Tectonic significance of structures within the salt deposits Altaussee and Berchtesgaden–Bad Dürrnberg, Northern Calcareous Alps

Christoph LEITNER*) & Franz NEUBAUER

Dept. Geography and Geology, University of Salzburg, Hellbrunner Straße 34, A-5020 Salzburg, Austria;

*) Corresponding author, christoph.leitner@sbg.ac.at

KEYWORDS

Northern Calcareous Alps
Haselgebirge
Structures
Rocksalt
Halite
Alps

Abstract

The Northern Calcareous Alps (NCA) are a fold-and-thrust belt. Its Mesozoic units were detached, thrusted and stacked along the rheologically weak, evaporitic Upper Permian to Lower Triassic Haselgebirge Formation, which represents the principal décollement level. It occurs in connection with Juvavic tectonic units, but is also widespread outside Juvavic units as indicated by occurrences at the base of Tirolic tectonic units from Hall in Tirol to Hinterbrühl next Vienna. Exposed in salt mines, rocksalt and mudrock form a two component tectonite with a wide range of fabrics: mostly as crush breccia, protocataclasite, mylonite and ultramylonite. The structural trend differs from one salt deposit to another. Nevertheless, all structures are consistent within each deposit. The axes of isoclinal folds within rocksalt are parallel to the lineation, which is typical for highly sheared ductile rocks. White halite fibers in strain shadows and white halite fibers from veins in mudrock display a similar orientation to the halite mineral lineation and axes of isoclinal folds. Many veins in the mudrock formed as a result of a crack-and seal mechanism. Interpreting the growth direction of fibres antitaxially, the inner, often red-colored part is older relative to the white outer part. The orientation of the white fibres represents the last increment of salt deformation in all Alpine salt deposits. The salt structures within the interior of salt bodies relate to the structures in its surroundings. The study of ages of included and underlying rocks, uncovers evidence of pre-Cretaceous (e.g. Jurassic) salt tectonism, but the salt structures from these earlier events have disappeared. The structures fit best to the Upper Cretaceous to Paleogene fold-and-thrust events of the NCA and, in some cases, were modified in Miocene times.

Die Nördlichen Kalkalpen bilden einen Falten- und Überschiebungsgürtel mit der permisch-untertriassischen Haselgebirge Formation als ihrer stratigraphischen Basis. Deren evaporitische Gesteine dienten als Hauptabscherhorizont. Die Haselgebirge Formation beschränkt sich in ihren Vorkommen nicht nur auf die Juvavischen Einheiten, sondern findet sich auch an der Basis tirolischer Einheiten. Das alpine Salz ist in Bergbauen aufgeschlossen und bildet dabei einen Tektonit aus Steinsalz, Tonstein, Anhydrit und untergeordnet Nebensalzen (als Brekzie, Protokataklasit, Mylonit und Ultramylonit). Die Orientierung der Strukturen ist in den Salzlagerstätten unterschiedlich. Dennoch sind die Strukturen innerhalb der Lagerstätten zueinander konsistent. So sind etwa die Steinsalz-Minerallineation und die Achsen isoklinaler (Futteral-)falten zueinander parallel, wie dies in Gesteinen nach duktiler high strain deformation allgemein zu beobachten ist. Die Orientierung der weißen Salzfasern in Druckschattenhöfen, sowie des weißen Faserkluftsalzes in Tonsteinklüften zeigen ebenfalls die Orientierung der Steinsalz-Minerallineation und der Faltenachsen. Dahingegen lässt rotes Faserkluftsalz keine eindeutige Orientierung erkennen. In allen alpinen Lagerstätten beobachtet man bei den salzgefüllten, zweifärbigen, antitaxialen Tonsteinklüften einen inneren roten und einen äußeren weißen Bereich. Die weiße Fasersalzkristallisation repräsentiert das Ausklingen des letzten Hauptereignisses tektonischer Verformung. Die Makrostrukturen des Salzgesteins sind unmittelbar mit der regionalen Geologie verbunden. Es gibt Hinweise auf jurassische Tektonik, doch sind diese Strukturen weitgehend überprägt. Die Makrostrukturen lassen sich am besten mit den kretazischen bis paläogenen Überschiebungs- und Verfaltungsstrukturen der Nördlichen Kalkalpen korrelieren. Teilweise wurden diese Makrostrukturen im Miozän überprägt.

1. Introduction

Salt dynamics play an important role in the design of sedimentary basins and fold-and-thrust belts as shown in textbook compilations (Hancock, 1994; Warren, 2006; Lacombe et al., 2007; Littke et al., 2008). Compared to other common rocks, the rheology of rocksalt is unique. It recrystallizes at low temperatures and is thus very sensitive to changes in the local stress field (e.g. Urai et al., 2008).

Thick rocksalt bodies occur in several major tectonic settings: (1) intracratonic sag basins, (2) extensional rift basins and passive continental margins, and (3) compressional settings. In extensional settings, gravitationally induced raft tectonics may develop with an underlying continuous salt layer functioning as décollement level. Salt accumulates in salt rollers, which may evolve into a reactive diapirism (Jackson and Talbot, 1994; Hudec and Jackson, 2007). The most important driving force for salt movement is differential loading, which may be induced by (i) gravitational loading, (ii) displacement loading or (iii) thermal loading (Hudec and Jackson, 2007). Buoyancy becomes important at around 1500 m overburden and needs a tectonic trigger to become active. There are three main modes of diapiric uprise: In reactive piercement, the diapir stops its rise as soon as the extension stops. In active piercement, the diapir rises actively by isostasy or lateral compression (up-building). In passive piercement, the diapir rises continuously in accordance with the sedimentation rate (down-building). Most well developed diapirs have passed through these stages. Compressional settings intensify existing structures. In this way, anticlines develop, which carry a salt core. Typical structures are teardrop diapirs often associated with thrusts at their bottoms (Hudec and Jackson, 2007). Salt sheets may appear during down-building as lateral salt escapes due to differential loading of sediment accumulation as a plug-fed extrusion. Salt sheets may also result from compression of existing diapirs as plug-fed thrusts or from not yet accumulated salt layers as source-fed thrusts (Hudec and Jackson, 2006).

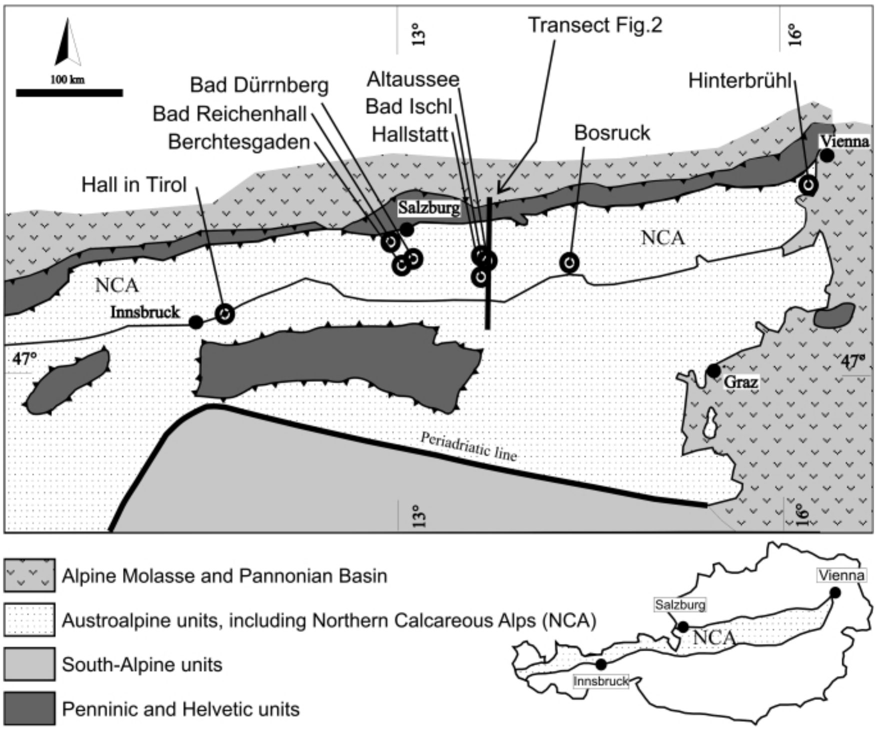

Figure 1: Overview sketch map of the Eastern Alps. Main tectonic units and location of salt mines in the central NCA. Insert at right bottom gives the position within Austria. Circles mark rocksalt deposits.

In compressional settings, the amount of shortening is important. Formations comprising rocksalt or other evaporites at the base of thrusted cover units exist, for instance, in the Appalachians (Davis and Engelder, 1985), Swiss Jura (Sommaruga, 1999), Salt Range in Pakistan (Jadoon and Frisch, 1997) and Zagros Mountains (Sherkati et al., 2005; Alavi, 2007).

The Northern Calcareous Alps (NCA; Figs. 1, 2) form a thin-skinned fold-and-thrust belt, which is part of the Austroalpine nappe complex of the Austrian Eastern Alps. The NCA include Lower Permian to Eocene clastic and carbonatic formations. The Upper Permian to Lower Triassic Haselgebirge Formation (Buch, 1802; Klaus, 1965; Spötl and Pak, 1996; Spötl, 1988a, 1988b) close to the base is an evaporitic succession which represents one of the major detachment levels (e.g. Linzer et al., 1995). It is poorly exposed at the surface. However, a number of operating mines in central sectors of the Northern Calcareous Alps provide subsurface exposures, where the salt has been mined for more than 3,000 years like in Hallstatt and Bad Dürrnberg (Stöllner, 2003; Klein, 2006; Grabner et al., 2007).

Halite, mudrock and subordinate anhydrite and polyhalite form an evaporitic mélange (Schauberger, 1931, 1949, 1986). In the salt mines, the average halite content ranges between ca. 30–65 wt %. In the following, "halite" is used as the name of the mineral, "rocksalt" refers to the monomineralic rock of halite with only minor xenolithic inclusions, "salt rock" refers to rocks with various halite contents and "salt" is an undifferentiated expression. Rocksalt and mudrock form a two-component tectonite: mostly as crush breccia, protocataclasite (≈ haselgebirge, 10–70 wt % halite), mylonite and ultramylonite (≈ kerngebirge, >70 wt % halite; Leitner et al., 2011; Tab.1).

The central sectors of the Northern Calcareous Alps suffered high diagenetic to low grade metamorphic conditions at around 200–300°C during the Late Jurassic to early Late Cretaceous (Kralik et al., 1987; Spötl, 1992; Götzinger and Grum, 1992; Gawlick et al., 1994; Wiesheu and Grundmann, 1994; Spötl et al., 1996; 1998a, 1998b; Wiesheu, 1997; Spötl and Hasenhüttl, 1998; Rantitsch and Russegger, 2005). Age estimates for this thermal peak range between 150 Ma and 90 Ma (Kirchner, 1980; Kralik et al., 1987; Hejl and Grundmann, 1989; Götzinger and Grum, 1992; Gawlick et al., 1994; Spötl et al., 1996; 1998a, 1998b; Gawlick and Höpfer, 1996; Ran-

rock type (according to Schauberger, 1986)	halite in wt %	in terms of structural classification of fault rocks (e.g. Wise et al., 1984)
rocksalt (nearly pure halite rock)	100 - 90	ultramylonite
kerngebirge (rich in halite)	90 - 70	mylonite
haselgebirge (medium content of halite)	70 - 10	protocataclasite, cataclasite, protomylonite, mylonite
mudrock (deformed/ undeformed)	10 - 0	crush breccia

Table 1: Nomenclature of salt rocks after Schauberger (1986), simplified. On the right, the well-established structural classification of fault rocks.

titsch and Russegger, 2005; Frank and Schlager, 2006).

The aim of this study is to constrain the conditions and the geological frame of the development of the visible tectonic structures within the mines. Detailed mapping of mesoscale structures was carried out in the mines of Berchtesgaden, Bad Dürrnberg and Altaussee in 2006–2009; Hallstatt, Hall in Tirol and Bad Ischl were visited for comparison.

2. Geological setting

2.1 Northern Calcareous Alps (NCA)

The classic division within the Northern Calcareous Alps defines the Bajuvaric, Tirolic and Juvavic nappe complexes (Figs. 1, 2). Thrusting prograded from South to North (Linzer et al., 1995; Neubauer et al., 2000).

The age of formations in the Northern Calcareous Alps ranges from late Carboniferous or early Permian to Eocene. Rocksalt deposits are mostly found in the Lower Juvavic unit. The westernmost part of the expanding Triassic Tethys Ocean is called Meliata Ocean, and is represented by rare deep sea sequences occurring in the eastern parts of the NCA (Faupl and Wagreich, 2000; Mandl, 2000; Neubauer et al., 2000 and references therein). The Meliata Ocean was closing during Late Jurassic (e. g., Dallmeyer et al., 2008). Coevally, the sea floor dropped and reached a maximum water depth with the formation of radiolarites in the footwall plate (NCA) by thrust loading. The Lower Juvavic nappes containing the rocksalt took their position during eo-Alpine (i.e. pre-Late Cretaceous) nappe tectonics during Late Jurassic times (Mandl, 2000; Frisch and Gawlick, 2003; Missoni and Gawlick, 2010). At the transition from Early to Late Cretaceous, nappe stacking of Austroalpine units continued due to the subduction of Austroalpine continental crust.

In the Eocene, the second stage of the Alpine orogeny occurred, resulting in the collision of the stable European continent with the overriding Austroalpine units. The NCA as we know them today were detached from their basement and thrusted over the Rhenodanubian Flysch and Helvetic domains resulting in a wide thin-skinned nappe complex (Linzer et al., 1995; Neubauer et al., 2000). The detachment from basement occurred beneath the northern- and lowermost unit, the Bajuvaric nappe (Fig. 2). Deformation of Upper Cretaceous to Eocene Gosau basins deposited on uppermost nappes (Tirolic and Juvavic nappes) suggests significant post-Middle Eocene deformation. In Miocene times, due to still ongoing intracontinental convergence, parts of the decoupled crystalline basement of the Northern Calcareous Alps escaped in west-east direction, causing the formerly subducted material of the South Penninic Ocean to emerge at the surface in the Hohe Tauern window as a metamorphic core complex. The Northern Calcareous Alps were also affected to a large extent. Mainly strike-slip faults were active as recorded by structural data (Decker et al., 1994; Peresson & Decker, 1997; Linzer et al., 1997, Neu-

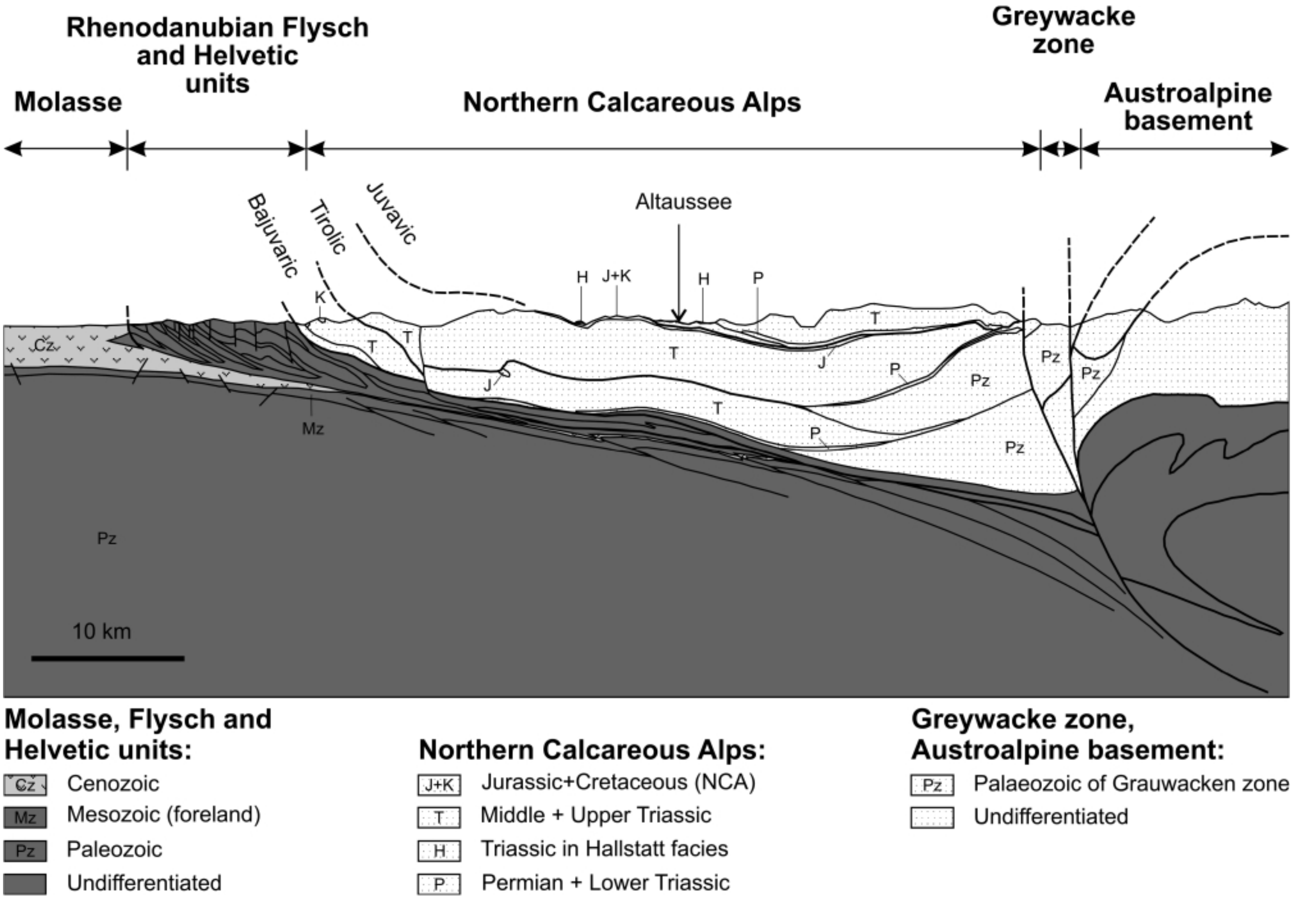

Figure 2: Geological transect of the central NCA (modified after Schmid et al., 2004).

bauer et al., 2000, Pueyo et al., 2007).

In the Quaternary, ice glaciers eroded the mountains and formed a relief with overdeepened valleys.

2.2 The salt mines of the NCA (Austria and Germany)

The underground mines of Berchtesgaden and Bad Dürrnberg are located within the same salt body, but were mined from two different sides due to the historic land tenure between Austria and Germany. At the surface, the body extends SW–NE, and is 0.5–2.0 km wide and ca. 7 km long (maps: Prey, 1969; Ganss, 1978; Del-Negro, 1979). The bottom was found by drilling at a depth of 1000 m deep below the surface (Drilling B 307, pers. comm. Südsalz GmbH). The average halite content of the Haselgebirge Fm. is 55 wt %. The abandoned underground mine of Bad Dürrnberg is located at the eastern end (Fig. 3), the underground mine of Berchtesgaden is located at the western end (Fig. 4). The large Berchtesgaden-Bad Dürrnberg body is encased between a lower Tirolic nappe and a higher Upper Juvavic nappe. The salt body incorporates mainly Middle–Upper Triassic limestones of the Hallstatt facies typical for the Lower Juvavic unit (Tollmann, 1985), which is nearly complete in this area. It includes the Werfen Fm., Gutenstein Fm., Steinalm Fm., Schreyeralmkalk Fm., Raibler Fm., Hallstatt Fm., Zlambach Fm. and Dürrnberg Fm., ranging in age from Early Triassic to Early Jurassic (Plöchinger, 1976, 1984, 1990, 1996; Gawlick and Lein, 1997, 2000; Gawlick et al., 2001; Tab. 2). Rocks from the underlying western part of the salt body, close to Berchtesgaden, belong to the newly introduced Birkenfeld Fm. (Toarcian to Aalenian, ≈ 184–174 Ma; Gawlick et al., 2009). Braun (1998) interpreted rocks incorporated into the salt body as Tauglboden Fm. (Kimmeridgian to Tithonian, ≈ 155–149 Ma). The youngest known completely incorporated rocks within the Haselgebirge Fm. belong to the Jurassic Oberalm Fm. (Kellerbauer, 1996). Plöchinger (1976, 1984) found Haselgebirge clasts within the Oberalm Fm. (Tithonian to Berriasian, ≈ 149–140 Ma) near the eastern border of the salt body, close to Bad Dürrnberg. In easternmost parts, Haselgebirge Fm. rocks are found within the Schrambach Fm. (Valanginian, ≈ 140–135 Ma; e.g. in a geothermal borehole at Marktschellenberg in 2009), and the Haselgebirge Fm. also exists on top of the Rossfeld Fm. (Hauterivian to Barremian, ≈ 135–125 Ma; e.g. Prey, 1969).

The salt body of Altaussee crops out around the mountain Sandling (map of Schäffer 1982). On map view, it has an extent of around 2.3 km² and has roughly the form of a wedge with its small side down (Fig. 5). The halite content of the Haselgebirge Fm. is 65 wt % and it is typically red due to polyhalite admixture. The bottom has not been reached by drilling down to 100 m below sea level (Proisl, 2003). The highest point of the Haselgebirge Fm. is located 1130 m above sea level. The only blocks incorporated within the Haselgebirge Fm. are limestones of the Hallstatt Fm. The deposit is surrounded by the newly introduced Middle Jurassic Sandlingalm Fm. (Gawlick et al., 2007). Radiolarite and cherty marls contain huge blocks of the Hallstatt Fm. in a wild-flysch facies (Medwenitsch, 1957). The Sandlingalm Fm. is supposed to have a stratigraphic thickness of ca. 700 m. The transition to the stratigraphically succeeding micritic limestones of the Oberalm Fm. appears to be cut out by faulting. The mountain Sandling covers the deposit and consists of Jurassic Oberalm and Plassenkalk Fms. (Wegerer et al., 2001; Gawlick et al., 2007).

The salt body of Hallstatt extends ca. 3.0 km in E–W direction and is around 600 m wide (maps and sections: Schäffer, 1982; Scheidleder et al., 2001). The highest point is 1350 m above sea level, the lowest Erbstollen level is at around 500 m above sea level (section of Schauberger in Habermüller, 2005). The salt body suitable for mining diminishes with depth, mostly because of incorporated country rocks. The base has not yet been reached at 100 m below the level of lake Hallstatt (pers. comm. Salinen Austria AG). The halite content of the Haselgebirge Fm. is around 55 wt % (Schauberger, 1931, 1949, 1953). The mining started in Celtic times, as indicated by a Bronze-age staircase found in the mine, which was dated accurately by dendrochronology at 1344 BC (Grabner et al., 2007). The succession of the Lower Juvavic unit is nearly complete: Werfen Fm., Gutenstein Fm., Steinalm Fm., Schreyeralmkalk Fm., Raibler Fm., Hallstatt Fm., Zlambach Fm. and rocks of the Adnet Fm. group. Rocks incorporated into the salt are Permian melaphyre volcanics (Schauberger, 1949; Zirkl, 1957), Permian clastic sediments, which were interpreted as a time equivalent to the Gröden Sandstone Fm. from northern Italy (Spötl, 1987), and rocks of the Hallstatt Fm. (Krystyn, 2008) are often associated with Jurassic rocks (Sandlingalm Fm.). The situ-

	Berchtesgaden	Bad Durrnberg	Altaussee	Hallstatt	Hall in Tyrol	Bad Reichanhall	Bad Ischl
Permian	-	-	-	volcanik rock	-	-	volcanik rock
Triassic	HK	TR, HK, ZL	HK	TR, HK, GR	RD	TR, RD	HK
Jurassic	BI*, RG, OB	DÜ	RG*	RG*	-	-	-
Crataceous	-	SCHR*	-	-	SCHR*	GOSAU	ROSS*
Tertiary	-	-	-	-	-	INNALP	-

Table 2: Completely incorporated enclaves of country rocks within the Haselgebirge Fm. Asterisk mark formations underlying the Haselgebirge Fm. Abbreviations: BI = Birkenfeld Fm. (limestone), DÜ = Dürrnberg Fm. (limestone), GOSAU = Gosau Group (conglomerate, limestone, marl), GR = equivalent to Gröden Fm. (siltstone, sandstone), HK = Hallstatt Fm. (mainly dolomite, limestone), INNALP = Intra-Alpine Tertiary (conglomerate, sandstone, marl), TR = Lower to Middle Triassic formations (e.g. Werfen, Gutenstein, Steinalm, Schreieralm, Raibler; mainly carbonates, sandstone), OB = Oberalm Fm. (limestone), RD = Reichenhall Fm. (dolomite, limestone), RG = Deep-sea facies Jurassic (Ruhpolding Radiolarite, Tauglboden, Sandlingalm formations; radiolarite, marl), ROSS = Rossfeld Fm. (sandstone, conglomerate), SCHR = Schrambach Fm. (marl), ZL = Zlambach Fm. (marl).

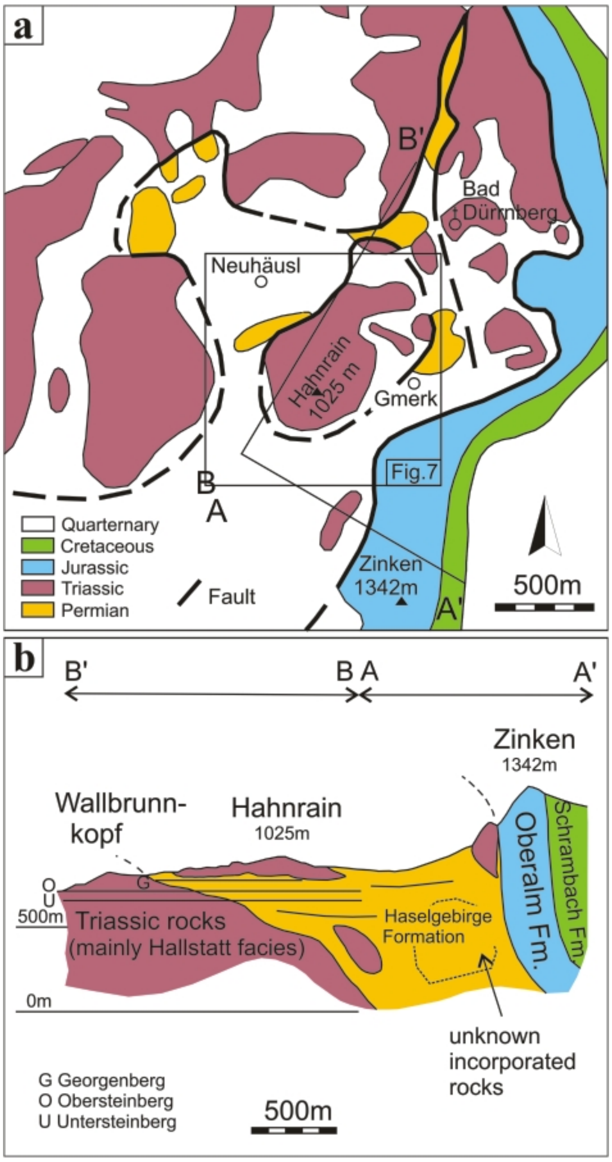

Figure 3: Bad Dürrnberg (a) Geological map simplified after Kellerbauer (1996) and (b) cross section simplified after Plöchinger (1996).

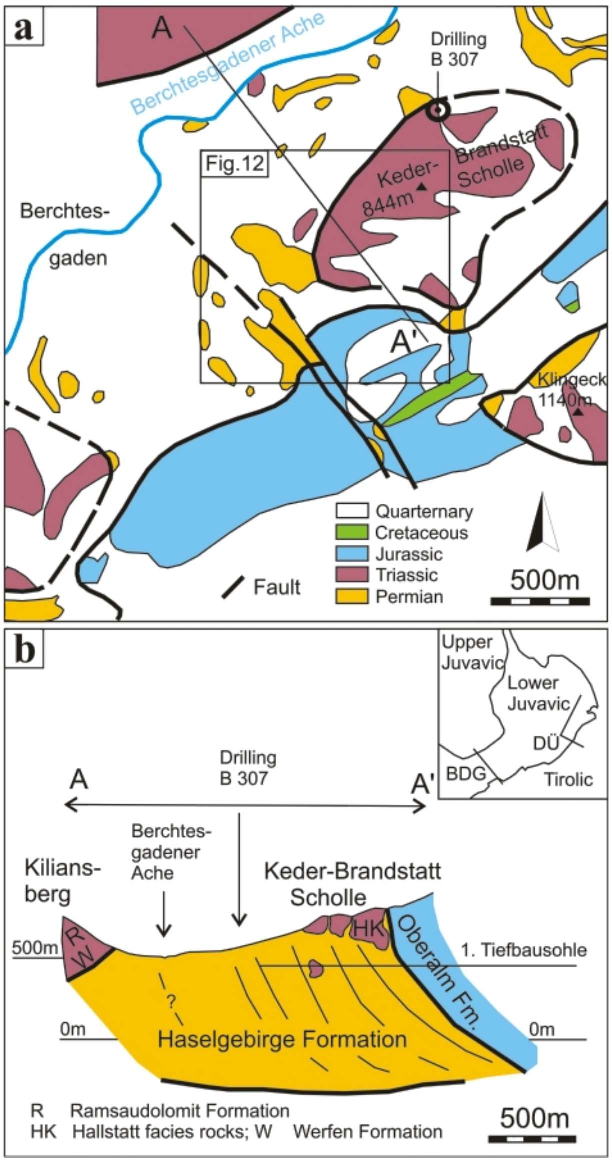

Figure 4: Berchtesgaden (a) Geological map and (b) cross section, both modified after Kellerbauer (1996).

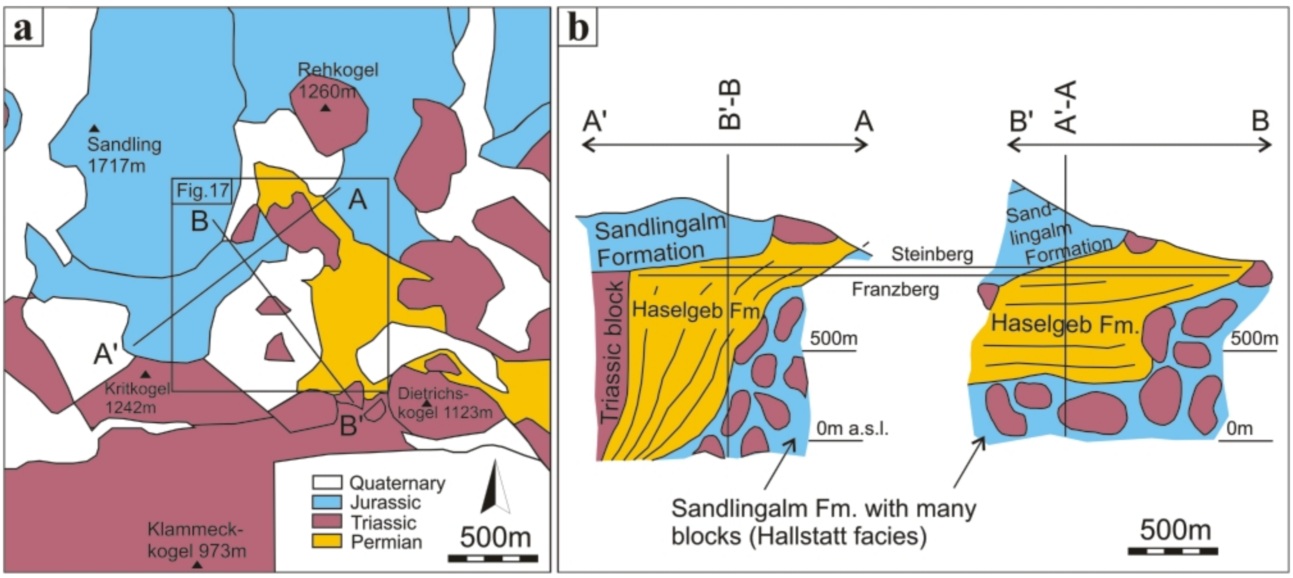

Figure 5: Altaussee (a) Geological map simplified after Schäffer (1982) and (b) cross sections.

ation is similar to Altaussee: Blocks composed of the Hallstatt Fm. are in contact with rocks of the Sandlingalm Fm. (former classified as Allgäu and Zlambach Fms.) which, together with the Haselgebirge Fm., are covered by an undeformed lid of Upper Jurassic rocks (Gawlick and Schlagintweit, 2006; Suzuki and Gawlick, 2009). A sedimentary contact between the Sandlingalm Fm. and the overlying Plassenkalk Fm. is missing (Suzuki and Gawlick, 2009). On a map view of Hallstatt, the Lower Juvavic unit, the rocksalt and the Jurassic cover are found within the area of the Upper Juvavic nappe.

The abandoned salt deposit of Hall in Tirol is ca. 1.4 km in E–W extension, and around 1 km² on map view at the level of Königsberg. The underground mine is located in the valley of Hall in 1300–1700 m above sea level. The deepest drilling was done to ca. 1000 m above sea level (structural maps: Schmidegg, 1951; Spötl, 1989b; surface map: Moser, 2008). The salt body lies between the lower Bajuvaric nappe and the higher Tirolic nappe and is interpreted to be cut off with depth (section in Oberhauser, 1980). The average halite content of the Haselgebirge Fm. is only around 30 %. The Haselgebirge also exhibits large bodies of dolomite-anhydrite rocks, which have been dated as Early Triassic (Spötl, 1988c). Rocks of gypsum partly exhibit protocataclasite and mylonite structures.

At Bad Reichenhall, natural brine springs have been known for a long time. Since 1970, saturated brine has been produced from boreholes, which were drilled down to 1200 m below the surface. The Haselgebirge Fm. contains dolomite-anhydrite rocks of the Reichenhall Fm., similar to Hall in Tirol. The outcrop is located between the lower Tirolic nappe and the higher Juvavic nappe. Interestingly, rocks of both, the Gosau Group (Late Cretaceous to Eocene) and of a further Eocene intramontane sedimentary basin are incorporated within the Haselgebirge Fm. (Hillebrand, 1962; Schauberger et al., 1976; Zankl and Schnell, 1979; map and section: Kassebaum, 2001).

The abandoned salt mine of Bad Ischl is small, estimated to cover 0.5 km² in map view. Outcrops at the surface are rare and the salt deposit is hidden by the overlying, respectively incorporated country rocks (map: Schäffer, 1982). The mined salt body extends in elevation from 500–1000 m above sea level. The salt is squeezed between Triassic, Jurassic and Cretaceous rocks (sections: Schadler, 1949; Mayrhofer, 1955; Medwenitsch, 1957). The lower boundary was not reached by a 300 m deep drilling from the lowest Erbstollen level (final depth 180 m a.sl., pers. comm. Saline Austria AG). In the west, the mine is connected to the adjacent, still working solution mining field in the Traun valley. The valley formed during the last ice age. In a depth of 270 m below surface, haselgebirge exists with around 50 wt % halite. The body is around 250 m thick, whereby the total dimension of this salt body is expected to be several square kilometers (Schauberger, 1986). Volcanic rocks were reported (Vozárova et al., 1999). It is, at least partly, underlain by Tirolic units and is tectonically overlain by Juvavic units.

3. Methods

During this study, all the salt mines of the NCA were visited. Additionally, the leached out outcrops in the currently excavated second tube of the Bosruck tunnel and the tourist gypsum mine Hinterbrühl were visited (Fig. 1).

The mesoscale structures formed during geodynamic processes and thus record the internal kinematics of salt deposits. Moreover, by linking structural orientation to age of deformation it is possible to draw conclusions about the dynamics of the geological setting.

All measured structural data was analysed and plotted using the program TectonicsFP (Ortner et al., 2002). All orientation data of planes and lineations are given with dip/plunge direction and dip/plunge angle.

4. Results

4.1 Rocksalt in underground mining

The salt rock exposes all types of transitions from nearly undeformed mudrock to nearly pure rocksalt (Tab. 1). Haselgebirge can reach different stages of homogenisation. In a stage of homogenisation, the mudrock components are not larger than equidimensional pieces of gravel (Deutsches Institut für Normung e.V., 2004). The matrix consists of red and white rocksalt. The components are often covered with a dark rim of slickensides. Sometimes, up to meter-sized clasts of anhydrite, polyhalite rock and mudrock are found within haselgebirge. These rocks often preserve structures from sedimentation, diagenesis or early tectonic destruction. Strain shadows, filled with halite occur locally at all scales. The macroscopic appearance of the salt rock often changes along the galleries within a few meters (e.g., Schauberger, 1931, 1949, 1953, 1986; Spötl, 1989a).

The average grain size of halite in rocksalt is 1–3 mm (Leitner et al., 2011). Rocksalt layers are usually internally foliated, stretched, folded and thinned, and expose a mylonitic foliation. The lineation of shape-preferred halite and aligned particles of mudrock, anhydrite and polyhalite has an overall similar orientation, but locally it often follows the shape of incorporated rigid blocks of country rocks. S-tectonites commonly display platy halite grains. σ- and δ- strain fringes with halite fibres around rigid rock pieces (commonly mudrock), aligned objects and drag folds are sense-of-shear indicators. However, Φ-type objects dominate. L-tectonites were also observed in distinct shear zones. The distinguishable layers reduce to centimeter-scale (Liniensalz in German). In the galleries, folds in rocksalt are isoclinal on the scale of meters, but isoclinal folds can be assumed at all scales.

The development of leaching caverns from their bottom to top has been documented systematically since the last two centuries. Their shape and aspect ratio in plan view depend on their height, the method of leaching and the dip of the foliation. Because leaching of haselgebirge is easiest at a high percentage of halite, caverns usually develop elongated shapes. In most cases, the strike of caverns is similar for the entire deposit.

4.2 Veins and slickensides in mudrock

In Alpine salt bodies, veins in mudrock with fibrous halite often exhibit slickensides on the wall rock. Sometimes, more than one generation of fibres is observed. Combinations of different colours of halite infill range from red to orange and white. From the observations described in the following it can be deduced that (i) the veins are of antitaxial type (Oliver and Bons, 2001; Hilgers and Urai, 2002, 2005), and (ii) slickensides originated before the opening of veins.

In the centers of veins, a median line of wall rock particles often exists. Fibres are normal or oblique to the wall rock, bend towards the median line and are nearly parallel to the wall in the central median line. Fibres in half of the ca. 40 investigated samples border sub-perpendicular to the wall rock surface. Fibres are usually continuous from the wall rock towards the vein center. In all of the samples, the white vein fillings were fibres. Its fibres are long (usually 2–10 mm) and thin (0.2 mm). Red and orange halite forms thick fibres (up to 0.5 mm) or grainy aggregates. The displacement is in the range of the vein thickness. Usually, white salt cuts off red salt vein infill. For veins with two or more differently coloured generations, the colour is arranged symmetrically, white fibrous halite always forms the outer parts and red halite the central part of the vein. Red halite infills are then often blocky, non-idiomorphic equidimensional grains (Fig. 6a–b). The red colour is likely submicroscopic hematite (compare Richter, 1962; Urai and Boland, 1985). The blocky nature can be caused by high supersaturation, when fracturing results in a fluid pressure drop (Oliver and Bons, 2001). Dynamic recrystallization may also lead to such a texture, but both phenomena require elevated temperature-pressure conditions. On the other hand, inhibited growth competition, which is a characteristic of fibrous growth, is a low-temperature process (Oliver and Bons, 2001). Development of facets and growth competition of white halite fibres are suppressed, where opening increments of the vein are small (Hilgers and Urai, 2002). No further grains were nucleated during vein growth. This implies that supersaturation was sufficiently low at the site of growth (Hilgers and Urai, 2002 and references therein).

Fractures in mudrock with slickensides combined with fibres are common (Fig. 6c–d). Fractures with only fibres make up about a quarter of all observations. Red veins more often show slickensides than those with a white infilling. Slickensides were found mirror-symmetrically. Both salt and mudrock act as seals, generating an overall hydrostatic overpressure and thus enabling cracking of mudrock. The fracture plane opened as a vein later during an extensional event, for instance by a tectonic rupture. Halite crystallized within the new-formed vein. Neighbouring salt patches are the source of either red or white halite indicating specific chemical conditions.

4.3 Slickensides in haselgebirge

Slickensides in haselgebirge are found in the upper levels of the mines. In Bad Dürrnberg, mined rocks of the Celtic Era are easy to identify by their leopard texture and chips of fatwood. They were cut through, which indicates a recent, active movement along these faults. Slickensides in the haselgebirge of the same type were also observed in the upper levels of Berchtesgaden, Altaussee and Bad Ischl.

4.4 Mesoscale structures in the Bad Dürrnberg mine

The foliation planes are flat-lying. A preferred NE–SW strike of the leaching caverns prevails. In the northern part of the deposit, their orientation turns into N–S strike. Lowest levels and central parts do not, or only subordinately, expose an elongation of the caverns (Fig. 7).

The plunge of the halite lineation (Ls) is gentle and directions

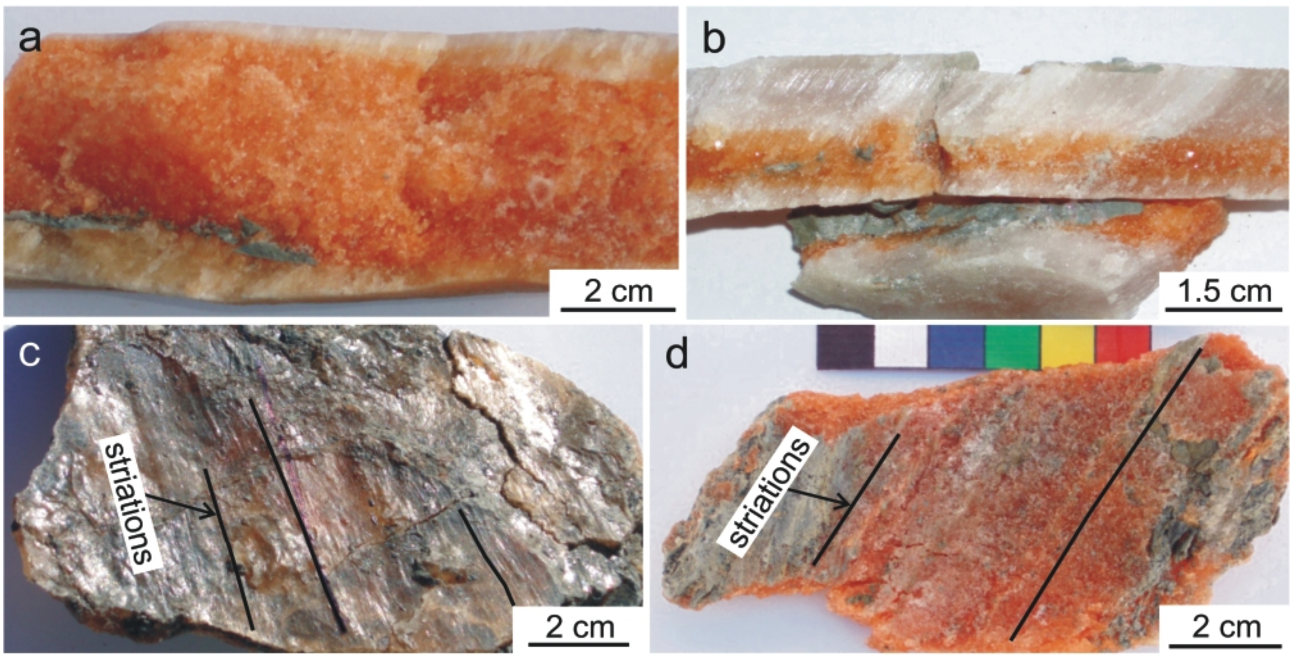

Figure 6: (a)-(b) Antitaxial halite veins in mudrock. (c)-(d) Slickensides on wall rock.

scatter broadly within forty degrees, but expose a general NE–SW direction. Nearly all data was measured within the center of the salt deposit, most of them on the levels of Obersteinberg and Untersteinberg. Fibres of white halite within strain shadows around mudrock clasts (Fs) indicate a NE–SW orientation, which is the same as the halite lineation. A definite transport direction could not be interpreted by means of shear sense indicators. Seven shear sense determinations indicate top to SW or S shear, whereas five suggest top to the NE or N transport. However, non-rotational deformation dominates.

Folds of argillaceous anhydrite, isolated in the haselgebirge matrix, formed during a tectonic event, earlier than the structures described in this study. Isoclinal folds in rocksalt are flat-lying folds, fold axes trending NE–SW, just like L_s and F_s do (Figs. 8, 9).

Halite veins were separated by colours (Fig. 10). Data of red and orange halite do not reveal a specific orientation. The red veins are supposed to represent former deformation stages. Measurements of white halite veins show no significant orientation except a subordinate preferred WNW–ESE strike. Eleven measured purple halite veins expose a preferred E–W to NW–SE strike. The E–W striking group could represent a reactivated orientation of some red veins, the other group correlates to the strike direction of white veins within the haselgebirge. Veins through haselgebirge or kernsalz contain only white fibrous halite. They possess no sharp wall boundaries and are on the scale of meters. They can be expected to be very sensitive to further deformation. We found two groups, one on the level of Obersteinberg and one on the level of Georgenberg. The first strikes steeply NW–SE, the other from Georgenberg is flat-lying with vertical fibres.

Fibres of white halite in veins from the center of the salt deposit show a preferred NE–SW orientation, which is identical to the orientation of the halite lineation and isoclinal folds in the rocksalt.

Slickensides in mudrock were found in red and white halite veins. No dominating orientation was visible, neither of the fault planes, nor of the lineations.

Slickensides in haselgebirge are found at all mining levels. The most impressive ones are exposed along the Ferro gallery, Obersteinberg level. The width of the gallery decreases faster here than elsewhere in the mine and has to be restored every couple of years (pers.comm. Salinen Austria AG). The normal faults show a vertical offset. Paleostress analysis gives a vertical σ_1 direction with a corresponding NW–SE σ_3-direction (Figs. 10, 11).

4.5 Mesoscale structures in the Berchtesgaden mine

The elongated leaching caverns are oriented similarly NE–SW (Fig. 12). Only at the very western end of the salt deposit, the caverns expose various shapes and orientations. Known from geological mapping of caverns, the foliation dips very steep at level Erste Tiefbausohle, and steep in the lower sectors (Leitner et al., 2011; Fig. 13). A representative orientation of the foliation for the main part of the deposit is 135/70. The

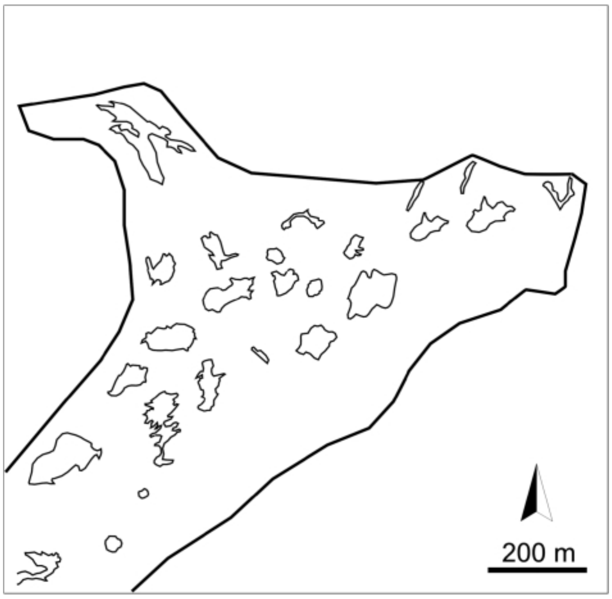

Figure 7: Bad Dürrnberg, Obersteinberg level, simplified, depth of caverns ca. 650–750 m a.s.l., no preferred orientation of shapes.

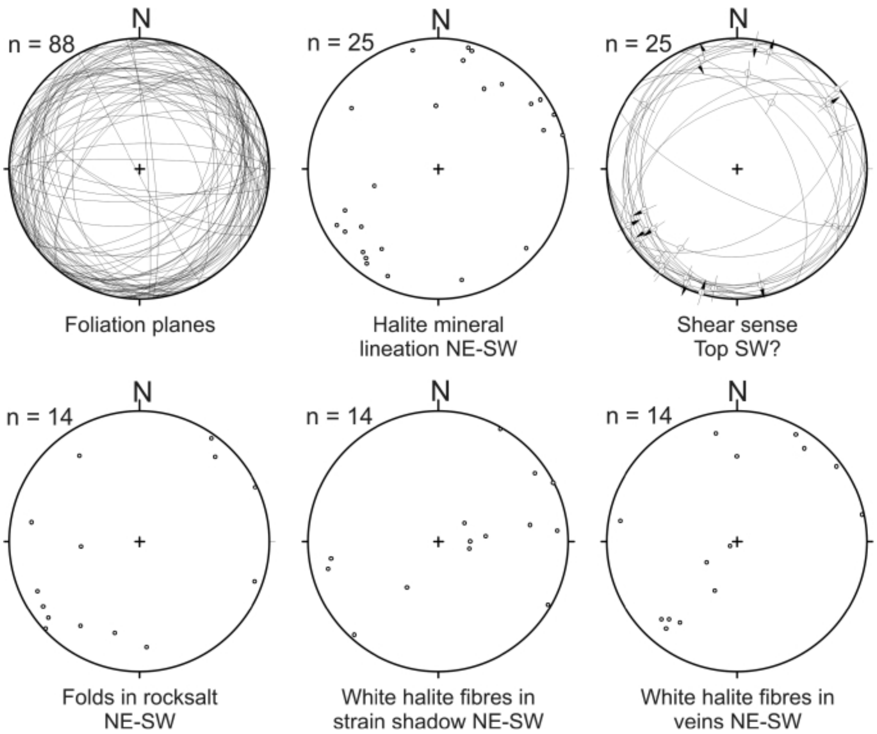

Figure 8: Bad Dürrnberg, orientation data of rocksalt (for explanation, see text). Equal area projection, lower hemisphere.

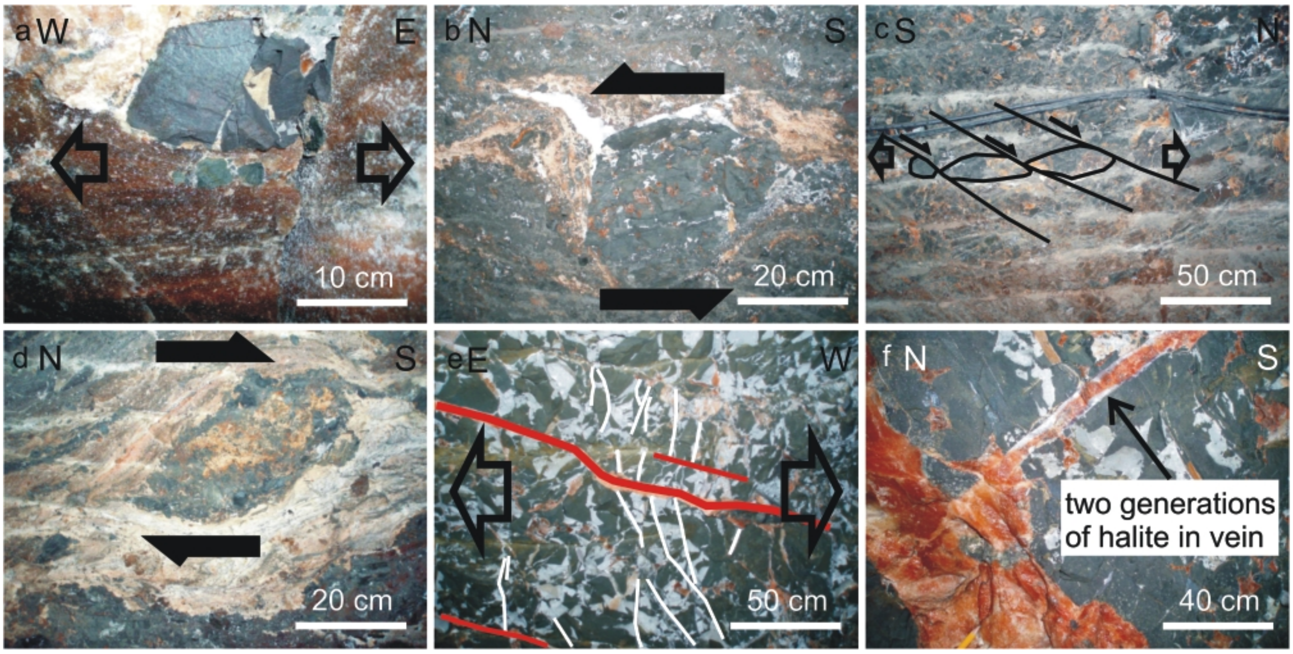

Figure 9: Bad Dürrnberg, photos illustrate flat orientation of foliation. (a) Clast in rocksalt breaks during non-rotational deformation. (b) δ-type porphyroclast with white halite in strain shadow. (c) Normal faulting due to extension. (d) σ-object consisting of mudrock. (e) Veins with white halite infill opened rectangular to the extension direction. (f) Mudrock with veins. Two generations of vein infill, inner red and outer white halite.

orientation corresponds to the southeastern border, respectively to the layers of the adjacent Oberalm Formation.

In a comprehensive plot of all measured halite lineations, only the NW area is empty, whereas the SE area exposes a maximum. White σ- and δ- strain fringes show a top-SE transport direction (Figs. 13, 14). When the all-encompassing halite lineation, associated with the white strain fringes was excluded from analysis, a subordinate second NE–SW orientation of the halite lineation remained.

The orientation of isoclinal fold axes spreads over the entire plot, exposing a slightly visible NE–SW preferred orientation. This orientation corresponds to the second, subordinate direction of the halite mineral lineation. Both structural elements were found in the same places.

Red (or orange), purple and combined red/white veins in mudrock show no preferred orientation (Fig. 15). In contrast, veins with white fibrous halite in mudrock strike predominantly NE–SW, dipping steeply to gently to NW. Veins through hasel-

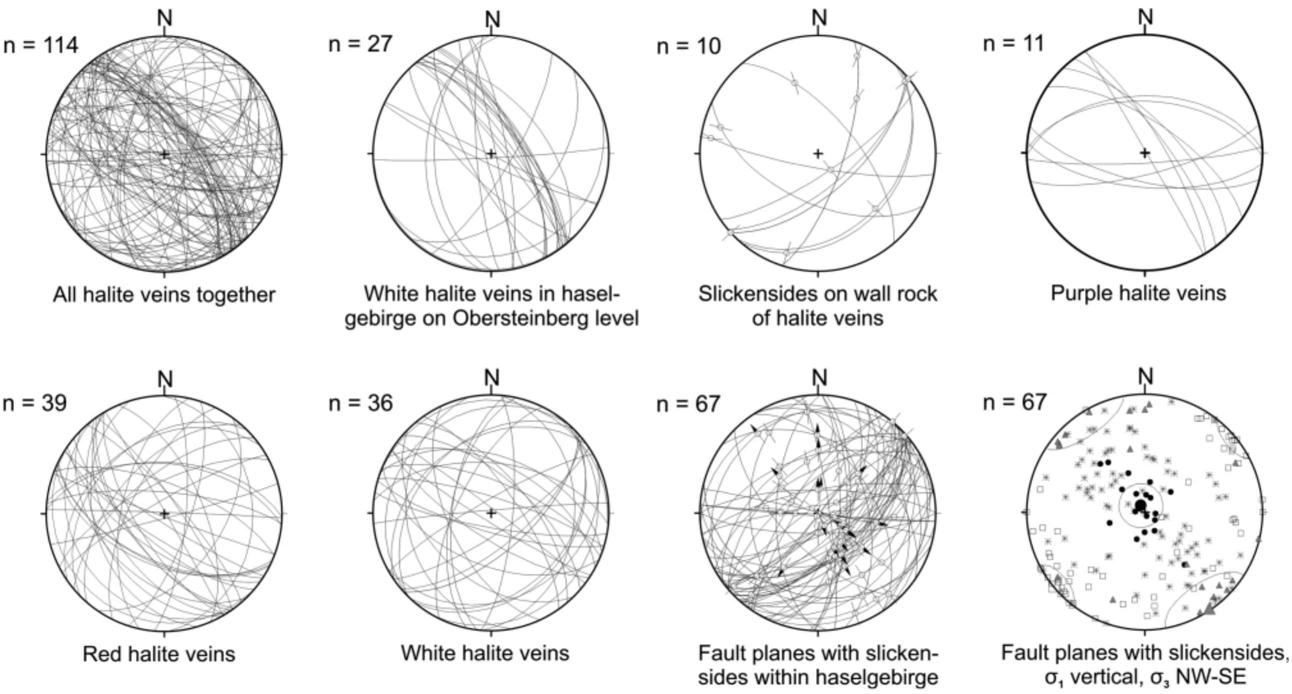

Figure 10: Bad Dürrnberg, orientation data of veins and fractures (for explanation, see text). Equal area projection, lower hemisphere.

gebirge were recognized in only two places, where they cross the foliation. They strike NE–SW.

White halite fibres show a maximum of directions to the SE. This direction corresponds to the orientation of white fibres within strain shadows around clasts and the dominant halite lineation (compare Fig. 13).

Slickensides in mudrock were found within red and white halite veins. Slickensides along the wall rock of the veins revealed no preferred orientation.

Beneath a carbonate block floating in the evaporites, exposed to the surface ("Keder-Brandstatt-Scholle - KBS"), within dark anhydrite, open extensional fractures strike NE–SW. They are filled with nearly pure nitrogen (pers. comm. Südsalz GmbH). The orientation of white veins is vertical in this area and some of them lack infilling. In this corner, a gap filled with brine was encountered, which documents the temporary infiltration of water. Next to this place, also below the KBS, within a zone of rare salts, an extensional fracture striking NE–SW opened after excavation, and documents the orientation of the local recent stress field.

4.6 Mesoscale structures in the Altaussee mine

The strike of caverns is in general NNW–SSE (Fig. 16) and is similar within the entire deposit. In Altaussee, many caverns are nearly circular. The foliation is similarly oriented at nearly all levels, with an average value of 250/55. At the margins, the foliation follows the borders to the wall rocks of the deposit, for instance along the NW boundary to the mountain Sandling.

The orientation of the halite mineral lineations scatters around NW (Figs. 17, 18). Subordinate W-trending lineations exist at all levels. Other than in the Berchtesgaden and Bad Dürrnberg mines, strain shadows with white fibrous halite are subordinate, although they are found sporadically at all levels. Non-rotational deformation is dominant in all places. Definite downward movement was found only in the outer parts at Franzberg and Steinberg levels in two places. As seen from sense of shear indicators, the dominating transport direction is an upward transport direction towards the SE to E. The paleostress calculation revealed WNW–ESE transpression with a top-ESE, upward movement with a sinistral component.

The isoclinal folds in rocksalt expose a blurred NW–SE orientation. Most of them dip NW and W. They exhibit the same orientation as the halite lineation.

Veins filled with polyhalite are ± parallel to the sedimentary layers of mudrock. Because of the alignment of the mudrock clasts to the salt rock foliation, the polyhalite veins expose the same orientation as the foliation (Fig. 19). The red-coloured halite veins are by far the most measured veins. Two preferred orientations may represent earlier stages, but no definite paleostress directions could be reconstructed. Orange veins expose similar orientations as the red veins. Combined red and white veins strike N–S, similar to some white veins. The white halite veins strike N–S and NE–SW. Their average dip to the SE fits to the halite mineral lineation. Veins through haselgebirge were not measured in the Altaussee mine.

The orientation of white halite fibres of veins in mudrock corresponds to the orientation of the halite mineral lineation and

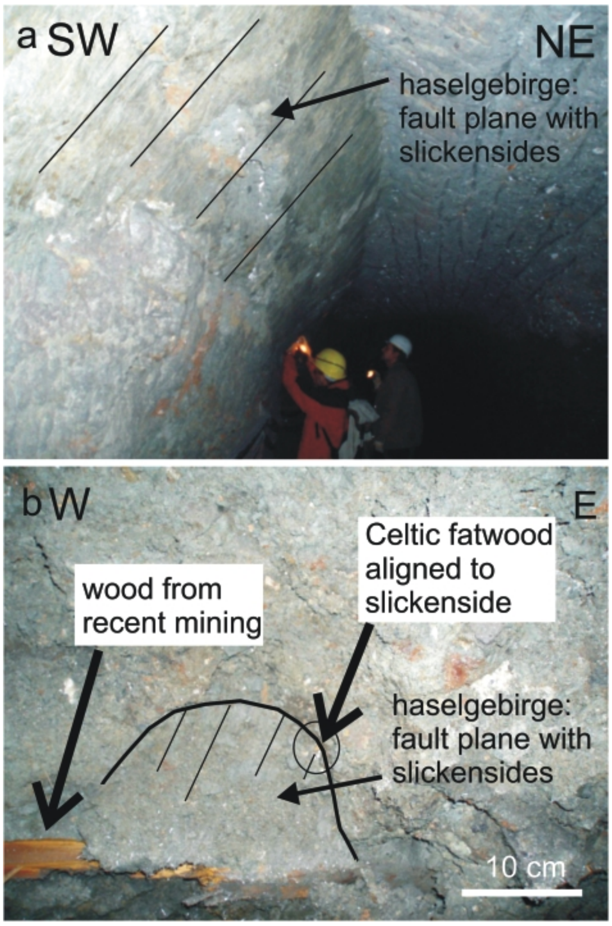

Figure 11: Bad Dürrnberg. (a) Normal faults in haselgebirge on Obersteinberg level, (b) younger than Celtic times.

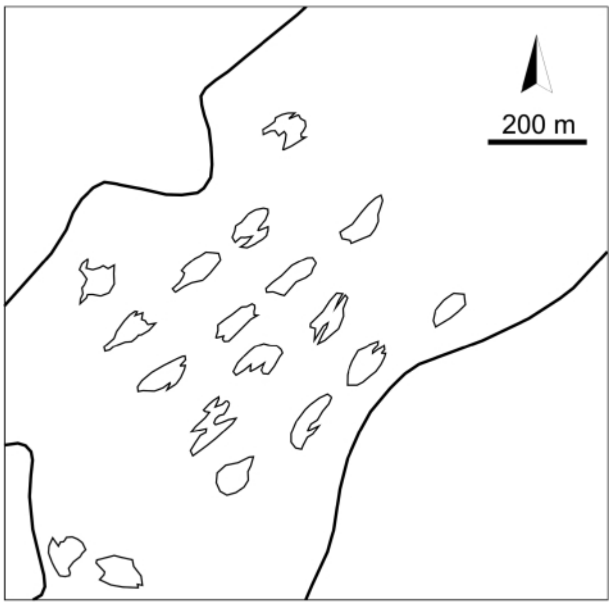

Figure 12: Berchtesgaden, level of Erste Tiefbausohle, simplified, depth of caverns ca. 350–450 m a.s.l., shapes are elongated NE–SW.

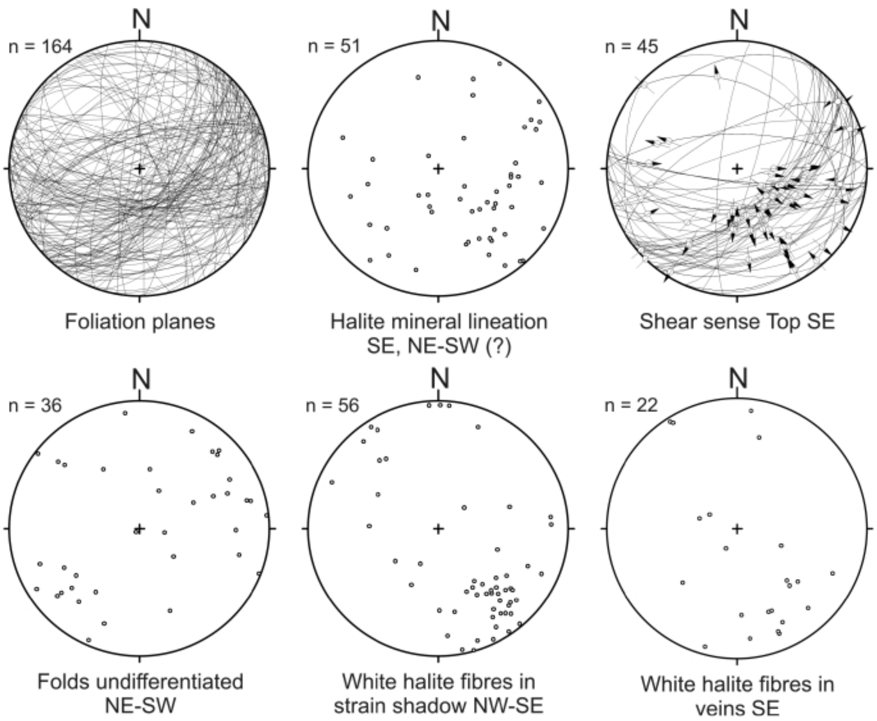

Figure 13: Berchtesgaden, orientation data of rocksalt (for explanation, see text). Equal area projection, lower hemisphere.

roughly to the axes of isoclinal folds.

Slickensides in mudrock, mostly as wall rock of veins, were not analysed in detail and revealed no significant results.

Few open fractures within dark an-hydrite strike NW–SE. They do not correspond to any late structural event observed in the mine.

5. Discussion

5.1 Structures in the salt deposits

All structural elements like foliation, halite lineation, isoclinal fold axes, strain shadows, veins and fibres in veins are consistent within each deposit as discussed in the following: The orientation of isoclinal folds coincides with the orientation of the halite mineral lineation, which is typical for high strain ductile deformation. The folds are thus to be interpreted as sheath folds during axial surface foliation (e.g. Passchier and Trouw, 1998; Alsop and Holdsworth, 2004). The foliation in the host rocks flow around blocks of anhydrite/ carbonates of various size. The many Φ-type objects, clasts with strain shadows with approximately orthorhombic symmetry, may not only develop in coaxial flow, but also at high strain in non-coaxial simple shear flow (Passchier and Trouw, 1998). White strain shadows are common within haselgebirge and kerngebirge in Berchtesgaden and Bad Dürrnberg and subordinate in Altaussee. Mudrock components within rocksalt sometimes broke through and white fibres developed in between. These fibres relate kinematically to the halite mi-

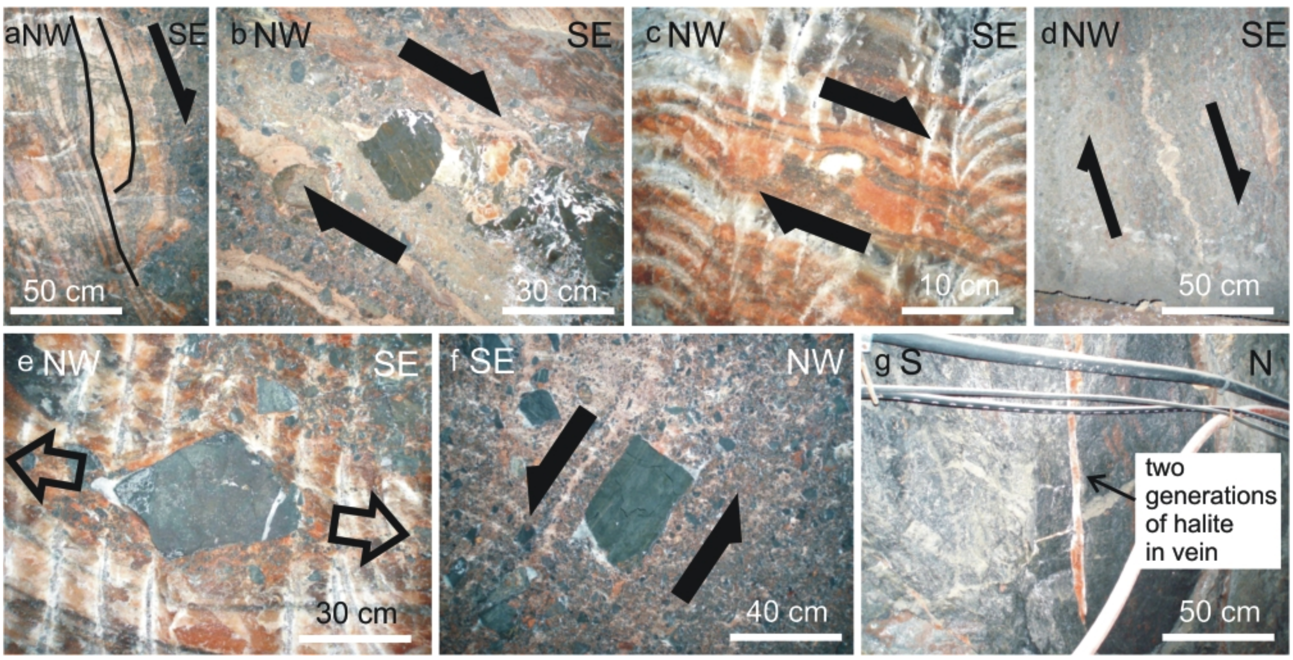

Figure 14: Berchtesgaden, photos illustrate normal fault orientation of the foliation. (a) Drag fold in rocksalt. (b) σ-clast with white halite fibres in strain shadows, country rock is haselgebirge. (c) Nodule of rigid non-halite salt (white clast) oblique to foliation circumfluent by rocksalt. (d) δ-type mantled porphyroclast, sandstone with sandstone clast within haselgebirge. (e) Φ-type object. Mudrock clast aligned to the foliation, with white halite in strain shadow and within crack. (f) σ-clast with white halite fibres in strain shadows, well homogenised haselgebirge. (g) Anhydrite cataclasite. Two generations of vein infill, inner red and outer white halite.

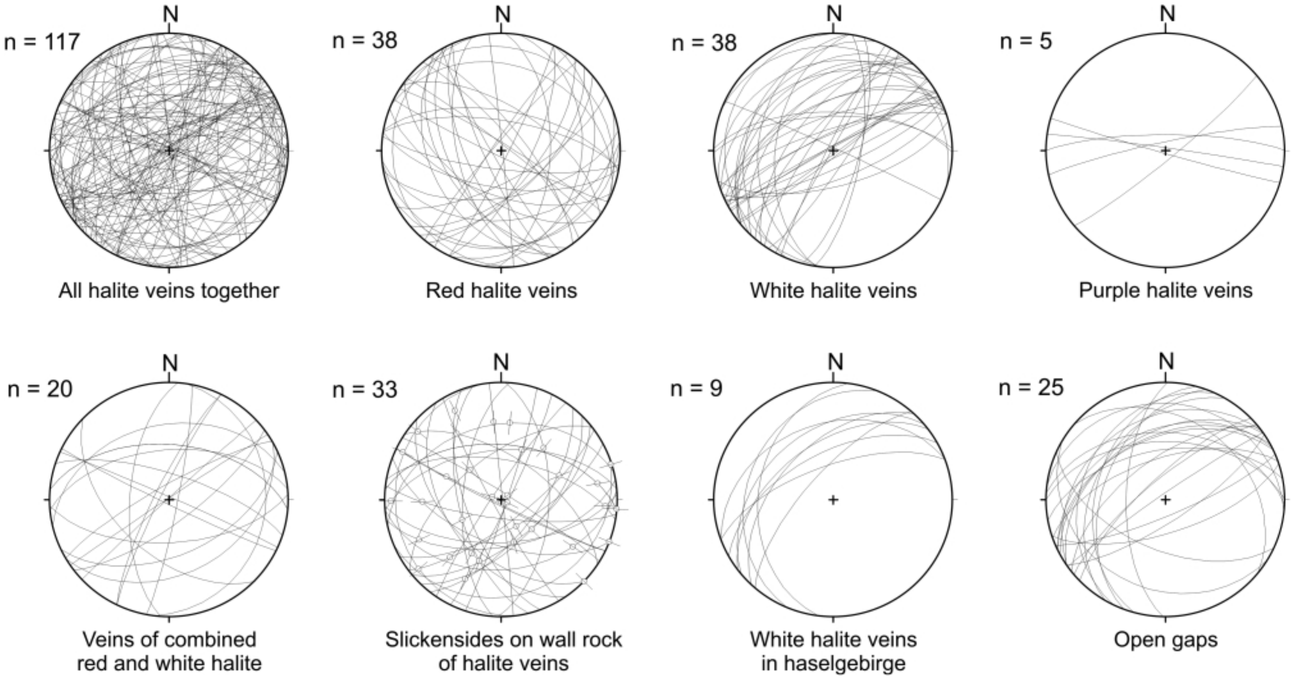

Figure 15: Berchtesgaden, orientation data of veins and fractures (for explanation, see text). Equal area projection, lower hemisphere.

neral lineation and isoclinal folds. All observed structural elements – foliation, lineation, isoclinal folds, strain shadows and extension veins – formed within one all-pervasive event. However, it is supposed that the white halite fibres document only the last (small) increment of the continuous salt rock deformation. A correspondence between the foliation, halite mineral lineation, and isoclinal folds was reported form Hallstatt. The orientation of white halite fibres in veins is identical to the mineral lineation and isoclinal folds (Arnberger, 2006).

Nevertheless, a superposition of various structural stages is possible. In Berchtesgaden, a second halite mineral lineation was found, which corresponds to the foliation and the orientation of isoclinal fold axes (Fig. 13). Additionally, this direction corresponds to the one in the same salt body in Bad Dürrnberg. This orientation is interpreted to represent the older event.

The youngest structures in relative age succession are veins within rocksalt or haselgebirge, open fractures and normal faults with slickensides within haselgebirge.

5.2 Tectonic development of the salt deposits

In Berchtesgaden-Bad Dürrnberg, the foliation in rocksalt relates to the tectonic situation of the neighbouring Oberalm Fm. respectively to the Rossfeld syncline. The NE–SW striking structures could have originated from a NW-directed compression in Late Cretaceous to Paleogene times associated with the formation of the Rossfeld syncline. (Linzer et al., 1995, 1997; Peresson and Decker, 1997; Fig. 20). From the western to the eastern end of the salt body, the formations in contact with the salt body become younger (Birkenfeld → Tauglboden → Oberalm → Schrambach → Rossfeld Formations). Haselgebirge Fm. rocks deposited as clasts of various size within other sediments show that during a long time span of at least 20 Ma (≈145–125 Ma), salt tectonism and diapirism was repeatedly active (Plöchinger, 1976, 1984; Prey, 1969; Kellerbauer, 1996). But salt structures from these former events are hard to identify or have disappeared completely. The overprinting stage with white halite fibres, dominating in the salt mine of Berchtesgaden, indicates NW–SE extension (Fig. 20). It formed when the rocks were exhumed in an extensional setting relative to the Rossfeld syncline. This could have occurred at various times from the Late Cretaceous to recent.

In Altaussee, the tectonic emplacement of the Lower Juvavic unit is debated controversially (Mandl, 1982, 2010; Gawlick et al., 2007). As known from new deep drillings from with-

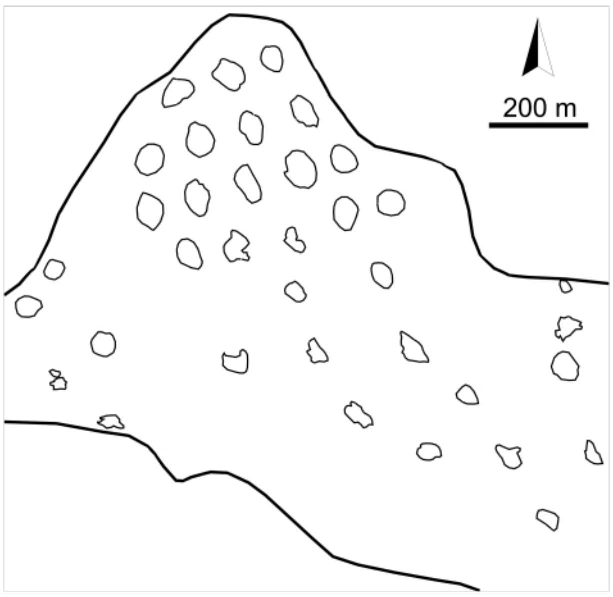

Figure 16: Altaussee, Franzberg level, simplified, depth of caverns ca. 820–900 m a.s.l., shapes are slightly elongated NW–SE.

in the mine, the rocksalt deposit extends down to 100 m below sea level. The country rocks at this depth are unknown. The salt deposit is covered by carbonates of Oberalm, Plassenkalk and Sandlingalm Fms., which are permeable to ground water. If the salt body was a submarine sliding block (Gawlick et al., 2007), the residual material would have to be much thicker than the observed thickness of 50 m. More probably, the mobile salt was squeezed tectonically from below (compare Fig. 5). This could have happened at any time after the deposition of the Sandlingalm Fm., most probably also post-depositional to the overlying Oberalm Fm. A first dextral strike-slip movement might have occurred in Late Cretaceous (?) or Paleogene times by a NW- and N-directed compression according to the structural maps in Peresson and Decker (1997). However, the calculated palaeostress fits best for a late Miocene E–W compression with thrusting (Peresson and Decker, 1997; Linzer et al., 1997; Fig. 20). Two stages of similar orien-tation of structures occurred, indicating an extrusion by squeezing from below.

In Hallstatt, the foliation is nearly subvertical, and trends E–W. The borders and the salt layers dip with ca. 40° to the north and steepen to 70° at greater depths (Schauberger, 1949, 1953; Habermüller, 2005). There, the orientation of isoclinal fold axes were used to determine the direction of tectonic transport. A dextral shear sense was deduced by asymmetric porphyroclasts (Habermüller, 2005). Three D-modelling and structural analysis in the salt mine indicate that the salt body is related to a major WNW-striking dextral strike-slip fault from eo-Alpine thrusting during the Late Cretaceous to Eocene (Linzer et al., 1995). The tectonic model interprets the salt body to have migrated into the

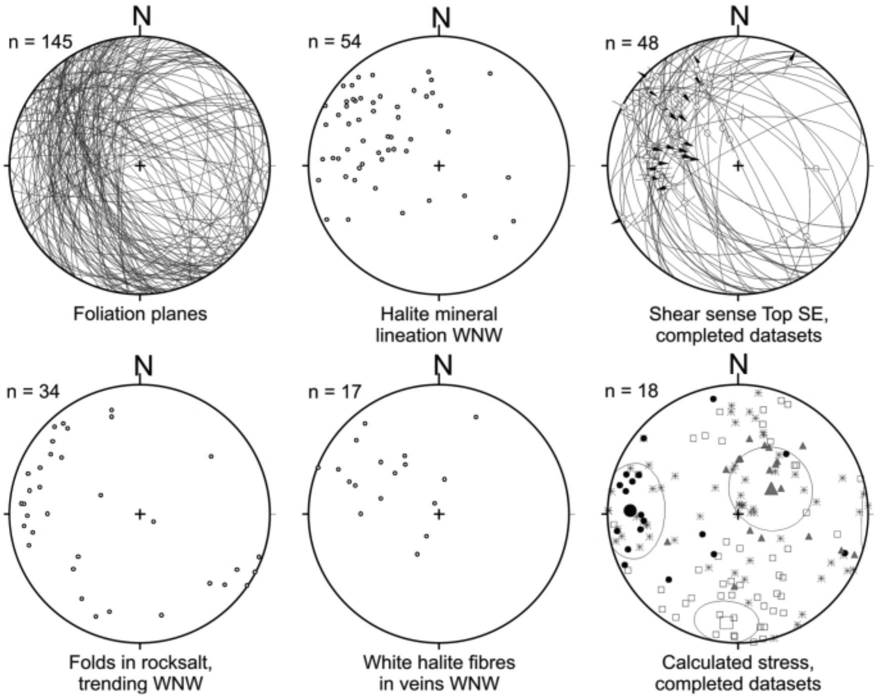

Figure 17: Altaussee, orientation data of rocksalt (for explanation, see text). Equal area projection, lower hemisphere.

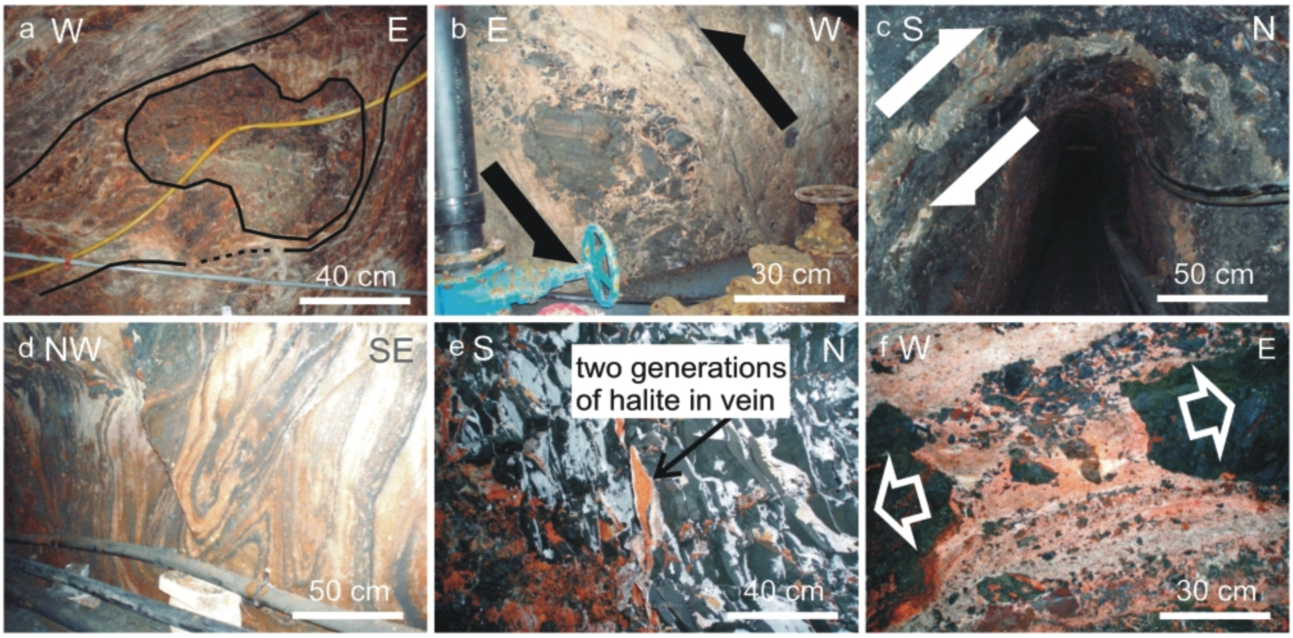

Figure 18: Altaussee, style of deformation and reverse faulting of foliation. (a) Stream line body around rigid object. (b) Circumfluent shale clast, folds in adjecent rocksalt. (c) View along gallery towards W. Layer of sandstone in mudrock matrix. (d) Isoclinal folds in rocksalt. (e) Veins in mudrock, filled with inner red and outer white halite. (f) Non-rotation deformation with strain shadows filled with white halite in red halite matrix.

transfer zone in late stages of deformation and risen during this dextral shear movement (Cotton and Koyi, 2000; Habermüller, 2005; Arnberger, 2006, Schmid, 2009; Fig. 20).

Ages of structures for the other deposits are considered as follows: From beneath the rocksalt deposit of Hall in Tirol tectonized Cretaceous marls of the Schrambach Fm. were reported by Spötl (1989b). Squeezing of these rocks postdates the mid-Cretaceous, when the upper Tirolic Inntal nappe took its position on top of the lower Bajuvaric Lechtal nappe. The general dip of the salt layers is 40° to the south. The rocksalt deposit of Bad Reichenhall contains marls and limestones of the Cretaceous to Paleogene Gosau Group (Schauberger et al., 1976; Zankl and Schnell, 1979). Eocene marls and sandstones of a succeeding intra-Alpine basin were incorporated into the Haselgebirge Fm., too, thus postdating Eocene. Kassebaum (2001) interpreted a pull-apart basin in connection with an E–W compression in Miocene. From the salt mine of Bad Ischl, Lobitzer et al. (2006) dated a tectonically overthrusted breccia as Rossfeld Fm. with the help of nannofossils. The foliation of the Haselgebirge Fm. in Bad Ischl postdates the deposition of the Rossfeld Fm. Two other Haselgebirge Fm. occurrences should be mentioned here: (1) The Haselgebirge Fm. from the currently under construction excavated Bosruck tunnel in the very southern part of the NCA. There, rocks of the Gosau Group are intercalated into leached Haselgebirge Fm. This indicates that the Haselgebirge Fm. came into its position after the sedimentation of the Gosau Group (Nowy and Lein, 1984). (2) In Hinterbrühl, near Vienna, leached out Haselgebirge Fm. is found between the Bajuvaric and the overlying Tirolic unit. It demonstrates the presence of Haselgebirge Fm. below the Tirolic units involved in thrusting from the eastern end of the NCA (Wessely, 2006), via the central NCA (e.g. Weber, 1958) to the western part of the NCA (Hall in Tirol).

5.3 Implications for regional tectonics

During Triassic times, a rift system most probably developed during the extension and opening of the Tethyan Ocean. There are first hints of diapirism by incorporation of Haselgebirge Fm. rocks in Hallstatt Fm. and the varying thickness of Hallstatt Fm. layers (Lein, 1981; Mandl, 1984). In Jurassic times, diapirs may have developed by compressional tectonics similar to models summarized in Hudec and Jackson (2007). The western part of the Tethys, the Meliata Ocean, was being closed during Late Jurassic times. As documented from several places, parts of the Triassic outer shelf facies, the Hallstatt facies rocks were resedimented within Jurassic deepsea sediments: Ruhpolding Radiolarite, Tauglboden, Strubberg, Sillenkopf, and Sandlingalm Formations (Lein, 1981; Mandl, 1982, Tollmann, 1987, Böhm, 1988; Braun, 1998; Missoni et al., 2001; Gawlick et al., 1999, 2007).

In Late Jurassic and Cretaceous times, the salt bodies were transformed and subsequently modified by the Alpine orogeny. The rheologically weak Haselgebirge Fm. was used as a detachment level and the Alpine nappe units were stacked. Age dating of polyhalite suggests Jurassic and Cretaceous overprinting stages (Leitner et al., 2008). As seen from analogue experiments, internal structures of salt (Chemia and Koyi, 2008; Dooley et al., 2009) and nappe stacking of country rocks may become complex, when salt moves to different levels (Guglielmo et al., 2000; Bonini, 2003). The Zagros Mountains with the Hormoz salt at their base could represent a comparable stage of development in the NCA (compare figures in the review paper of Alavi, 2007). In the Zagros, the basement is not yet sheared off, but deep-sea facies material is obducted onto the fold-and-thrust belt. The present geological situation there could be similar to the time, when the Jurassic Meliata Ocean was already closed.

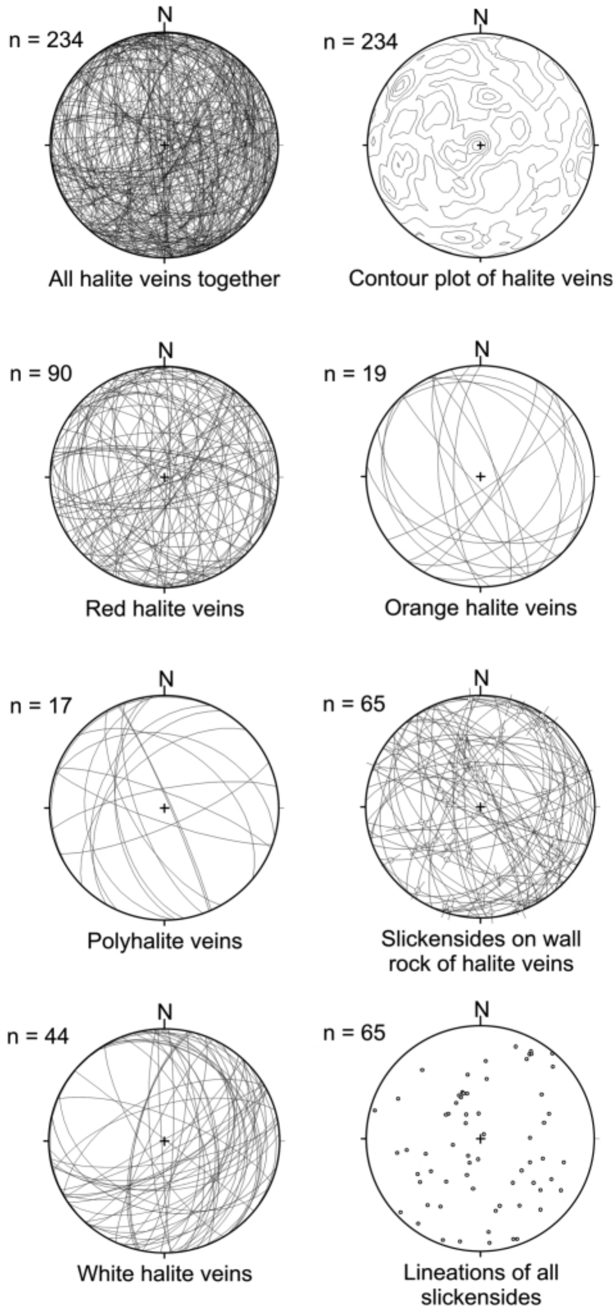

Figure 19: Altaussee, orientation data of veins and fractures (for explanation, see text). Equal area projection, lower hemisphere.

During Late Cretaceous to Paleogen and in Miocene times, the salt along the detachment levels accumulated and was squeezed from below to close to the erosional surface. At this time, the observable mesoscale structures in salt mines developed.

During the Pleistocene glaciation, the mountains including the top of salt bodies were eroded. In Bad Reichenhall, a Nagelfluh cover deposited during the Riss/ Würm interglacial saved the underlying Haselgebirge Fm. from further erosion, whereby a 300 m thick rim of halite-free Haselgebirge Fm. developed. All other Haselgebirge Fm. outcrops showing an only 50–80 m wide rim indicate quite a short exposure of the salt body to the present-day surface.

6. Conclusions

The Alpine Haselgebirge Formation occurs in connection with Juvavic units, but is also wide-spread outside Juvavic units as indicated by occurrences at the base of Tirolic tectonic units from Hall in Tirol to Hinterbrühl next Vienna. The present study allows to draw the following major conclusions about the mesoscale rocksalt structures of the Upper Permian to Lower Triassic Haselgebirge Formation and implications for the regional setting of the NCA:

1. Structural data from different salt bodies is internally consistent and coherent for the orientation of foliation, halite lineation, veins and fibres in veins. They document mainly an all-pervasive deformational event.
2. The white fibres document the last small increment of the all-pervasive event. White fibres can be found in all rocksalt deposits.
3. The overall structures of the salt relate to the geometry of the salt body and the structures of the surrounding region. Incorporated rocks and underlying rocks indicate relative ages of the mesoscale salt structures in relation to the surrounding rocks.
4. Our study uncovers evidence of pre-Cretaceous (e.g. Jurassic) salt tectonism, but the salt structures from these earlier events are hard to identify or have disappeared. The internal structures of the Alpine salt bodies relate best to structural events, which shaped the NCA fold-and-thrust belt from the Late Cretaceous to Paleogene times, and were modified in some cases in Miocene times.

Acknowledgements

We thank the mining companies Südsalz GmbH, Berchtesgaden salt mine and Salinen Austria AG for their support of access to the underground sites. The following persons are thanked for their support: Michael Klade, Johann Brochenberger, Gerd Hofer, Michael Mayr, Stefan Kellerbauer and Franz Lenz. Wolfgang Beer, K+S AG and Gerhard Breitfelder, BFS are thanked for the opportunity to visit the Zechstein Salt mines for comparison. Reza S.A.Jafari Sadr, Islamic Azad University (Iran) invited us to Iran to visit the Hormoz Salt, Iran. Furthermore, we want to thank the Seegrotte Hinterbrühl Schaubergwerk GmbH for the visit of its gypsum mine and Alexander Gruber for the guide tour through the Bosruck tunnel. Ewald Hejl, Johann Genser, Harald und Dana Leitner, Stephan Leitner, Christian Feldbacher, Klaus Arnberger, Mario Habermüller, Melanie Keil, Alexandra Verant and Raphael Leitner are thanked for excursions in the NCA and fruitful discussions. We gratefully acknowledge detailed reviews by Wolfgang Schollnberger, Michael Wagreich and an anonymous reviewer, who helped to clarify ideas and presentation. Isabella Merschdorf proofread the final manuscript. The final work was supported by grant P22,728 of the Austrian Science Fund (FWF).

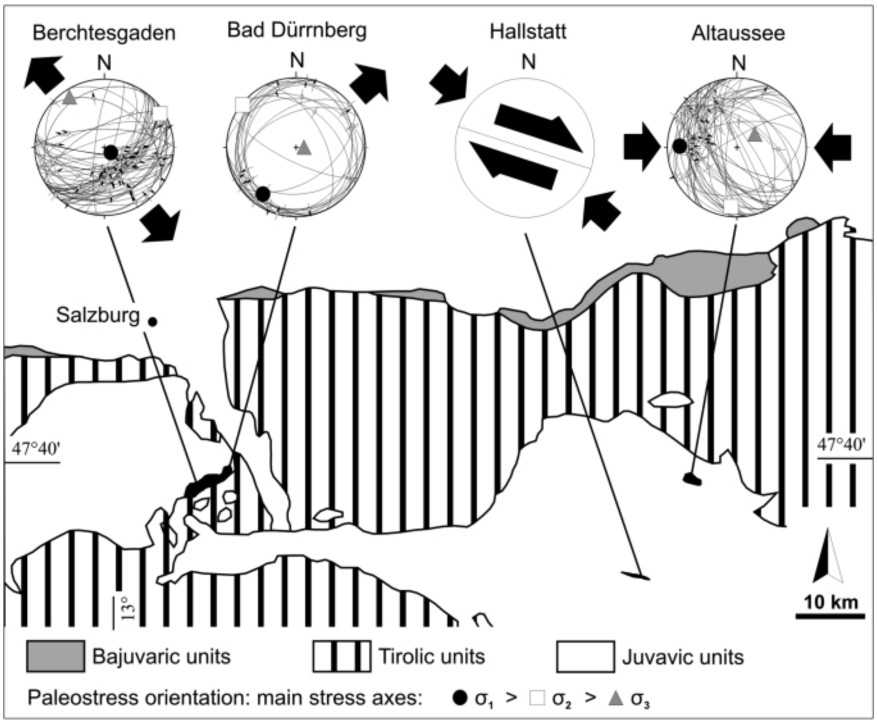

Figure 20: Palaeostress orientation within rocksalt deposits (for explanation see text).

References

Alavi, M., 2007. Structures of the Zagros fold-thrust belt in Iran. American Journal of Science, 307, 1064– 1095.

Alsop, G.I. and Holdsworth, R.E., 2004. The geometry and to-pology of natural sheath folds: a new structural analysis. Journal of Structural Geology, 26, 1561–1589.

Arnberger, K., 2006. Detachement folding above the Permian Haselgebirge: Palinspastic reconstruction of alpine west-directed thrusting (Plassen, Hallstatt, Upper Austria). Diploma thesis, University of Vienna, V+101 pp.

Böhm, F., 1988. Geologie des Grimming-Westabschnittes. Mitteilungen der Gesellschaft der Geologie und Bergbaustudenten in Österreich, 34/35, 151–184.

Bonini, M., 2003. Detachement folding, fold amplification, and diapirism in thrust wedge experiments. Tectonics, 22, doi: 10.1029/2002TC001458.

Braun, R., 1998. Die Geologie des Hohen Gölls. Nationalpark Berchtesgaden, Forschungsbericht 40, Berchtesgaden, 192 pp.

Buch, L.v., 1802. Geognostische Beobachtungen auf Reisen durch Deutschland und Italien. Band 1, Haude und Spencer, Berlin.

Chemia, Z. and Koyi, H., 2008. The control of salt supply on entrainment of an anhydrite layer within a salt diapir. Journal of Structural Geology, 30, 1192–1200.

Dallmeyer, R.D., Neubauer, F. and Fritz, H., 2008. The Meliata suture in the Carpathians: Regional significance and implications for the evolution of high-pressure wedges within collisional orogens. In: Siegesmund, S., Fügenschuh, B. and Froitzheim, N. (eds.), Tectonic Aspects of the Alpine-Dinaride-Carpathian System. Geological Society Special Publications, London, 298, pp. 101–115.

Davis, D.M. and Engelder, T., 1985. The role of salt in Fold-and-Thrust Belts. Tectonophysics, 119, 67–88.

Decker, K., Peresson, H. and Faupl, P., 1994. Die miozäne Tektonik der östlichen Kalkalpen: Kinematik, Paläospannungen und Deformationsaufteilung während der "lateralen Extrusion" der nördlichen Zentralalpen. Jahrbuch der Geologischen Bundesanstalt, 137, 5–18.

Del-Negro, W., 1979. Erläuterungen zur geologischen Karte der Umgebung der Stadt Salzburg 1:50.000. Wien: Geologische Bundesanstalt, 41 pp.

Deutsches Institut für Normung e.V., 2004. DIN EN ISO 14688-2: Geotechnische Erkundung und Untersuchung – Benennung, Beschreibung und Klassifizierung von Boden; Teil 2: Grundlagen für Bodenklassifizierungen. Beuth, Berlin, Wien, Zürich, 16 pp.

Dooley, T.P., Jackson, M.P.A. and Hudec, M.R., 2009. Inflation and deflation of deeply buried salt stocks during lateral shortening. Journal of Structural Geology, 31, 582–600.

Faupl, P. and Wagreich, M., 2000. Late Jurassic to Eocene Paleogeography and Geodynamic Evolution of the Eastern Alps. In: Neubauer, F. and Höck, V. (eds.), Aspects of Geology in Austria. Mitteilungen der Österreichischen Geologischen Gesellschaft, 92, pp. 79–94.

Frank, W. and Schlager W., 2006. Jurassic strike slip versus subduction in the Eastern Alps. International Journal of Earth Sciences, 95, 431–450.

Frisch, W. and Gawlick, H.-J., 2003. The nappe structure of the central Northern Calcereous Alps and its disintegration during Miocene tectonic extrusion – a contribution to understanding the orogenic evolution of the Eastern Alps. International Journal of Earth Sciences, 92, 712–727.

Ganss, O., 1978. Geologische Karte von Bayern 1:100.000, Bl. 667 Bad Reichenhall, mit Profiltafel. Bayerisches Geologisches Landesamt, München.

Gawlick, H.-J., Krystyn, L. and Lein, R., 1994. Conodont colour alteration indices: Palaeotemperatures and metamorphism in the Northern Calcareous Alps – a general view. Geologische Rundschau, 83, 660–664.

Gawlick, H.-J. and Höpfer, N., 1996. Die mittel- bis frühjurassische Hochdruckmetamorphose der Hallstätter Kalke (Trias) der Pailwand – ein Schlüssel zum Verständnis der frühen Geschichte der Nördlichen Kalkalpen. In: Thein, J. und Schäfer, A. (eds.), Geologische Stoffkreisläufe und ihre Veränderungen durch den Menschen. Schriftenreihe der Deutschen Geologischen Gesellschaft 1, pp. 30–32.

Gawlick, H.-J. and Lein, R., 1997. Neue stratigraphische und fazielle Daten aus dem Jakobberg- und Wolfdietrichstollen des Hallein-Bad Dürrnberger Salzberges und ihre Bedeutung für die Interpretation der Geologischen Verhältnisse im Bereich der Hallein-Berchtesgadener Schollenregion. Geologisch Paläontologische Mitteilungen Innsbruck, 22, 199–225.

Gawlick, H.-J., Frisch. W., Vecsei., A. Steiger, T. and Böhm, F., 1999. The change from rifting to thrusting in the Northern Calcerous Alps as recorded in Jurassic sediments. Geologische Rundschau, 87, 644–657.

Gawlick, H.-J. and Lein, R., 2000. Die Salzlagerstätte Hallein-Bad Dürrnberg. Exkursionsführer Sediment 2000. Mitteilungen der Gesellschaft der Geologie- und Bergbaustudenten in Österreich, 44, 263–280.

Gawlick, H.-J., Suzuki, H. and Missoni, S., 2001. Nachweis von unterliassischen Beckensedimenten in Hallstätter Fazies (Dürrnberg-Formation) im Bereich der Hallein – Berchtesgaden Hallstätter Zone und des Lammer Beckens (Hettangium – Sinemur). Mitteilungen der Gesellschaft der Geologie- und Bergbaustudenten in Österreich 45, 39–55.

Gawlick, H-J. and Schlagintweit, F., 2006. Berriasian drowning of the Plassen carbonate platform at the type-locality and its bearing on the early Eoalpine orogenic dynamics in the Northern Calcareous Alps (Austria). International Journal of Earth Sciences, 95, 451–462.

Gawlick, H.-J., Schlagintweit, F. and Suzuki, H., 2007. Die Ober-Jura bis Unter-Kreide Schichtfolge des Gebietes Höherstein-Sandling (Salzkammergut, Österreich) – Implikationen zur Rekonstruktion des Block-Puzzles der zentralen Nördlichen Kalkalpen, der Gliederung der karbonatischen Radiolaritflyschbecken und der Entwicklung der Plassen-Karbonatplattform. Neues Jahrbuch für Geologie und Paläontologie Abhandlungen, 243, 1–70.

Gawlick, H.-J., Missoni, S., Schlagintweit, F., Suzuki, H., Frisch W., Krystyn L., Blau, J. and Lein, R. 2009. Jurassic Tectonostratigraphy of the Austroalpine domain. Journal of Alpine Geology, 50, 1–152.

Grabner, M., Klein, A., Geihofer, D., Reschreiter, H., Barth, F., Sormaz, T. and Wimmer R., 2007. Bronze age dating of timber from the salt-mine at Hallstatt, Austria. Dendrochronologia, 24, 61–68.

Götzinger, M.A. and Grum, W., 1992. Die Pb-Zn-F-Mineralisationen in der Umgebung von Evaporiten der Nördlichen Kalkalpen, Österreich – Herkunft und Zusammensetzung der fluiden Phase. Mitteilungen der Gesellschaft der Geologie- und Bergbaustudenten in Österreich, 38, 47–56.

Guglielmo, G., Vendeville, B.C. and Jackson, M.P.A., 2000. 3-D visualization and isochore analysis of extentional diapirs overprinting by compression. AAPG Bulletin, 84, 1095–1108.

Habermüller, M., 2005. West-directed thrusting in the Dachstein Nappe: Quantification of the eo-Alpine deformation around the Echerntal valley (Hallstatt, Austria). Diploma thesis, University of Vienna, IV+87 pp.

Hejl, E. and Grundmann, G., 1989. Apatit-Spaltspurdaten zur thermischen Geschichte der Nördlichen Kalkalpen, der Flysch- und Molassezone. Jahrbuch der Geologischen Bundesanstalt, 132, 191–212.

Hancock, P.L. (ed.), 1994. Continental Deformation. Pergamon Press, Oxford, New York, Seoul, Tokyo, XI+421 pp.

Hilgers, C. and Urai, J.L., 2002. Microstructural observations on natural syntectonic fibrous veins: implications for the growth process. Tectonophysics, 352, 257–274.

Hilgers, C. and Urai, J.L., 2005. On the arrangement of solid inclusions in fibrous veins and the role of the crack-seal mechanism. Journal of Structural Geology, 27, 481–494.

Hudec, M.R. and Jackson, M.P.A., 2006. Advance of allochthonous salt sheets in passive margins and orogens. AAPG Bulletin, 90, 1535–1564.

Hudec, M. and Jackson, M., 2007. Terra Infirma: Understanding Salt Tectonics. Earth Science Reviews, 82, 1–28.

Jackson, M.P.A. and Talbot, C., 1994. Advances in Salt Tectonics. In: Hancock, P.L. (ed.) Continental Deformation. Pergamon Press, Oxford, New York, Seoul, Tokyo, pp.159–179.

Jadoon, I.A.K. and Frisch, W., 1997. Hinterland-vergent tectonic wedge below the Riwat thrust, Himalayan foreland, Pakistan: Implications for hydrocarbon exploration. AAPG Bulletin, 81, 438–448.

Kassebaum, C., 2001. Die Geologie des Kirchholzgebietes im Becken von Bad Reichenhall, mit besonderer Berücksichtigung der Faziesbeziehungen zwischen dem Haselgebirge und den Reichenhaller Schichten. Diplomarbeit, Philipps-Universität Marburg, 136 pp.

Kellerbauer, S., 1996. Geologie und Geomechanik der Salzlagerstätte Berchtesgaden. Münchner Geologische Hefte, Reihe B: Angewandte Geologie 2, XII+101 pp.

Kirchner E., 1980. Vulkanite aus dem Permoskyth der Nördlichen Kalkalpen und ihre Metamorphose. Mitteilungen der Österreichen Geologischen Gesellschaft, 71/72, 385–396.

Klaus, W., 1965. Zur Einstufung alpiner Salztone mittels Sporen. Verhandlungen der Geologischen Bundesanstalt, Sonderheft G, 288–292.

Klein, A., 2006. Bronzezeitliche Holznutzung in Hallstatt. Diploma thesis, University of Natural Resources and Applied Life Sciences, Vienna, 122 pp.

Kralik, M., Krumm, H. and Schramm, J.M., 1987. Low Grade and Very Low Grade Metamorphism in the Northern Calcareous Alps and in the Greywacke Zone: Illite – Crystallinity Data and Isotopic Ages. In: Flügel, H.W. and Faupl, P. (eds.), Geodynamics of the Eastern Alps. Deutike, Wien, pp. 164–178.

Krystyn, L., 2008. Exkursion 1. The Hallstatt pelagics – Norian and Rhaetian Fossillagerstaetten of Hallstatt. Berichte der Geologischen Bundesanstalt, 76, 81–98.

Lacombe, O., Lavé, J., Roure, F. and Verges, J. (eds.), 2007. Thrust Belts and Foreland Basins. From Fold kinematics to hydrocarbon Systems. Berlin, Heidelberg, New York: Springer, XXIII+491 pp.

Leitner, C., Neubauer, F., Genser, J. and Rantitsch, G., 2008. Ductile deformation and $^{40}Ar/^{39}Ar$ age of fabrics of Permian polyhalite/anhydrite rocks of Eastern Alps. Geophysical Research Abstracts, 10, EGU2008-A-02828.

Leitner, C., Neubauer, F., Urai, J.L. and Schoenherr, J., 2011. Structure and Evolution of a Rocksalt-Mudrock-Tectonite: the Haselgebirge in the Northern Calcareous Alps. Journal of Structural Geology, 33, 970–984.

Linzer, H.-G., Ratschbacher, L. and Frisch, W., 1995. Transpressional collision structures in the upper crust: the fold-thrust belt of the Northern Calcerous Alps. Tectonophysics, 242, 41–61.

Linzer, H.-G., Moser, F., Nemes, F., Ratschbacher, L. and Sperner, B., 1997. Build-up and dismembering of the eastern Northern Calcareous Alps. Tectonophysics, 272, 97–124.

Littke, R., Bayer, U., Gajewski, D. and Nelskamp, S. (eds.), 2008. Dynamics of Complex Intracontinental Basins. The Central European Basin System. Springer, Berlin [u.a.], XXIV+520 pp.

Lobitzer, H., Hradecka, L., Mayr, M., Svoboda, M. and Svabenicka, L., 2006. Bericht 2005 über fazielle und mikropaläontologische Untersuchungen der „Ischler Brekzie“ im Kaiser-Franz-Josef-Erbstollen auf Blatt 96 Bad Ischl. Jahrbuch der Geologischen Bundesanstalt, 146, 133–136.

Mandl, G.W., 1982. Jurassische Gleittektonik im Bereich der Hallstätter Zone zwischen Bad Ischl und Bad Aussee (Salzkammergut Österreich). Mitteilungen der Gesellschaft der Geologie- und Bergbaustudenten in Österreich, 28, 55–76.

Mandl, G.W., 1984. Zur Trias des Hallstätter Faziesraumes – ein Modell am Beispiel Salzkammergut (Nördliche Kalkalpen, Österreich). Mitteilungen der Gesellschaft der Geologie- und Bergbaustudenten in Österreich, 30/31, 133–176.

Mandl, G.W., 2000. The Alpine Sector of the Tethyan shelf – Example of Triassic to Jurassic sedimentation and deformation from the Northern Calcerous. In: Aspects of Geology in Austria. Mitteilungen der Österreichischen Geologischen Gesellschaft 92, pp. 61–77.

Mandl, G.W., 2010. Zur jurassischen Radiolaritbecken-Entwicklung am Nordrand der Ischl–Ausseer Hallstätter Zone (Nördliche Kalkalpen, Österreich), Journal of Alpine Geology, 52, 175–176.

Mayrhofer, H., 1955. Beiträge zur Kenntnis des alpinen Salzgebirges/ mit einer strukturellen und stofflichen Bearbeitung des Ischler Salzbergs und einem Entwurf einer tektonischen Entstehungshypothese des Haselgebirges. Zeitschrift der Deutschen Geologischen Gesellschaft, 105, 752–775.

Medwenitsch, W., 1957. Die Geologie der Salzlagerstätten Bad Ischl und Alt-Aussee (Salzkammergut). Mitteilungen der Geologischen Gesellschaft in Wien, 50, 133–199.

Missoni, S., Schlagintweit, F., Suzuki H. and Gawlick, H.-J., 2001. Die oberjurassische Karbonatplattformentwicklung im Bereich der Berchtesgadener Kalkalpen (Deutschland) – eine Rekonstruktion auf der Basis von Untersuchungen polymikter Brekzienkörper in pelagischen Kieselsedimenten (Sillenkopf-Formation). Zentralblatt Geologischer Paläontologischer Teil I, 2000, 117–143.

Missoni, S. and Gawlick, H.-J., 2010. Evidence for Jurassic subduction from the Northern Calcareous Alps (Berchtesgaden; Austoalpine, Germany). International Journal of Earth Sciences (in press), doi: 10.1007/s00531-010-0552-z.

Moser, M., 2008. Geologische Karte der Republik Österreich 1:50.000, Blatt 118 Innsbruck. Zusammenstellung ausgewählter Archivunterlagen der GBA im Rahmen des GBA-Projektes Geofast. Geologische Bundesanstalt, Wien.

Neubauer, F, Genser, J. and Handler, R., 2000. The Eastern Alps: Result of a two-stage collision process. In: Neubauer, F., and Höck, V. (eds.), Aspects of Geology in Austria. Mitteilungen der Österreichischen Geologischen Gesellschaft, 92, pp. 117–134.

Oberhauser, R. (ed.), 1980. Der geologische Aufbau Österreichs. Springer, Wien, New York, VIII+700 pp.

Oliver, N.H.S. and Bons, P.D., 2001. Mechanisms of fluid flow and fluid-rock interaction in fossil metamorphic hydrothermal systems inferred from vein-wallrock patterns, geometry and microstructure. Geofluids 1, 137–162.

Ortner, H., Reiter, F. and Acs, P., 2002. Easy handling of tectonic data: the programs TectonicVB for Mac and TectonicsFP for Windows(TM). Computers & Geosciences, 28, 1193–1200.

Passchier, C.W. and Trouw, R.A.J., 1998. Microtectonics. SpringerVerlag, Berlin et al., XIV+289 pp.

Peresson, H. and Decker, K., 1997. The Tertiary dynamics of the northern Eastern Alps (Austria): changing palaeostresses in a collisional plate boundary. Tectonophysics, 272, 125–157.

Pichler, H., 1963. Geologische Untersuchungen im Gebiet zwischen Rossfeld und Markt Schellenberg im Berchtesgadener Land. Beihefte zum Geologischen Jahrbuch, 48, 29–204.

Plöchinger, B., 1976. Die Oberalmer Schichten und die Platznahme der Hallstätter Masse in der Zone Hallein – Berchtesgaden. Neues Jahrbuch Geologisch Paläontologischer Abhandlungen, 151, 304–324.

Plöchinger, B., 1984. Zum Nachweis jurassischer–kretazischer Eingleitungen von Hallstätter Gesteinsmassen beiderseits des Salzach-Quertals (Salzburg). Geologische Rundschau, 73, 293– 306.

Plöchinger, B., 1990. Erläuterungen zu Blatt 94 Hallein. – Geologische Karte der Republik Österreich 1:50 000. Geologische Bundesanstalt, Wien., 76 pp.

Plöchinger, B., 1996. Das Halleiner Salinargebiet (Salzburg) im Geotopschutz-Projekt. Jahrbuch der Geologischen Bundesanstalt, 139, 497–504.

Prey, S., 1969. Geologische Karte der Umgebung der Stadt Salzburg. Geologische Bundesanstalt, Wien.

Proisl, M., 2003. Planung der Aus- und Vorrichtung westlich des Zentralschachtes und unterhalb des Erbstollenhorizontes des Salzbergbaues Altaussee. Diploma thesis, Mining University of Leoben, 76 pp.

Pueyo, E.L., Mauritsch, H.J., Gawlick, H.-J., Scholger, R. and Frisch, W., 2007. New evidence for block and thrust sheet rotations in the central northern Calcareous Apls deduced from two pervasive remagnetization events. Tectonics, 26, doi: 10.1029/2006TC001965.

Rantitsch, G. and Russegger, B., 2005. Organic maturation within the Central Northern Calcareous Alps (Eastern Alps). Austrian Journal of Earth Sciences, 98, 68–76.

Richter, A., 1962. Die Rotfärbung in den Salzen der deutschen Zechsteinlagerstätten, 1. Teil. Chemie der Erde, 22, 508–546.

Schadler, J., 1949. Die Ergebnisse der geologischen Neukartierung im Gebiete des Ischler und Ausseer Salzberges. Berg- und Hüttenmännische Monatshefte, 94, 56–60.

Schäffer, G., 1982. Geologische Karte der Republik Österreich 1:50.000, Blatt 96 Bad Ischl. Geologische Bundesanstalt, Wien.

Schauberger, O., 1931. Die Fließstrukturen im Hallstätter Salzlager. Berg- und Hüttenmännische Monatshefte, 79, 27–38.

Schauberger, O., 1949. Die stratigraphische Aufgliederung des alpinen Haselgebirges. Berg- und hüttenmännische Monatshefte, 94, 46–56.

Schauberger, O., 1953. Zur Genese des alpinen Haselgebirges. Zeitschrift der Deutschen Geologischen Gesellschaft, 105, 736–751.

Schauberger, O., Zankl, H., Kühn, R. and Klaus, W., 1976. Die geologischen Ergebnisse der Salzbohrungen im Talbecken von Bad Reichenhall. Geologische Rundschau, 65, 558–579.

Schauberger, O., 1986. Bau und Bildung der Salzlagerstätten des ostalpinen Salinars. Archiv für Lagerstättenforschung der Geologischen Bundesanstalt, 7, 217–254.

Scheidleder, A., Boroviczeny, F., Graf, W., Hofmann, T., Mandl, G.W., Schubert, G., Stichler, W., Trimborn, P. and Kralik, M., 2001. Pilotprojekt "Karstwasser Dachstein". Band 2: Karsthydrologie und Kontaminationsrisiko von Quellen. Archiv für Lagerstättenforschung, 21, 155 pp.

Schmid, N., 2009. Detachment folding and salt tectonics in the Permian Haselgebirge (Hallstatt, Northern Calcareous Alps). Master thesis at the University of Vienna, V+102 pp.

Schmid, S.M., Fügenschuh, B., Kissling, E. and Schuster, R., 2004. Transects IV, V, VI: The Alps and Their Forelands. In: Cavazza, W., Roure, F.M., Spakman, W., Stampfli, G.M., and Ziegler, P.A. (eds.), The TRANSMED Atlas. The Mediterranean region from crust to mantle. Springer, Berlin et al.

Schmidegg, O., 1951. Die Stellung der Haller Salzlagerstätte im Bau des Karwendelgebirges. Jahrbuch der Geologischen Bundesanstalt, 94, Festschrift (1949/51), 159–207.

Sherkati, S., Molinaro, M., Frizon de Lamotte, D. and Letouzey, J., 2005. Detachment folding in the Central and Eastern Zagros fold-belt (Iran): salt mobility, multiple detachments and late basement control. Journal of Structural Geology, 27, 1680–1696.

Sommaruga, A., 1999. Décollement tectonics in the Jura foreland fold-and-thrust belt. Marine and Petroleum Geology, 16, 111–134.

Spötl, C., 1987. Eine klastisch-evaporitische Oberperm-Entwicklung im Hallstätter Salzberg (Salzkammergut, Österreich). Mitteilungen der Österreichischen Geologischen Gesellschaft 80, 115–141.

Spötl, C., 1988a. Sedimentologisch-fazielle Analyse tektonisierter Evaporitserien – eine Fallstudie am Beispiel des alpinen Haselgebirges (Permoskyth, Nördliche Kalkalpen). Geologisch-Paläontologische Mitteilungen, Innsbruck, 15, 59–69.

Spötl,C., 1988b. Schwefelisotopendatierungen und fazielle Entwicklung permosythischer Anhydrite in den Salzbergbauen von Dürrnberg/Hallein und Hallstatt (Österreich). Mitteilungen der Geselschaft der Geologie- und Bergbaustudenten in Österreich, 34/35, 209–229.

Spötl, C., 1988c. Evaporitische Fazies der Reichenhaller Formation (Skyth/Anis) im Haller Salzberg (Nördliche Kalkalpen, Tirol). Jahrbuch der Geologischen Bundesanstalt, 131, 153–168.

Spötl, C., 1989a. The Alpine Haselgebirge Formation, Northern Calcareous Alps (Austria): Permo-Scythian evaporites in an alpine thrust system. Sedimentary Geology, 65, 113–125.

Spötl, C., 1989b. Die Salzlagerstätte von Hall in Tirol – ein Überblick über den Stand der geologischen Erforschung des 700jährigen Bergbaubetriebes. In: Veröffentlichungen des Museum Ferdinandeum, Sonderdruck, pp. 137–167.

Spötl, C., 1992. Clay minerals in Upper Permian evaporites from the Northern Calcareous Alps (Alpines Haselgebirge Formation, Austria). European Journal of Mineralogy, 4, 1407–1419.

Spötl, C., Kralik, M. and Kunk, M.J., 1996. Authigenic Feldspar as an Indicator of Paleo-Rock/Water Intercalations in Permian Carbonates of the Northern Calcareous Alps, Austria. Journal of Sedimentary Research 66, 139–146.

Spötl, C. and Pak, E., 1996. A strontium and sulfur isotopic study of Permo-Triassic evaporites in the Northern Calcareous Alps, Austria. Chemical Geology, 131, 219–234.

Spötl, C., Kunk, M.J., Ramseyer, K. and Longstaffe, F.J., 1998a. Authigenic potassium feldspar: a tracer for the timing of palaeofluid flow in carbonate rocks, Northern Calcareous Alps, Austria. In: Parnell, J. (ed.) Dating and Duration of Fluid Flow and Fluid-Rock Interaction. Geological Society, London, Special Publication No. 144, pp. 107–128.

Spötl, C., Longstaffe, F.J., Ramseyer, K., Kunk, M.J. and Wiesheu, R., 1998b. Fluid-rock reactions in an evaporitic mélange, Permian Haselgebirge, Austrian Alps. Sedimentology, 45, 1019–1044.

Spötl, C. and Hasenhüttl, C., 1998. Thermal History of an evaporitic Mélange in the Northern Calcareous Alps (Austria): a Reconnaissance Illite 'crystallinity' and Reflectance Study. Geologische Rundschau, 87, 449–460.

Stöllner, T., 2003. The Economy of Dürrnberg-bei Hallein. An Iron Age salt-mining centre in the Austrian Alps. Antiquaries Journal, 83, 123–194.

Suzuki, H. and Gawlick H.-J., 2009. Jurassic radiolarians from cherty limestones below the Hallstatt alt mine (Northern Calcareous Alps, Austria). Neues Jahrbuch für Geologie und Paläontologie-Abhandlungen, 251, 155–197.

Tollmann, A, 1985. Geologie von Österreich. Außerzentralalpiner Anteil Deuticke, Wien, pp. XV+710.

Tollmann, A., 1987. Late Jurassic/Neocomian Gravitational Tectonics in the Northern Calcareous Alps in Austria. In: Flügel, H.W. and Faupl, P. (eds.) Geodynamics of the Eastern Alps. Deutike, Wien, pp. 112–125.

Urai, J.L. and Boland, J.N., 1985. Development of microstructures and the origin of hematite in naturally deformed carnallite. Neues Jahrbuch der Mineralogischen Monatshefte, 1985, 58–72.

Urai, J.L., Schléder, Z., Spiers, C.J. and Kukla, P.A., 2008. Flow and transport properties of salt rocks. In: Littke, R., Bayer, U., Gajewski, D. and Nelskamp, S. (eds.), 2008. Dynamics of Complex Intracontinental Basins. The Central European Basin System. Springer, Berlin [u.a.], pp. 277–290.

Vozárova, A., Vozár, J. and Mayr, M., 1999. High-pressure metamorphism of basalts in the evaporite sequence of the Haselgebirge: An evidence from Bad Ischl (Austria). Abhandlungen der Geologischen Bundesanstalt, 56, 325–330.

Warren, J.K., 2006. Evaporites. Sediments, Resources and Hydrocarbons. Springer Verlag, Berlin, Heidelberg, New York, XVI+1035 pp.

Weber, F., 1958. Zur Geologie der Kalkalpen zwischen Traunsee und Almtal. Mitteilungen der Geologischen Gesellschaft in Wien, 51, 295–352.

Wessely, G., 2006. Geologie der österreichischen Bundesländer – Niederösterreich. Wien, Geologische Bundesanstalt, 416 pp.

Wegerer, E., Suzuki, H. and Gawlick, H.-J., 2001. Zur stratigraphischen Einstufung von Kieselsedimenten im Bereich des Sandling (Nördliche Kalkalpen, Callovium–Oxfordium). Mitteilungen der Gesellschaft der Geologie- und Bergbaustudenten in Österreich, 45, 67–87.

Wiesheu, R and Grundmann, G., 1994. Fluid inclusion studies of anhydrites from the Permo-Skythian beds of the Haselgebirge Formation (Northern Calcareous Alps, Austria/Germany). International Mineralogical Association, 16th general meeting; Abstracts, pp. 439.

Wiesheu R., 1997. Geologisch-geochemische Untersuchungen zur Rekonstruktion der thermischen Geschichte des Haselgebirges. Dissertation, University TU München. Hieronymus, München, VII+95 pp.

Wise, D.U., Dunn, D.E. and Engelder, J.T., 1984. Fault-related rocks – suggestions for terminology. Geology, 12, 391–394.

Zankl, H. and Schnell, O., 1979. Der geologische Bau des Talkessels von Bad Reichenhall (Nördliche Kalkalpen). Geologisches Jahrbuch, 22, 11–20.

Zirkl, E.J., 1957. Der Melaphyr von Hallstatt. Jahrbuch der Geologischen Bundesanstalt, 100, 137–177.

Received: 7 June 2011
Accepted: 31 September 2011

Christoph LEITNER[*)] & Franz NEUBAUER
Dept. Geography and Geology, University of Salzburg, Hellbrunner Straße 34, A-5020 Salzburg, Austria;
[*)] Corresponding author, christoph.leitner@sbg.ac.at