennantite, wittichenite, wurtzite	Veselovský et al. (2007)
Rožná, western Moravia	Granulitic to migmatitic biotite hornblende and biotite gneisses	Quartz, albite, muscovite, biotite, lepidolite, cookeite, tourmaline (dravite, elbaite, var. rubellite, var. indigolite, schorl, foitite), bertrandite, beryl, hydroxylherderite, amblygonite, montebrasite, brazilianite, triplite, apatite, rossmanite, topaz, columbite-(Mn), cassiterite, hornblende, zircon	
Blížná I	Calcite–dolomite marble	Microcline, quartz, albite, plagioclase, tourmaline (schorl, elbaite–iddicoatite, uvite), axinite, datolite, dumortierite, diopside, bastnäsite-(Ce), allanite-(Ce), parisite-(Ce), monazite-(Ce), titanite, epidote, calcite, zircon, apatite, pyrochlore, scheelite	Novák et al. (1999b)
Blížná II	Graphite-bearing biotite gneiss	Microcline, quartz, albite, plagioclase, muscovite, spessartine, tourmaline (dravite, schorl, elbaite, olenite, thortveitite, monazite-(Ce), zircon, apatite, columbite-(Mn), rutile, niobian rutile, cassiterite, pyrite	Novák et al. (2012)

(continued)

Table 2.2 (continued)

Locality	Host rock		Morphology	Reference
Scheibengraben pegmatite 1.5 km E of Maršíkov	Medium-grained hornblende gneiss	Garnet, beryl, columbite-tantalite, fluorapatite, schorl, zircon, garnet, triplite, topaz, native bismuth, albite, K-feldspar, quartz, muscovite, euclase, bertrandite, uranmicrolite, microlite, ryersonite, gahnite	Lenticular body	Novák et al. (2003)
Maršíkov I and III		Quartz, muscovite, K-feldspar, sillimanite, beryl chrysoberyl, bavenite, chlorite, epidote, biotite, zircon, gahnite, garnet, fersmite, columbite-(Mn), tantalite, pyrochlore, microlite	Metapegmatite	Černý et al. (1992)
Ruda nad Moravou	Serpentinized Iherzolite	Quartz, plagioclase, K-feldspar, grossularite, diopside, epidote, clinzoisite, disassite, allanite, titanite, zircon, baddeleyite, zirconolite, gittinsite, uraninite, thorite, fluorapatite, monazite-(Ce), fersmite, pyrochlore-group minerals, rutile, niobian rutile, biotite, Ti-rich magnetite, ilmenite, chromite, magnesiohornblende, actinolite, pargasite, tremolite	Dike	Novák and Gadas (2010)
Věžná I pegmatite	Serpentinized Iherzolite	K-feldspar, oligoclase, quartz, biotite, smoky quartz, "cleavelandite", muscovite, fluorapatite, pollucite, "fluor-elbaite", albite, polyolithionite, trilithionite, muscovite, niobian rutile, monazite- (Ce), xenotime-(Y), zircon, lepidolite, triplite, Cs-rich beryl, cheralite, hübnerite, native Bi, anthophyllite, Cr-enriched actinolite, phlogopite, vermiculite, chlorite, phlogopite, cordierite, celadonite, beryl, bertrandite, epididymite, milarite, Cs-rich analcime, chabasite-K, harmotome, "kerolite" (calc. serpentine, saponite)	Dike	Dosbaba and Novák (2012)

G 1 Central Granite, G 2 Rim Granite, G 3 Core Granite, G 4 Tin Granite (Richter and Stettner 1979)

above mentioned geodynamic zones or a unit of its own undergoing Caledonian and Variscan deformations is still controversially debated (Bederke 1924; Collins et al. 2000; Mazur et al. 2006).

Here I only provide an abstract of that complex history and concentrate on those geological facts that are closely related to the emplacement of pegmatites only.

As a basic principle, the most modern models on these very divers lithologically units, favor an eastward extension of the Variscan tectonostratigraphic units into the Sudetes (Aleksandrowski and Mazur 2002; Kryza et al. 2004; Mazur et al. 2006). Interrupted by periods of extensional tectonic, the amalgamation of the Sudetes took place from the Silurian through the early Carboniferous. Flysch-type sediments are interpreted as a sign of active subduction of oceanic crust during the Late Devonian, suggesting that ophiolite obduction and significant overthrusting in the Sudetes occurred as an integral part of the Variscan orogeny (Collins et al. 2000).

The geodynamic unit is cut through by some prominent lineamentary fault zones such as the Elbe-Fracture zone, forming its southwestern edge and the Moravo-Silesian Thrust Zone, dipping toward the northwest. There are also internal ductile faults, e.g., the Main Intra-Sudetic Fault, which according to Don (1991) represents a deep-seated crustal feature separating Caledonian and Variscan parts of the Sudetes. The pre-Permian fault movements are compressional, extensional and of strike-slip type, bounding tectonic units with metamorphic rocks attaining, in places, high-pressure conditions of blue schist, eclogite and granulite facies conditions (Aleksandrowski et al. 1997; Aleksandrowski and Mazur 2002). Such fracture reflecting the internal subdivision of basement block have been active over a long period of time even if the change the deformational style and direction of movement through time. They play a role, not only for the geodynamic evolution of the Bohemian Massif but also fostered the heat flow from the mantle and the emplacement of minerals deposits, *inter alia* of pegmatitic deposits.

During the late Variscan orogeny, as in many other parts of the Central European Variscides, felsic intrusions penetrated the crust during the Carboniferous and bimodal volcanic volcanism was active by the beginning of the Permian (Kryza 1995a). Although the plutonic activity started very early, at approximately 350 Ma, there are two distinct phases alternating with periods during which granitic activity was low. One was around 325–330 Ma the other around 280 Ma (Kryza 1995a). SHRIMP zircon dating of granitic rocks conducted to a fine-tuning of the granitic activity with magmatic events around 340, 328, 312, 305–300 and 295–280 Ma (Oberc-Dziedzic et al. 2010; Kryza et al. 2012; Oberc-Dziedzic and Kryza 2012).

Also not uncommon to other geodynamic zones of the Central European Variscides, this granitic activity can be correlated with a late Variscan metamorphism (Kryza 1995b; Awdankiewicz et al. 2013). The Góry Sowie Block, in the West Sudetes, SW Poland, consists of a gneiss–migmatite complex with subordinate amounts of amphibolites, calc-silicate rocks, ultrabasic rocks and granulites. U/Pb dating of monazite and xenotime yielded ages of c. 380 Ma and constrain the

timing of the last metamorphic–migmatitic event, a Devonian high-temperature metamorphism in the Sudetes. Rb–Sr mica–whole-rock dating for samples with D2, D3 and D5 deformation characteristics provide ages between 362 and 375 Ma (Bröcker et al. 1998).

Mineral Deposits

A wide range of mineral deposits, were mined in the past but today no longer considered as economic in the Sudetes on the Czech, German and Polish territories (Mochnacka et al. 1995). According to these authors the five principal categories of minerals deposits may be established for this north-easternmost part of the Bohemian Massif: (1) Metamorphosed deposits related to submarine volcanism and sedimentation (Fe- oxide- and Fe-sulfide deposits), (2) deposits related to pre-Variscan and Variscan magmatism (Cr-, Ti-Fe-, Cu-Ni-, U-, Th- deposits), (3) Vein-type and stratabound hydrothermal deposits (U-, Cu-, Pb-, Zn-, Ag-, As-, Fe-, Sn-, Au deposits), (4) Stratabound deposits of sedimentary affiliation (Cu-Ag-, U-, Au-Ti deposits), (5) Deposits and occurrences related to weathering (Ni-Mg-Fe-, Al deposits). For the current topic, only those mineral associations related to granites, pegmatites, skarns and contact-metasomatic processes are mentioned in this chapter and were referred to in the next paragraph.

In the Karkonosze Granite veinlets host pitchblende and uraninite, mostly related to a strong episyenitization (Lis and Sylwestrzak 1979). In the same region at Markocice near Bogatynia, in the metamorphic wall rocks of the afore-mentioned granite, Th-bearing pegmatites, called metasomatic syenites occur (Jęczmyk and Juskowiakowa 1989; Mochnacka and Banaś 2000). They contain a rather exotic mineral assemblage with monazite, thorite, cheralite, grayite, huttonite, ningyoite, voglite, thorogummite accompanied by various sulfides. Kucha (1980) reported ThO₂ contents of 56.4–69.9 wt% from the huttonitic monazite-(Ce), which lies between ThSiO₄ and CePO₄. In the Fore-Sudetic Block rare metal-bearing pegmatite veins are known from the Szklary serpentinite massif containing chrysoberyl, spessartite, columbite-(Mn) and manganotantalite, stibiocolumbite, holtite, pyrochlore, beusite, paradocrasite, stibarsen, and manganiferous apatite (Pieczka 2000). Another lens-shaped zoned pegmatite called Skalna Brama pegmatite is located near Szklarska Poręba within the Karkonosze Granite. It is a REE-pegmatite containing zirconolite, gadolinite, fergusonite–formanite, aeschynite, arsenopyrite, uraninite, monazite, zircon, and xenotime (Gajda 1960 a, b; Kozłowski and Sachanbiński 2007; Szełęg and Škoda 2008). In view of the age of intrusion of the Karkonosze granite, the pegmatite is younger than 329 ± 17 Ma (Duthou et al. 1991).

In the Strzegom-Sobótka Massif, miarolitic pegmatites hosting more than 90 different minerals were encountered in the two-mica monzogranite whose of age of formation was chronological constrained to 324 ± 7 Ma by Pin et al. (1989). The various minerals allow for an attribution of this pegmatitic mineralization to a REE-Nb-Ta-Be-B-Sc-F-W granitic pegmatites (Janeczek and Sachanbiński 1989; Ciesielczuk et al. 2008). The Michałkowa pegmatite complex made up of lenses and

veins with its mineralized structures cutting through gneisses and amphibolites of the Góry Sowie Mts. Its lenses run subparallel to the foliation. Van Breemen et al. (1988) reported an age of 370 ± 4 Ma of this pegmatite. Apart from the typical minerals of pegmatites, the phosphate sarcopside which is pseudomorphosed by vivianite was described for the first time from this locality by Websky (1868). According to its diagnostic minerals, the pegmatite has been classified as tabular to vein-type B-P pegmatite

Proximal to the Karkonosze Granite at Kowary magnetite and hematite-bearing skarns occur. Beyond the border, in the Czech part of the Sudetes, at Obří Důl scheelite mineralization is related to the granitic influence on marble layers (Chrt 1959). This idea did not remain unchallenged as Pertold (1978) advocated a syngenetic origin of these tungsten deposits.

2.1.6.2 The Moravo-Silesicum

Lithology and Structural Geology

The Moravo-Silesian zone extends from Austria, through the Czech Republic into Poland, bounding the Bohemian Massif, or in other words the Moldanubian Zone towards the SE (Misař and Urban 1995). It consists of the autochthonous Cadomian basement, called the Brunovistulicum overlain by Devonian to Carboniferous sedimentary rocks and the allochthonous Variscan units of the Moravicum and the Silesicum. Several tectonic thrust planes mark the overriding Moldanubian and Lusitan nappes onto the Moravo-Silesian zone. Towards the East, the Moravo-Silesian zone submerges underneath the Carpathian foredeep as far east as the Peripenninic Lineament which is the concealed boundary of the Bohemian Massif (Máška and Zoubek 1960). Like its western parts in the Alpine Mountain range, these Variscan rocks of the Carpathians also became reactivated during the Alpine orogeny and reappeared as intra-Alpine massifs (Grecula and Roth 1978) (section 2.2.4). Paleofacial comparisons with other geodynamic units, which have been discussed previously in this book, stress the striking similarities between the coal-bearing Upper Silesian Basin and the Subvariscan Foredeep (Sect. 2.1.1) while the late Variscan flysch facies of the Moravo-Silesian zone finds its match in the Rhenohercynian Zone (Sect. 2.1.2). As a logical consequence, the basement in the eastern parts of the Silesian zone was correlated with the Mid-German Crystalline Rise (Misař et al. 1983) (Sect. 2.1.3).

Mineral Deposits

After emphasizing the many similarities to exist between the Rhenohercynian and the Moravo-Silesian zones in terms of paleofacies and geodynamic evolution both of which are characterized by extensional processes during the Devonian and subsequent compressional tectonic processes, it is more than a tempting idea to see also

striking similarities between the mineral deposits in both geodynamic realms, located so far away from each other in the Central European Variscides (Aichler et al. 1995). In the Moravo-Silesian Zone, submarine Lahn-Dill iron ore are encountered closely related to basic volcanic rocks. Fe-bearing base metal deposits with subordinate amounts of Au formed in a geodynamic setting similar to that known from Rhenohercynian Basin. The Devonian volcano-sedimentary series (Vrbno Group), however, underwent regional metamorphism up to green schist facies conditions (Patočka and Vrba 1989; Kalenda and Vaněček 1989). Extensive mining was focused on deposits in the N part of the Moravo-Silesian Zone at Zlaté Hory, Horní Město, Oskava, and Horní Benešov in the Czech Republic. The total ore exploited from these deposits amounts to 100 Mt of mostly low grade ore (Aichler et al. 1995). The sulfur isotope ratios obtained from barites closely resemble those from Meggen and Rammelsberg, whereas the sulfide sulfur is isotopically much lighter (Hladíková et al. 1992). High radiogenic Pb contents of the galena-enriched ore shows that upper crustal rocks have contributed much to the metal-bearing hydrothermal or exhalative solutions creating the stratabound mineralization in the Moravo-Silesian Zone (Vaněček et al. 1985).

There are also conspicuous similarities between the pegmatites in the Spessart, being part of the Mid-German Crystalline Rise and its most likely counterpart at the easternmost part of the Bohemian Massif, where barren feldspar or primitive pegmatites exist, according to Novák (2005). A few REE-bearing pegmatites, hosting allanite as it is the case in the Spessart, occur in the Moravo Silesian zone. At Maršíkov I and III Be-REE metapegmatites with sillimanite crop out (Černý et al. 1992) (Table 2.2). Boron and beryllium is more widespread than lithium. It has to be noted that there are also differences such as the Scheibengraben pegmatite 1.5 km E of Maršíkov, tabular Be-Nb pegmatite in medium-grained hornblende gneisses (Novák et al. 2003) (Table 2.2). While pre-Variscan granites are common, granitic pegmatites are rare, a scenario also known from the northwestern edge of the Central European Variscides. According to Novák (2005), the following relations can be quoted – $B \gg P + F$, $Be \gg Li$ – for the Moravo Silesian zone, which is not only with respect to the paleofacies a match to the Mid-German Crystalline Rise.

2.2 The Geological and Metallogenetic Evolution of the Variscides Within the Alpine Mountain Range with Special Reference to Pegmatites

2.2.1 The Variscan Massifs in the Alpine-Carpathian Mountain Range

Less than 50 km south of the highland boundary fault which runs along the River Donau (Danube) and terminates the uplifted block of the Bohemian Massif, the geomorphological expression of the Moldanubian Zone, the spectacular mountains of

the Alpine Orogen rise from hilly landscape of the molasse basin (Fig. 2.1d) (Froitzheim et al. 2008; Rasser et al. 2008; Reichert et al. 2008). The present investigations reveal that there were two major tectonic activities, one during the Cretaceous and another during the Paleogene and Neogene provoking that the late Paleozoic and Mesozoic rocks that were under the sea within the Neo-Tethys elevated over the sea level and were transformed into the present-day high-altitude mountain ridge, stretching from Grenoble, France, to Vienna, Austria. Immediately East of Vienna, Austria, this modern fold belt of the Alpine Mountain Range changed its direction of strike from ENE towards NNE, and running along the southeastern border of the afore-mentioned Bohemian Massif, forms another branch of the Alpine-Himalayan Fold Belt, called the Western Carpathian Mountains. The late tectonic phases of the Alpine Orogeny resulted from the northward plate movement of Africa, getting it closer to the Eurasian continent, whose geodynamic history was related in the previous sections with special reference to the emplacement of pegmatitic rocks in the various geodynamic units along a NW-SE transect from the Subvariscan Foredeep through the Moldanubian Zone (Sect. 2.1). This transect does not end in the southernmost tip near Vienna, where the Monotonous Series, the Varied Series and the Gföhl Unit represent the crystalline basement of the Moldanubian Zone in Austria nearest to the Alpine Mountain Range. Pegmatitic rocks have also been encountered further south in a geodynamic setting closely related to the one known from the Moldanubian Zone of the Central European Variscides (Petrakakis 1997).

In the western Alps crystalline basement rocks are exposed in the Helvetic realm, among others in the Gotthard and Aare Massifs, while immediately south of it Paleozoic rocks are at outcrop in the Penninic realm (Trümpy 1980). Heading east, in the Tauern Window and the “Altkristallin” (Old Crystalline Rocks) Paleozoic rock are of more widespread occurrence (Tollmann 1977).

Another series of rocks next to the Moldanubian Zone is located within the Western Carpathian Mountains which are traditionally divided into the Outer, Central and Inner Western Carpathians. The Central Western Carpathians comprise three superunits, the Tatricum, Veporicum and Gemericum (Hovorka et al. 1992; Vozárova and Vozár 1988, 1996; Ludhová and Janák 1999). Of those superunits, the two last ones are of particular interest as to the presence of Paleozoic rocks and pertinent mineral deposits.

2.2.2 The Variscan Massifs and Their Associated Pegmatites in the Swiss Alpine Mountain Range and the External Moldanubian Zone

Among the most well-studied and -dated Variscan massifs in the Swiss Alps, the Aar Massif reveals several similarities with its extra-Alpine Variscan counterparts to the north (Schaltegger and Corfu 1995). The Tödi Granite evolved around 333 Ma contemporaneously with the older granites from the Bayerischer-Böhmer Wald (318–338 Ma) and the granite at Triberg (333±20 Ma) and Münsterhalden

(333 ± 5 Ma), in the Schwarzwald, all of which belong to the Moldanubian Zone (Walther 1992). The Central Aar Granite (289 Ma) and its microgranite (299 Ma) are considerably younger than the older granite. Aplitic veins have been reported from the Aar Massif, but mineral assemblages typical of pegmatites are missing (Amacher und Schüpbach 2011). Schneiderhöhn (1961) has already reported in his comprehensive study on pegmatites, that pegmatites and aplites are poorly represented in the Paleozoic rocks of the Swiss Alps. He cited the Aar Massif as an example, where in the amphibolites of the schistose envelope pegmatitic and aplitic rocks are scarcely exposed whereas in the Mont Blanc Massif, these felsic rocks are absent. Why, in spite of their close chronological and geodynamic resemblance to the most prominent pegmatite terrane in the Central European Variscides, are these Variscan massifs in the Western Alps devoid of these rocks ? To answer this question needs a closer look at the two uplifted basement blocks of the Moldanubian Zone in southwestern Germany and France next to the internal massifs of the Alpine realm. One of them forms the eastern (Schwarzwald Mts.) and the other the western flanks of the Rhein Graben Rift (Vosges Mts.) (Fig. 2.1d).

The crystalline basement of the Schwarzwald has been subdivided into four tectonometamorphic complexes. At the northernmost tip of the basement uplift the Baden-Baden Zone is assigned to the Saxo-Thuringian zone by Franke (1989) and was intruded by a suite of Early Carboniferous high-K, calc-alkaline I-type plutonic rocks composed of diorites, granodiorites and granites which are also exposed in the Vosges Mts. (Altherr et al. 2000). In the Central Schwarzwald Gneiss Complex metapsammitic gneisses were brought about by a HT-LP regional metamorphic event of approximately $730\text{--}780$ °C/ $0.40\text{--}0.45$ GPa (Kalt 1995). All intrusions into this gneiss complex are homogeneous two-mica or only muscovite-bearing S-type granites, the youngest of which were dated at 325 ± 7 Ma and developed from granitic magmas of crustal origin (Kalt et al. 2000). Further south, in the Badenweiler-Lenzkirch Zone, arc relics were identified in the metamorphic rocks. At the southern extremities of the Schwarzwald, the Southern Schwarzwald Gneiss Complex is located. Metaaluminous to slightly peraluminous biotite granites and peraluminous two-mica granites were intruded into this metamorphic complex, spanning an age of intrusion from 334 ± 2 Ma, determined on monazite, through 328 ± 2 Ma, obtained from a dike of granite porphyry (Schaltegger 2000). The peak of HT-LP metamorphism was reached almost contemporaneously with or immediately before the intrusion of the granitic magmas into the metamorphic rocks. According to Altherr et al. (2000), the granitic suite of the Schwarzwald and the Vosges Mountains resulted from a series of intrusion of crustal-derived felsic and mantle-derived more basic dioritic magmas. The Zone of Baden-Baden and its prolongation to the West, the Lalaye-Lubine Zone dissecting the Vosges Mts. in WNW-ENE direction, represents a deep-seated suture zone between two different terranes, the Saxo-Thuringian and Moldanubian zones.

The Schwarzwald is one of the oldest mining regions in Germany, mainly based upon vein-type Pb-Zn deposits, e.g., in the Schauinsland and in the Münstertal-Wiesental, Ag-Bi-Co-Cu-U vein deposits around Wittichen, Sb-As veins in the environs of St. Ulrich and Sulzburg and fault bound uranium deposits at Menzenschwand,

the latter yielded a U/Pb age for its pitchblende mineralization of 310 ± 3.5 Ma (Gehlen von, 1989). In stark contrast to the regional presence of base metal, precious metal and nuclear fuel deposits is the Schwarzwald's notoriously poor presence of elements known to be genetically related to granitic intrusions, such as Sn, Be, Nb or Li which is totally absent, even though almost half of the crystalline rocks exposed in the uplifted block of the Schwarzwald is made up of Variscan granites. The only granite-hosted mineralization bearing Sn and Be and hence has been mineralogically revisited again and again for its peculiar position, is located in the Triberg Granite Complex (Osann 1927; Fettel 1971; Oppelt 1988; Markl 1995; Markl and Schumacher 1996; Achstetter 2007).

The afore-mentioned mineralization within the composite intrusion of the Triberg Granite is a greisen-type Sn occurrence rather than a pegmatitic mineralization present in narrow veins, in miarolitic cavities and disseminated in parts of the granite (Schleicher 1994; Markl and Schumacher 1996). A small beryl-bearing pegmatite is hosted by the same granite, a two-mica leucogranite unit, and it was altered by the postdating greisen-forming fluids resulting in secondary beryl, albite, phenakite, bertrandite, and kaolinite. Pressure was estimated by the authors to be 1500 bars and the measured salinity is said to be 4–5 wt% NaCl equiv., while the temperature decreased from 550 to about 250 °C along a transect from the internal to the marginal parts.

A list of minerals in miarolitic cavities of the Triberg Granite at Hornberg is given below (Fettel 1971; Schorr 1984).

Albite, bertrandite, beryl, cassiterite, fluorite, hematite, kaolinite, metazeunerite, muscovite orthoclase, phenakite, quartz, zeunerite, zinnwaldite.

Corresponding to Schleicher (1994), the host granite derived from partial melting of a mid to lower crustal source. Analogous to this mineralization in the eastern Schwarzwald referred to above, in the Vosges Mts., on the western banks of the River Rhein, a similar mineral association also containing beryllium and tin was found in veinlets near Rothau-Alsace, France, (Hohl 1994).

List of minerals in a granitic pegmatite at Rothau-Alsace, France (Hohl 1994)

Bertrandite, beryl, fluorite, hematite, orthoclase (var. adularia), phenakite.

With respect to the chemical composition and textural type these Be-B-Sn pegmatites are more akin to the pegmatites straddling the boundary between the Saxo-Thuringian- Moldanubian boundary at the western edge of the Bohemian Massif see the pie chart diagram of Fig. 2.5a (for statistical reasons no equivalent pie chart diagram has been calculated for the Schwarzwald and the Vosges Mts., where only one occurrence is known in each basement uplift). Both pegmatites from the Vosges and Schwarzwald Mountains are lithologically alien elements, demarcating different suture zones between different geodynamic settings. Niobium, commonly accommodated in columbite s.s.s in Central European pegmatitic rocks, went quite a different way, as it was accommodated in the lattice of perovskite of the calcite carbonatite of the Kaiserstuhl in the Upper Rhine Graben (Chakhmouradian and Mitchell 1997). The extra- and intra-Alpine parts of the Moldanubian Zone to the West of the Bohemian Massif are strongly depleted both in pegmatites and aplites and, if present, the rare-element members of this group of felsic rocks

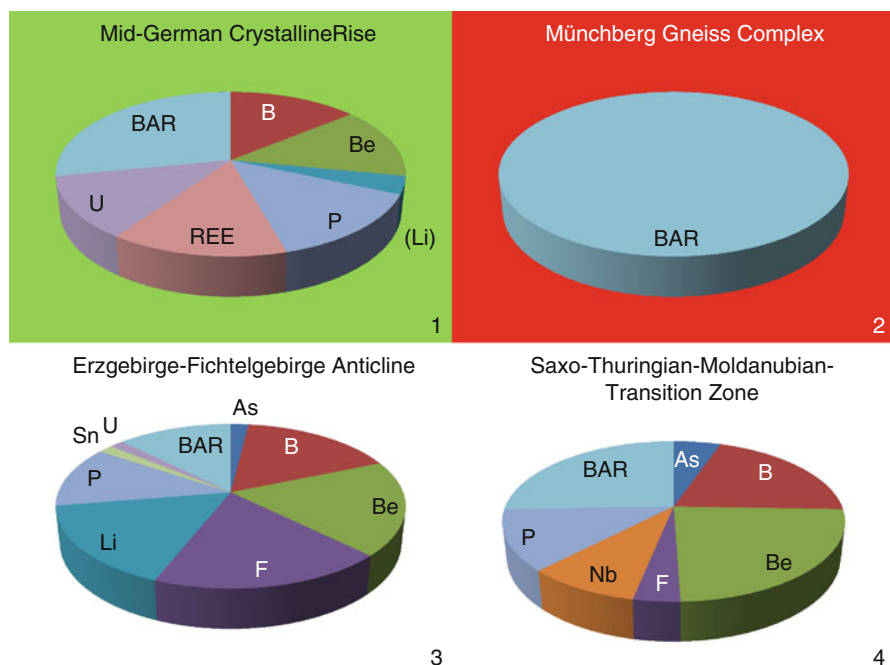


Fig. 2.5a Pie chart diagrams showing the chemical composition of pegmatitic rocks of the Central European Variscides and the intra-Alpine/Carpathian massifs. The numbers and colors in Fig. 2.5a, b, c, d refer to the areas on display in Fig. 2.5e the geological basis of which is given in Fig. 2.1d

designate a concealed suture zone between two ophiolites in Central Europe, the Saxo-Thuringian towards the North and the Ligurian-Massif-Central-Moldanubian ophiolites to the South (Matte et al. 1990; Franke et al. 1995; McKerrow et al. 2000).

2.2.3 The Variscan Massifs and Their Associated Pegmatites in the Austrian Alpine Mountain Range

In contrast to the westernmost Swiss part of the Alpine Mountain range, which is poor in pegmatites in the Austrian, more central part of the Alps, where the Moldanubian extra-Alpine Bohemian Massif comes as closely as possible to the Alpine fold belt, the number of pegmatitic rocks significantly increased, and forces to some explanation from the lithological and geodynamic point of view.

The most prominent intra-Alpine massif, made up of pre-Variscan crystalline rocks, subsequently being intruded by Carboniferous granitic melts, is exposed in the Tauern Window. Arc, fore arc and ensialic back arc environment are juxtaposed (Eichorn et al. 1999, 2000). As a consequence of the Late Devonian amalgamation of Gondwana, represented by the Tauern Window, and Laurussia-Avalonia an Early

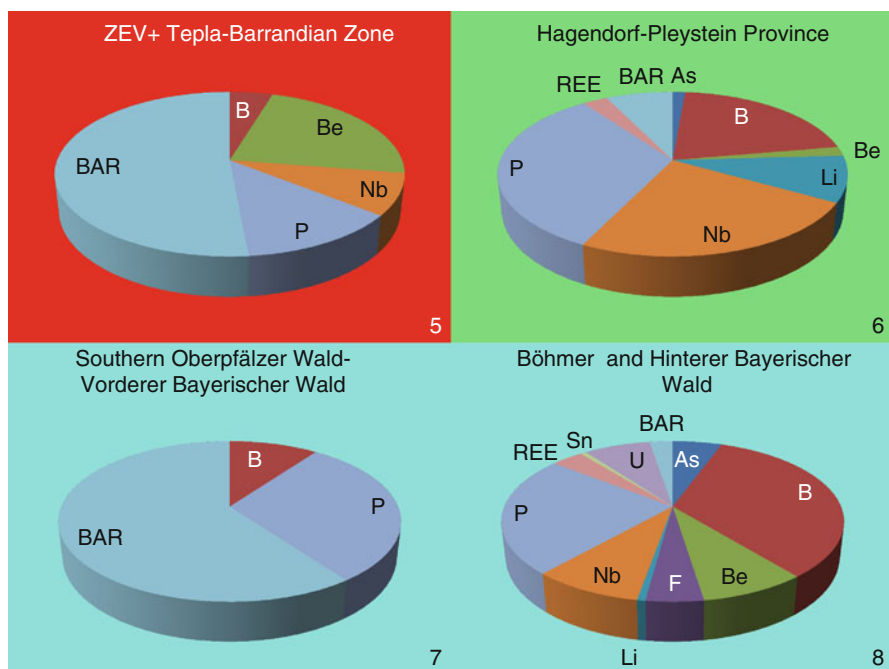


Fig. 2.5b Pie chart diagrams showing the chemical composition of pegmatitic rocks (see also Fig. 2.5a)

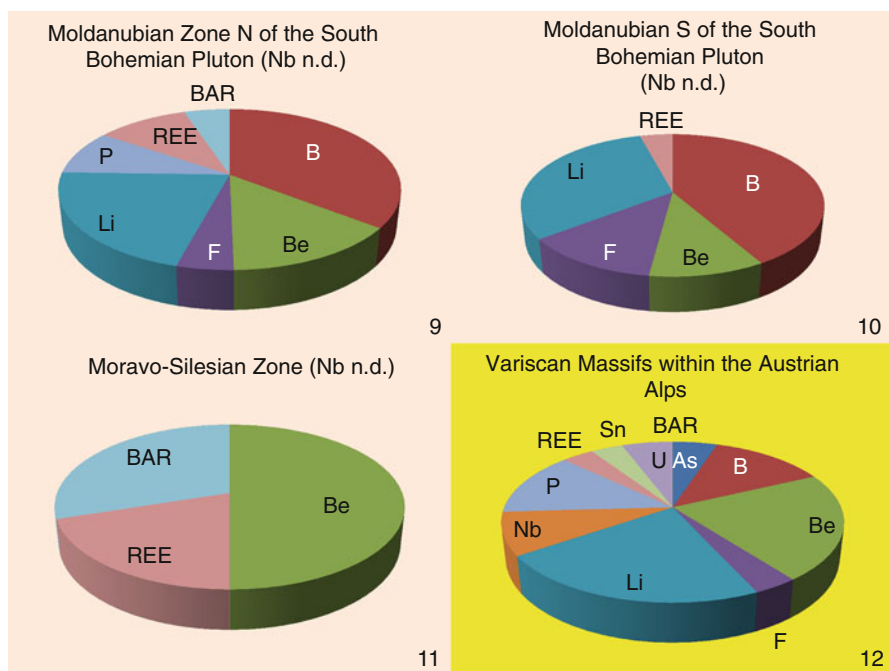


Fig. 2.5c Pie chart diagrams showing the chemical composition of pegmatitic rocks (see also Fig. 2.5a)

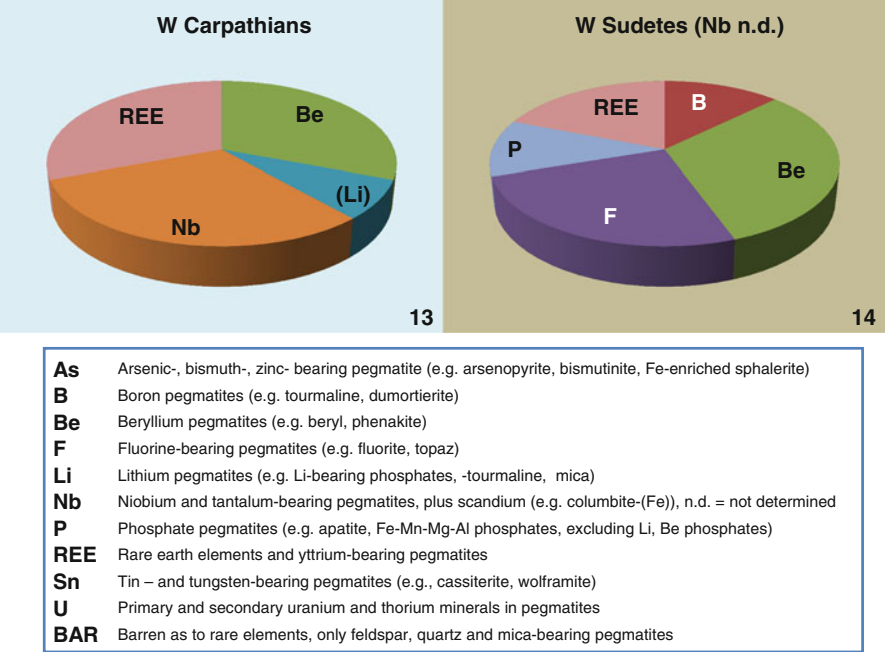


Fig. 2.5d Pie chart diagrams showing the chemical composition of pegmatitic rocks (see also Fig. 2.5a)

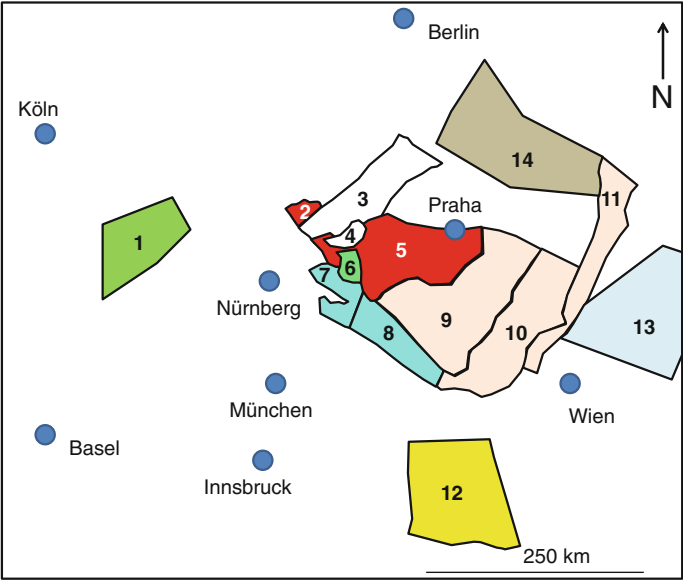


Fig. 2.5e Overview of the topographic position of the pegmatitic provinces (see also Figs. 2.1d and 2.5a)

magmatism was initiated in this crustal section, now present as the Central Gneiss Complex (Lammerer and Weger 1998). I-type granitic rocks lithologically reflect subduction process (Finger et al. 1997). The afore-mentioned magmatic activity in the Austrian Alps closely resembles that from the Swiss and French Alps in the Aar Massif, Aiguilles Rouges Massif and Mont Blanc Massif (Fig. 2.1d).

Featuring commodity groups, a variegated group of ore deposits and of pegmatitic deposits, the intra-Alpine Paleozoic massifs performs metallogenetically almost as well as their northern extra-Alpine analogue, the Bohemian Massif. A comprehensive overview of the mineral deposits has been provided in Dill et al. (2008a, b). Rating the metallogenetic evolution along the Alpine Mountain Range in terms of the abundance of mineral deposits, simply by a visual inspection of the metallogenetic map 1: 2,500,000 unravels, where the frequency of mineral occurrences and deposits reaches its maximum (Dill et al. 2008b). It is the area between the Tauern Window and the Vienna Basin.

In the Eastern Alps, S of Innsbruck, the Monteneve/Schneeberg deposit, Italy, forms part of a horizon mineralized with Zn-Pb minerals that extend over about 20 km, within a paragneiss formation of pre-Silurian age (Frizzo et al. 1982). The ore bodies contain Cd- and Mn-rich sphalerite and Ag-rich galena, with minor pyrrhotite, chalcopyrite, pyrite and stibnite. Another mineralization in the Eastern Alps of Paleozoic age occurs in the Speik Terrane at Kraubath, Austria, with Cr and PGE minerals in a highly dismembered back-arc ophiolite (Malitch et al. 2003). Amphibolites and gneisses in the Ötztal and Kreuzeck Mountains contain stratiform polymetallic Fe-Cu-Zn-Pb deposits in back-arc settings at Raggabach, Austria (Ebner et al. 2000). There are several more mostly rather small deposits in the Paleozoic rocks of the Eastern Alps.

Without any doubt the most outstanding island-arc related metallotect of the Habach Terrane (Frisch and Neubauer 1989) is exposed in the Tauern Window in the Eastern Alps, where 1967 the two ore bodies of the Mittersill scheelite deposit were discovered (Höll 1975). These deposits bridge the gap between the wealth of base metal deposits and the pegmatitic deposits in this region of the Alps. According to Eichhorn et al. (1999) the evolution of the Mittersill scheelite deposit commenced with the development of a volcanic arc at ca. 550 Ma as indicated by the emplacement of volcanic-arc basalts. Approximately coeval crustal thinning occurred in a back-arc region, accompanied by the emplacement of tholeiitic basalts and the intrusion of minor diorites. Subsequently, gabbroic and ultramafic melts intruded into the arc and back-arc region followed by normal I-type granitoid melts with mantle signature until 530 Ma. Subsequently, highly differentiated, yet still mantle-dominated granitic melts were locally intruded between 530 Ma (EOZ) and 520 Ma (K2) in the Mittersill ore deposit. Variscan-age magmatism around 340 Ma is likely to have brought about a second phase of scheelite mineralization which was superimposed on the primary Early Paleozoic phase in the Mittersill deposits.

In the Middle Eastern Alpine unit *sensu* Tollmann (1986) more than ten spodumene occurrences have been discovered since 1876 (Seeland 1876), the larger ones are listed in Table 1.2. Pioneer studies during this case history on spodumene have been performed by Meixner (1952, 1966) and by Höller (1959, 1964) who

mineralogically confirmed the early discoveries and increased the number of new finds in Steiermark and Kärnten. Many of these felsic rocks attracted the attention of mining engineers, mainly for the considerable amount of Na- and K-enriched feldspar concentrated in lenses with up to 100,000 t, sufficient to supply the domestic ceramic industry but too low in their rare element contents to spark any exploration for Nb, Li or Be (Učík 2005). Only one area stands out among these pegmatites in Austria and, not surprisingly, was scouted by many mineralogists. It is the spodumene pegmatite of the Koralpe that eventually turned into trial mining operation and after suspending this preparatory work in the run up of exploitation is currently subject of a new exploration campaign (Postl and Golob 1979; Göd 1978, 1989; Niedermayr 1990; Taucher et al. 1992, 1994). The area can be designated the type locality of the rare Ca-Be Phosphate Weinebeneite $[\text{CaBe}_3(\text{PO}_4)_2(\text{OH})_2 \cdot 4 \text{H}_2\text{O}]$ (Walter et al. 1990). Representative of the great number of Li-bearing pegmatites in the Middle Eastern Alpine unit, the mineralogically most renowned one and the only subjected to underground operations, the spodumene deposit from the Koralpe, is given a more detailed treatment by summarizing the wealth of data collected by the above authors.

The lithology of the crystalline basement of the Koralpe is rather varied, being composed of kyanite- and garnet-bearing mica schists, paragneisses, amphibolites, eclogites, metagabbro and marbles. Kleinschmidt et al. (1975) unraveled the complex lithology and claimed Ordovician and Silurian rocks to contribute to the built-up of the “Phyllitgruppe” (phyllite group) at the southern border of the Saualpe. Habler and Thöni (2001) dealt with the metapelites and metapegmatites intercalated into the crystalline basement of the Austroalpine nappe complex in the Eastern Alps. Their geothermobarometric investigations on gneisses of this basement section yielded temperatures around 600 °C at a pressure of 0.4 GPa. According to these authors the pegmatite formation is correlated with the low-pressure metamorphism in the metapelites, which based upon Sm–Nd-dating of magmatic garnet from the pegmatite gneiss is placed at 249 ± 3 Ma. This high temperature metamorphism provoked the mobilization of felsic mobilizates with quartz, feldspar and mica, termed as pegmatites by regional geologists. The geothermobarometric studies above well agree with the phase diagram, showing the various stability fields of Li-bearing silicates in a P-T plot (London 2008). Under the existing physical-chemical conditions spodumene is the stable phase. During a more recent study, including garnet, xenotime, apatite, monazite and feldspar and using Sm–Nd mineral isochrones, Thöni et al. (2008) were able to fine-tune their previous petrological and chronological investigations and furnished clear evidence for multiple emplacement of pegmatitic melts between 273 ± 2 and 258 ± 3 Ma, in some sites even younger with age down to 251 ± 7 to c. 230 Ma. Ensuing overprinting processes under eclogite-facies conditions with peak temperatures around 700 °C and a pressure at 2.2 GPa accompanied by intense deformation during Cretaceous time, were unable to obliterate previous isotopic signals and blur the magmatic nature of the afore-mentioned rocks.

Spodumene has been concentrated in layers conformably intercalated among the varied metamorphic lithologies. According to Göd (1989) two different types of spodumene ore can be distinguished from each other, the amphibolite-hosted AH pegmatite and the mica schist-hosted MH pegmatite. In the AH – type spodumene crystals are aligned subparallel to each other in the central pegmatite. The marginal part of the felsic rock is aplitic in texture and the contact zone to the barren amphibolite saw the growth of biotite, holmquistite, in places, associated with garnet, beryl, tourmaline and apatite.

The pegmatitic rocks of the MH-type are intensively deformed and foliated. As the orientation of their minerals is taken to the extreme it is hardly to be distinguished from the surrounding kyanite-bearing mica schists. Any aplitic margin so often seen in these felsic intrusive rocks is completely absent from the MH pegmatite. Similar to many other pegmatites in central Europe there is no parent granite close by. Different from many central European, this Alpine Li pegmatite was overprinted by an early Alpine regional metamorphism under amphibolite facies conditions and consequently the result has to be referred to as unzoned pseudopegmatite (MH type) while the AH type has to be called a zoned pseudopegmatite (Frank et al. 1987). Even if these Alpine pegmatitic rocks differ by mineral association from the pegmatoids and metapegmatitic rocks of the Zone of Erbsdorf-Vohenstrauß along the western edge of the Bohemian Massif, there are also striking textural similarities which may be accounted for by the horizontal thrustal movement. Disregarding the presence of spodumene, there are many similarities between the primary pegmatitic minerals of the Koralpe pseudopegmatites and those pegmatites scattered along the western edge of the Bohemian Massif. Some of these minerals are listed here: Quartz, albite, microcline, muscovite, apatite, beryl, ferrisicklerite, columbite-(Fe), heterosite, triphylite, lithiophyllite, tourmaline, cassiterite, Nb rutile. Holmquistite, on the other hand, seems to be one of the diagnostic minerals typical of the Alpine regional metamorphism and as such its absence from the pegmatites in the NE Bavarian Basement is not a surprise.

The various spodumene-bearing pegmatitic rocks mentioned here in this section and exemplified by the pegmatite-hosted Koralpe lithium deposit are not the only evidence for the emplacement of pegmatites in the central part of the Alpine mountain range (Thöni and Miller 2004). Older meta-pegmatites were recorded by both authors from three localities in the Ötztal Basement, in Tyrol (Eastern Alps). Garnet-whole rock or garnet-feldspar Sm–Nd isochrone ages span the interval 445 ± 3 and 473 ± 3 Ma, indicating a Middle to Late Ordovician heat event which lead to the emplacement of pegmatites, now called metapegmatites owing to its subsequent overprinting (Thöni and Miller 2004)- see also Fig. 3.1a. The Alpine Mountain Range has metapegmatites similar to those from the western edge of the Bohemian Massif – see allochthonous ZEV and Tepla Barrandian Zones – and pseudopegmatites, which were subjected to a high-T remobilization during the early Alpine orogeny in its bounds. The latter are interpreted as Late Variscan rare-metal pegmatites s.str. of the Bohemian Massif which underwent Mesozoic remobilization.

2.2.4 The Variscan Massifs and Their Associated Pegmatites in the Slovak Carpathian Mountain Range

Evidence for intensive Silurian rifting and volcanism is not only found in the Eastern Alps but was also recorded from the Western Carpathians, in Slovakia (Grecula 1982; Grecula et al. 1995). The oldest known stratabound mineral deposits in the Carpathian Mountains are subeconomic black shale-hosted sulfide mineralizations with disseminated pyrite and a varied spectrum of rare elements such as V, Sb, Pb, Zn, Cu, As, Ag and Ni, particularly widespread in the Lesser Carpathians (Tatricum) and in the Gemericum (Chovan et al. 1992). During the Devonian, in the Gemericum base metal deposits developed closely associated with hematite and magnetite deposits at Jalovičí vrch and Hutná dolina both of which are genetically linked to basalts and keratophyres (Grecula 1982; Grecula et al. 1995). Rb/Sr isotopic ages of granites in the Gemericum indicate a Permian age of intrusion for these felsic rocks (290 ± 40 to 220 ± 32 Ma; Kovách et al. 1986). They are held by some as the heat source of siderite-sulfide veins in the Carpathian Mts., while others discard this idea and put forward a metamorphic-hydrothermal model for these siderite-sulfide mineralizations in the Gemericum (Radvanec et al. 2004). A large Sb-Au-As province extends across the Western Carpathians.

As far as the pegmatites are concerned, not unexpectedly, an intra-Alpine counterpart to the Bohemian Massif can also be found within the northern Carpathians. This mountain ridge is not only the NE prolongation of the eastern Alpine Mountain Range but it is closer to the Bohemian Massif than the Easter Alps, although the direct boundary between the two is concealed by a thick pile of sediments laid down in the younger foreland basin of the Carpathian Mts.. With regard to the mineralogical composition there are some similarities, but as to the economic potential, the Carpathian pegmatitic province trails behind equivalent rocks in neighboring Austria where lithium pegmatites are widespread and currently under exploration in southeastern Austria (Sect. 2.2.3). By comparison, the Slovak part of this modern fold belt in Central Europe surpasses by some orders of magnitude the Paleozoic massifs of the western Alps which are located far off the central European uplifted basement blocks of the Variscides as to the potential of pegmatitic occurrences and the number of the mineralized sites (Uher and Broska 1995; Uher and Černý 1998; Uher et al. 1998, 2012).

It is mainly Be-Nb-Ta pegmatites in granites, one group bearing Ti- and Mg-poor minerals and another group of pegmatites carrying Ti- and Mg-enriched phases (Nb-Ta oxide minerals, garnet, beryl) that is characteristic for this mountain range. Uher et al. (1998a) attributed the first group of pegmatites to monazite-bearing orogenic granites and the second to allanite-bearing orogenic granites.

Sphene, fersmite, pyrochlore-group minerals and romeite occur in small dikes of relatively poorly fractionated pegmatite in the Variscan Prasiva biotite granodiorite-granite, in central Slovakia: They underwent strong hydrothermal alteration, involving concentration and depletion. Percolating fluids mobilized Nb, Ta, Ti, U, Fe, Si, and probably also Ca and Na from the primary minerals of the pegmatite while

introducing Sb and Pb from an external source. Uher et al. (1998b) held metamorphic-magmatic solutions responsible for this hydrothermal overprinting. As shown above, there are many Sb-, Au-, Pb-, Zn- and Sb sulfide deposits, although many of them no longer economic by international standards, in the Slovak branch of the Carpathian Mts. that are worth to be considered as a potential source for these fluids accountable for the alteration of the pegmatites. Uher et al. (2001) reported black tourmaline of the Adolf adit pegmatite near the Magurka gold-antimony deposits to have been penetrated by pyrite and stibnite in the wake of a late-stage hydrothermal overprint of the pegmatite.

Ferrotapiolite as a dominant product of alteration pseudomorphosing primary stibiotantalite was described by Novák et al. (2004) from the lepidolite pegmatite at Laštovičky, western Moravia, Czech Republic, which is geodynamically “round the corner”. Two compositionally distinct varieties of ferrotapiolite were recognized together with a Sb-rich phase. A rare mineral-bearing pegmatite from the Szklary serpentinite massif, in the Fore-Sudetic Block, SW Poland, also gave host to columbite-(Mn), tantalite-(Mn) and stibiocolumbite as the latest member among these Nb- and Ta oxides (Pieccka 2000). Uher and Černý (1998) calculated the temperature of zircon, present in barren and rare-element pegmatites to 700–580 °C. Beryl is the characteristic mineral of the Variscan granitic pegmatites which have a rather high age relative to the many pegmatites located in the adjacent Bohemian Massif, of 350 Ma and which are associated with S- and I- type granites-granodiorites of in the Malé Karpaty (Bratislava Massif), Považský Inovec, and Nízke Tatry Mountains. Beryl is the only rare mineral while Nb, Ta and Sn accessory minerals only appear at a more advanced level of pegmatite evolution, e.g., Moravany nad Váhom and Jezuitské Lesy, Slovakia (Uher et al. 2012). According to the authors, the average lithium contents fall in the range 120–830 ppm Li, with maximum values of 1400–1800 ppm (Švábsky Hill and Kamzík II). The highest Li contents are in beryl from the Moravany nad Váhom pegmatite with up to 5600 ppm. Lithium minerals of their own were not reported by the authors, a situation also known from the Spessart along the Mid-German Crystalline Rise, where Li is present as trace element in micas. It is not the only chemical congruence that can be reported from the pegmatitic rocks of these region being located at the periphery of the core zone of the Variscan orogen. Beryl plays a significant part among the pegmatitic suite of rocks, not only in the NW part of the Variscan Orogen and eastern part of the Alpine Orogen but also at the north-easternmost border of the Bohemian Massif, in the western and eastern Sudetes, which belong to the eastern extremities of the Saxo-Thuringian and Moravo-Silesian zones, respectively.

The geodynamic zonation based on pegmatites finds further support by the presence of REE-bearing pegmatites in all three peripheral geodynamic zones.

In conclusion, the Austrian Li-Be pegmatites, and the Carpathian pegmatite province with its Be-REE-Nb-Ta pegmatites is an example for the persistence of Variscan or Mesoeuropean pegmatites into Alpine or Neoeuropean pegmatites, being incorporated into ancient stable massifs with or without subsequent reactivation. Metapegmatites of early Variscan age suffered least during their incorporation into Neoeurope. Chemical similarities between pegmatitic rocks found at the

exo- and endocontact of the Bohemian Massif and pegmatitic rocks within the Alpine-Carpathian Mountain Ridge support this idea.

2.3 Pegmatites and Geodynamics-a Synopsis and Exploration Strategies

This section is not designed to only repeat and concentrate the most significant issues in form of a synoptical overview but to amalgamate these facts and forge a first-order exploration model for the selection of target areas and secondly to pinpoint the most fertile zones within such an exploration area with respect to pegmatite-related mineral deposits. Pegmatites are part of the metallogenetic evolution in an ensialic fold belt, the characteristic deposits of which were treated in the previous sections. Thereby some of these reference types of mineral deposits illustrated in the cartoon of Fig. 2.2a are cast into the role of marker mineralization for pegmatite-prone crustal sections while other ore deposits are held to be diagnostic for crustal section barren as to pegmatites.

2.3.1 *First Order – Model Pegmatites Like Ensialic Mobile Belts*

In the previous Sects. 2.1 and 2.2 two data sets, one summarizing the litho-tectonic results gathered during the most recent past and the other manifesting visibly the metallogenetic inventory were discussed as the geodynamic setting of pegmatitic rocks. Both data sets can hardly be brought in line with a full-blown Wilson cycle that might be held accountable for the evolution of the mid-European Variscides.

Many of the complex models describe rifting and ocean spreading, active continental margin settings with island arc magmatic activity caused by subduction, nappe stacking and last but not least collision-related felsic intrusions for the various uplifted basement blocks in central Europe (Hann 2003; Konopásek and Schulmann 2005). Similar processes were also claimed by students of the Cadomian orogeny a predecessor of the Variscan orogeny, to take place in the period of time from more than 550 Ma to 510 Ma (Willmer et al. 1995; Zulauf et al. 1999; Dörr et al. 2002). Subduction-related volcanic activity in the Gondwana continental crust accompanied off-shore by a volcanic arc similar to its modern counterpart in the western Pacific Ocean has been claimed for the core zone of the Variscides in the Bohemian Massif, where the Tepla-Barrandian is supposed to be representative of this geodynamic setting.

While in the western Pacific ophiolites and their genetically related deposits with Cu, Cr, Ni and PGE are abundant, similar deposits are almost absent in Central Europe, as has been demonstrated in the individual sections dealing with the economic geology of each geodynamic unit. Porphyry Cu-Au and their “smoking

guns” the epithermal Cu-Au deposits which render this Pacific area one of the most strongly exploited parts in terms of these types of deposits did not show up in central Europe either. This is not a matter of age and the erosive level but the different style of orogenies.

Going further east, in the central Asian interior, where gold, copper, molybdenum, rare earths elements and tungsten deposits were concentrated in the Kazakhstan-Kyrgyzstan border region during the Middle to Early Carboniferous age. The ore deposits in this region are situated within the Urals-Mongol Fold Belt and developed along an active plate margin. This compressional regime, including plate subduction, partial melting and igneous activity, was in full swing from the Devonian through the Carboniferous. Subsequent extension during Permian and early Triassic times may already herald the break-up of the Variscan/Hercynian continent and the incipient stages of the newly formed Tethys (Abdakhmanov et al. 1997; Rafailovich 1997). While granite-related Au, Cu, Mo, W, REE deposits, porphyry-type and epithermal gold deposits are widespread during the late Paleozoic, pegmatite deposits are a rarity.

The inferred metallogenetic evolution throughout the Variscan orogeny is typical of an ensialic mobile belt leading from an initial stage of rifting into a collisional stage giving rise to a complex stacking of crustal sections, involving subhorizontal thrustal movements and the intrusion of felsic magmatic bodies, with the pegmatites and aplites being part of this widespread mobilization of feldspar-quartz magmas. Partial melting of hot lower crust and the interaction with the mantle may account for the complete suite of intrusives from the early Carboniferous more basic syntectonic magmatic rocks to the posttectonic true granites. This sequence has a parallel from the metapegmatites, through the pegmatoids to the true pegmatites at the very end of the orogeny. Crustal thickening, an abnormally high radioactivity in this huge pile of continental crust and shear-zone related friction, in places added up by heat from the mantle are the “kitchen” or “incubator” for the granitic and pegmatitic rocks.

Pegmatites like ensialic orogens but hate ensimatic orogens (Fig. 2.2b). The idea of a metallogenetic evolution in an ensialic mobile belt, exemplified by the Central European Variscides is not a new model because it has already been published in detail by Dill (1985a), streamlined by Dill (1989) and corroborated in the aftermaths by the data of the numerous publications cited in this paper. The ideas were stimulated by the classification scheme put forward by Tankard et al. (1982) and Pitcher (1979, 1982, 1987). The ideas of these authors have been modified and adapted so as to create a geodynamic-metallogenetic basis to build upon succeeding discussion of pegmatites in an ensialic orogen. The characteristic features of the five geological environments are listed in the cartoon of Fig. 2.2b. The pegmatite-prone Variscan type is devoid of the classical subduction of oceanic crustal slaps, a characteristic feature shared also by the Alpine type orogen where pegmatitic rocks, although strongly modified in places reappear next to the uplifted Variscan blocks. It is not really a surprise to find Namibia among the countries rife with pegmatites, a country where Tankard et al. (1982) shaped their model in the Proterozoic Damara Province.

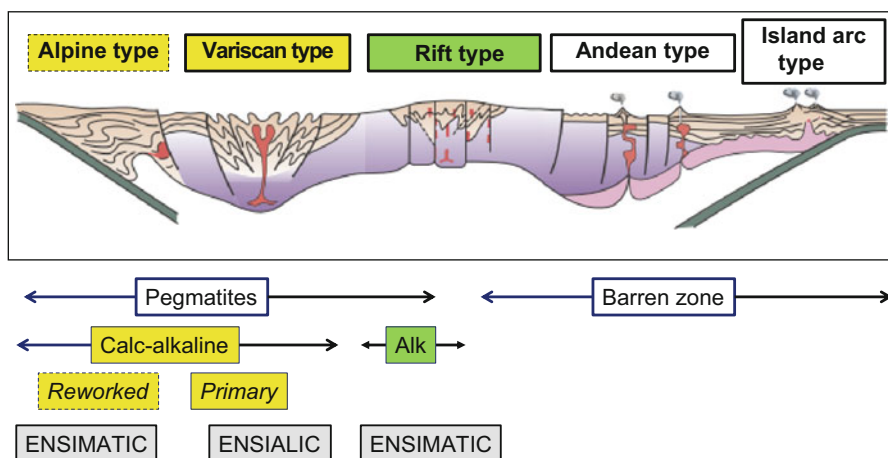


Fig. 2.2b Cartoon to show those environments favorable for the generation of pegmatites in relation to geodynamic settings detrimental to the evolution of pegmatitic rocks. *Alk* alkaline

Granites and pegmatites are “old ironstones” in geological terms, or in other words, they survive even under harsh physical-chemical conditions and may be tracked down to their predecessors or source area using the rare-element spectrum, e.g., Li, Nb-Ta, F and Be. The pseudopegmatites, pegmatoids and metapegmatites, predominantly widespread in the Austrian Alps are striking evidence for the incorporation into this modern fold belt and reactivation in the course of the Alpine metamorphic and kinematic process (reactivated Variscan pegmatites) (Sect. 2.2.3). It is not by chance that the Bohemian Massif is closest to the Alpine Mountain Range, the Li pseudopegmatites are of economic grade and where the Variscan uplifted blocks are depleted in pegmatites, as it is the case with the Schwarzwald-Vosges massifs the correlative Alpine massifs are devoid of productive pegmatites (Sects. 2.2.1 and 2.2.2). In the Western Carpathians, Slovakia, reworked slices of the crystalline basement of the Variscides are of widespread occurrence in the Mesozoic and Cenozoic sediments (Kohút 2013). Granitic rocks and their more basic predecessors originated from melting processes from the Devonian through the Carboniferous. Ensimatic mobile belts may not be the first choice for pegmatites to show up but if it comes to a reactivation of ensialic orogens at their margin, they cannot only stand the new geodynamic process within ensimatic fold belts, but even unfold their whole potential and upgrade.

Coupling the Variscan type orogen, the Alpine type orogen, and the primary *loci* of pegmatitization provide the basis to create a role model that not necessarily is confined to the Paleozoic-Mesozoic orogen. The processes inherent to this model may also be expected in older geological series, although their features may be less well documented there than in the type examples from Meso- and Neoeurope. Vice versa, the various types of pegmatitic rocks held to be typical of the various geodynamic realms can also be used as marker mineralization to disentangle Precambrian

geodynamic systems in ancient cratons. These pegmatitic rocks may guide us during exploration also to crustal sections prone to mineral deposits others than pegmatites which may be attributed to the five types of deposits illustrated in the cartoon of Fig. 2.2a, where a crustal wedge with coupled and decoupled lithospheric mantle and basement thrusts is shown.

2.3.2 Second Order – Model: Pegmatite Like It Hot and Need Friction

Giving just a glimpse at the geodynamic map of central Europe reveals that the pegmatites are distributed not randomly across the uplifted basement blocks of the Variscides. They tend to be linked to particular architectural elements and they are lithologically-controlled as demonstrated by the pie-chart diagrams (Fig. 2.5a, b, c, d, e).

Even though granites are exposed in the north-westernmost part of the Rhenohercynian Zone (Brocken Granite in the Harz Mts.) neither there nor in the immediate foreland pegmatitic mobilizates developed. The country rocks are unmetamorphosed and only, in places, attain very low grade regional metamorphism (Onken et al. 1995). Only near the southeastern margin of the Rhenohercynian Zone, along the Mid-German Crystalline Rise, pegmatites and pegmatoids formed in a suture zone which comparing to the adjacent Rhenohercynian shows a sudden increase in the metamorphic grade (Sect. 2.1.3) (Oncken 1997). You can trace this geodynamic zone through the external zone of the Sudetes in SW Poland (Sect. 2.1.6.1), whose boundary towards the East European Craton is marked by the prominent Tornquist Suture, into the Moravo-Silesian Thrust Belt (Sect. 2.1.6.2). The horseshoe-like belt bounding the Bohemian Massif is marked by deep-seated shear and thrust zones as far as the structural inventory is concerned and its pegmatites are dominated by REE-specialized pegmatites. The reactivated pendant to these REE-bearing pegmatites in the Moravo-Silesian Zone in the Alpine Massifs is situated in the Western Carpathians (Sect. 2.1.4). A second more central belt is confined to the Moldanubian Zone, where some REE-bearing pegmatites are lined up like pearls on the string along the thrust plane separating the medium to high grade Gföhl nappe from the low to medium grade Drosendorf unit (Sect. 2.1.5.1). De Jonge et al. (1997) recorded alteration and brecciation accompanied by saline solution activity at temperatures of greater than 450 °C in shear-zones of the Mount Isa Inlier, Australia. In the course of this retrograde metamorphism Y, Nb and LREE were enriched by 15 times as much as in the country rocks. A similar setting was investigated by Rolland et al. (2003) focusing on mid-crustal shear zones of the granite complex of the Mont Blanc Massif in the western Alps. The physical conditions determined to be at ~0.5 GPa, 400 °C lead to a selective enrichments of LREE or HREE together with Y, Ta, and Hf. The authors claim that REE mobility is unrelated to the deformation style and the intensity of strain and ascribe this REE enrichment of up to 5:1 compared to the initial granite whole-rock REE budget to a synkinematic alteration of pre-existing magmatic REE-bearing minerals during deformation-related

fluid-rock interaction. Fine-grained accessory minerals smaller than 20 μm in the host rock present in amounts of less than 2 wt% are sufficient to build up this REE concentration.

According to the current investigations, fluorine is an element diagnostic for the Saxo-Thuringian zone and its eastern prolongation the, W Sudetes. Its enrichment in granites and pegmatites marks the zone of continent-continent collision with off-shoots towards the core zone of the ensialic orogen. Deep-seated structure zones striking perpendicularly to the NE-SW-trending collision front of the Saxo-Thuringian Zone formed the conduits for the element to get enriched as south as the Saxo-Thuringian-Moldanubian contact zones. Yet this process did not influence the mineral assemblage of the HPPP to the full extent.

The allochthonous units of the Tepla-Barrandian, once forming a coherent nappe with the Münchberg Gneiss Complex and the Zone of Erbsdorf-Vohenstrauß are barren and not considered as prospective for rare-element-bearing pegmatitic rocks. Only in those parts of the ensialic orogen where it overrides the Moldanubian characterized by its HT event, its element association comes close to that of the varied assemblage known from the HPPP, showing similar amounts in Nb, B and P.

Lithium plays an important part in the primary ensialic orogen, the Central European Variscides and in its successor where the crustal section was reactivated under Alpine-type geodynamic conditions. At the boundary of the massif, along the shear and collision zones, Li is mainly accommodated into phyllosilicates such as lepidolite and zinnwaldite with an incipient stage of Li-bearing biotite already present in the suture zone of the Mid-German Crystalline Rise in front of the collision zone. Moving southward into the Moldanubian core zone, pegmatite contain lithium to be accommodated into the structure of phosphates and, as the boron contents rise, into tourmaline s.s.s., such as rossmanite and elbaite in the SE part of the Bohemian Massif. In the pseudopegmatites of the Austrian part of the Alpine mountain range, the re-activated lithium re-appears in form of spodumene (Sect. 2.2.3) and in the western Carpathians as trace element in beryl (Sect. 2.2.4). Lithium minerals are a direct response to the geodynamic variation in the ensialic orogen, reflecting changes in the physical-chemical regime as well as in the fracturing of the Bohemian Massif.

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