

TECTONIC SIGNIFICANCE OF STRUCTURES WITHIN THE SALT DEPOSITS ALTAUSSEE AND BERCHTESGADEN–BAD DÜRRNBERG, NORTHERN CALCAREOUS ALPS

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KEYWORDS

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ABSTRACT

The Northern Calcareous Alps (NCA) are a fold-and-thrust belt. Its Mesozoic units were detached, thrust 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 dienen als Hauptabscherhorizont. Die Haselgebirge Formation beschränkt sich in ihrem 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 Salzlagern 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 Faserklufsalzes in Tonsteinklüften zeigen ebenfalls die Orientierung der Steinsalz-Minerallineation und der Faltenachsen. Dahingegen lässt rotes Faserklufsalz 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).

In compressional settings, the amount of shortening is important. Formations comprising rocksalt or other evaporites at the base of thrust 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 Dürrenberg (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

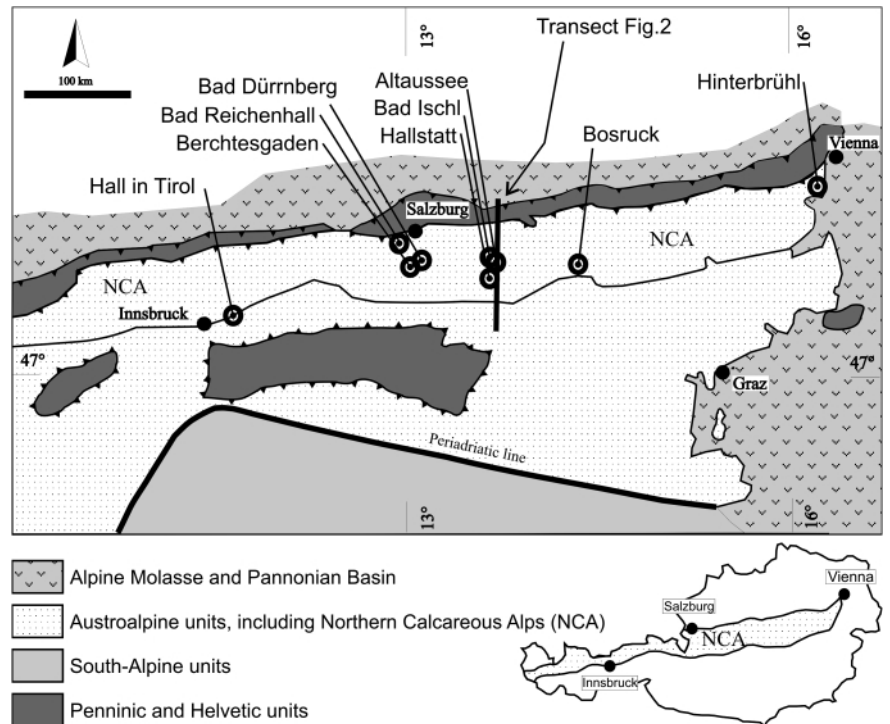


FIGURE 1: Overview sketch map of the Eastern Alps. Main tectonic units and location of salt mines in the central NCA. Insert at right bottom gives the position within Austria. Circles mark rocksalt deposits.

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 (\approx haselgebirge, 10–70 wt % halite), mylonite and ultramylonite (\approx 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; Göttinger and Grum, 1992; Gawlick et al., 1994; Wiesheu and Grundmann, 1994; Spötl et al., 1996; 1998a, 1998b; Wiesheu, 1997; Spötl and Hasenhüttel, 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; Göttinger and Grum, 1992; Gawlick et al., 1994; Spötl et al., 1996; 1998a, 1998b; Gawlick and Höpfer, 1996; Ran-

rock type (according to Schauburger, 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 Schauburger (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 Dürrenberg and Altaussee in 2006–2009; Hallstatt, Hall in Tirol and Bad Ischl were visited for comparison.

2. GEOLOGICAL SETTING

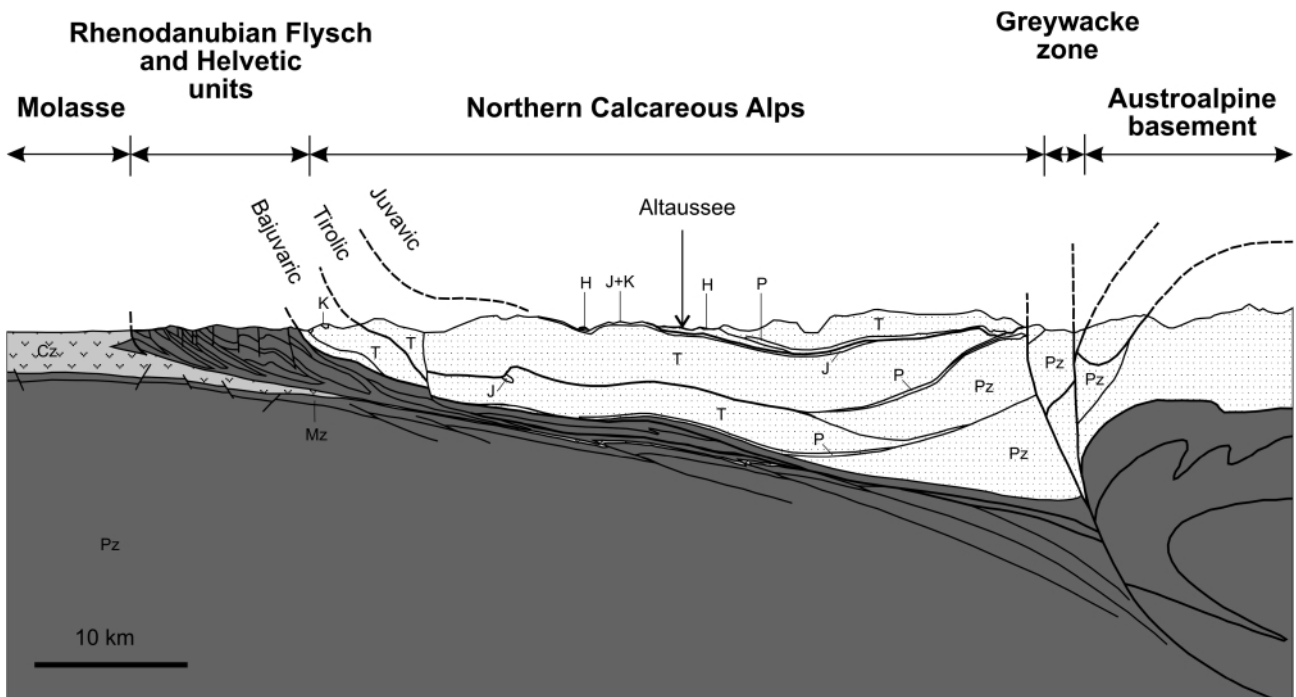
2.1 NORTHERN CALCAREOUS ALPS (NCA)

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 thrust 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-



Molasse, Flysch and Helvetic units:

- Cz Cenozoic
- Mz Mesozoic (foreland)
- Pz Paleozoic
- Undifferentiated

Northern Calcareous Alps:

- J+K Jurassic+Cretaceous (NCA)
- T Middle + Upper Triassic
- H Triassic in Hallstatt facies
- P Permian + Lower Triassic

Greywacke zone, Austroalpine basement:

- Pz Palaeozoic of Grauwacken zone
- Undifferentiated

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 Dürrenberg 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 Dürrenberg 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 Dürrenberg 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 Dürrenberg Fm., ranging in age from Early Triassic to Early Jurassic (Plöschinger, 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, \approx 184–174 Ma; Gawlick et al., 2009). Braun (1998) interpreted rocks incorporated into the salt body as Tauglboden Fm. (Kimmeridgian to Tithonian, \approx 155–149 Ma). The youngest known completely incorporated rocks within the Haselgebirge Fm. belong to the Jurassic Oberalm Fm. (Kellerbauer, 1996). Plöschinger (1976, 1984) found Haselgebirge clasts within the Oberalm Fm. (Tithonian to Berriasian, \approx 149–140 Ma) near the eastern border of the salt body, close to Bad Dürrenberg. In easternmost parts, Haselgebirge Fm. rocks are found within the Schrambach Fm. (Valanginian, \approx 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. (Hau-

terivian to Barremian, \approx 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 Schaubberger 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 % (Schaubberger, 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 (Schaubberger, 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 Reichenhall	Bad Ischl
Permian	-	-	-	volcanic rock	-	-	volcanic 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 = Dürrenberg 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, Schreyeralm, 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).

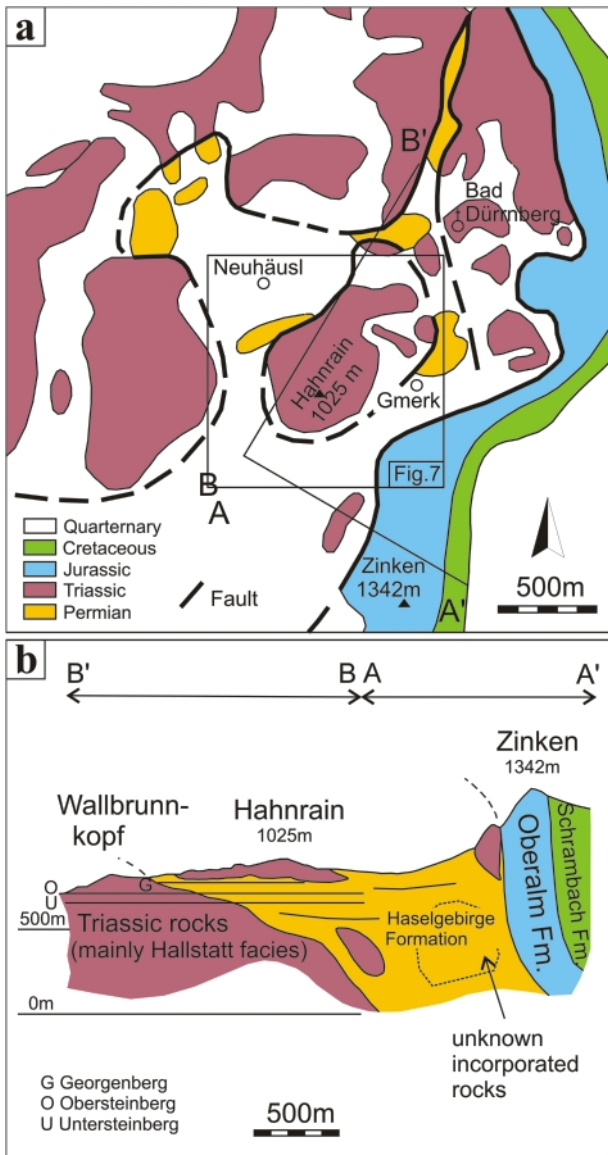


FIGURE 3: Bad Dürrenberg (a) Geological map simplified after Kellerbauer (1996) and (b) cross section simplified after Plöchingner (1996).

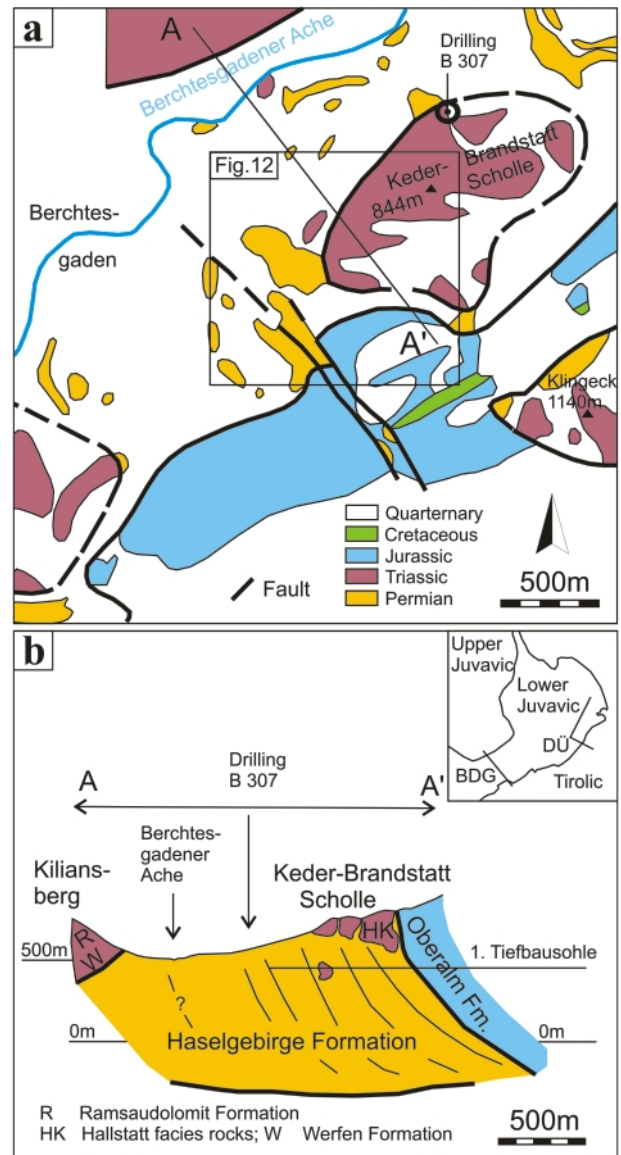


FIGURE 4: Berchtesgaden (a) Geological map and (b) cross section, both modified after Kellerbauer (1996).

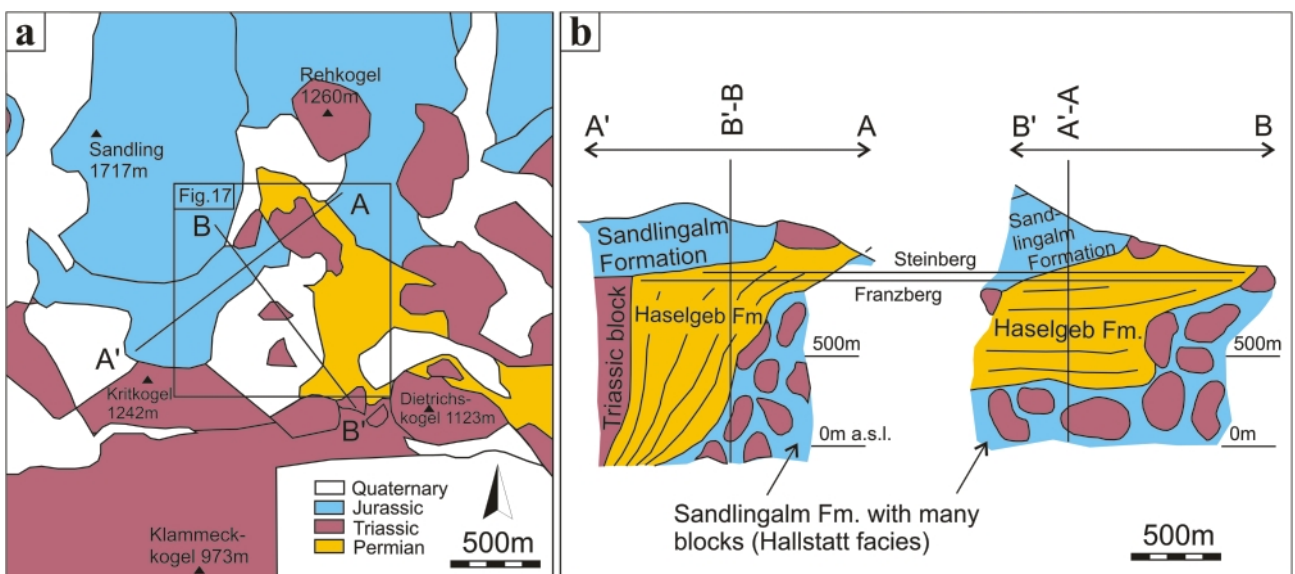


FIGURE 5: Altaussee (a) Geological map simplified after Schäffer (1982) and (b) cross sections.

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 protocataclasis 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; Schaubberger 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.s.l., 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 (Schaubberger, 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., Schaubberger, 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 of-

ten 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 HASELGERBIRGE

Slickensides in haselgebirge are found in the upper levels of the mines. In Bad Dürrenberg, mined rocks of the Celtic Era are easy to identify by their leopard texture and chips of fat-wood. 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

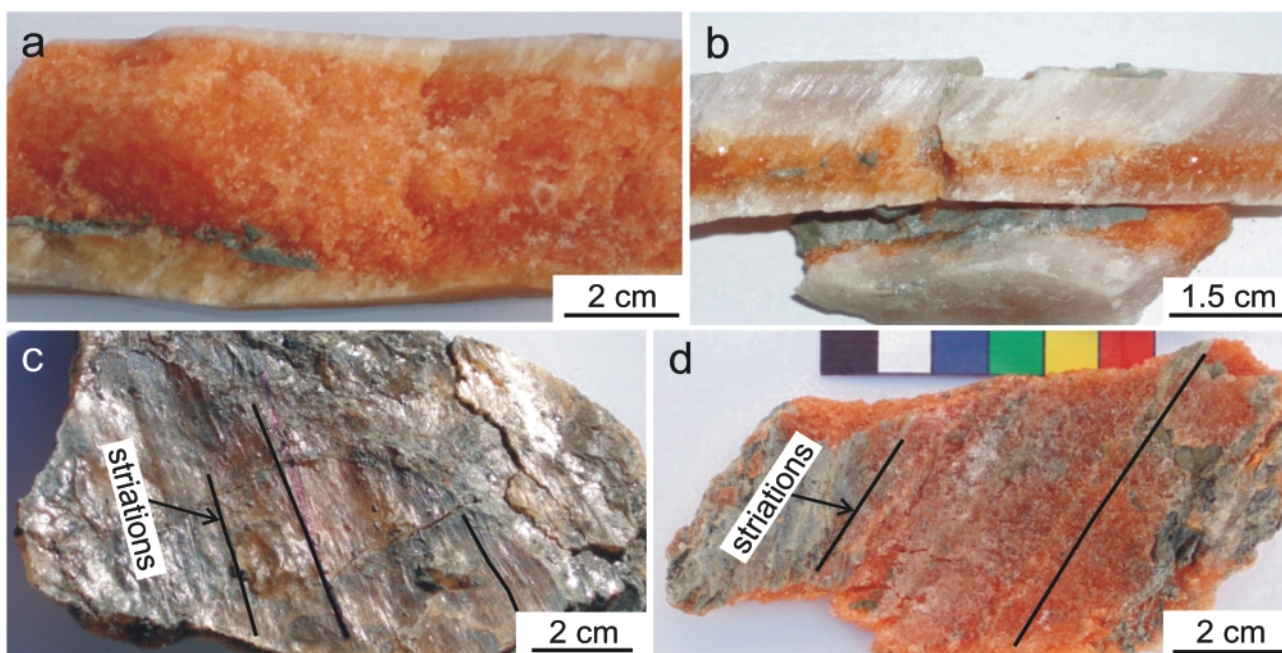


FIGURE 6: (a)–(b) Antitaxial halite veins in mudrock. (c)–(d) Slickensides on wall rock.

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 Tiefbausoehle, 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

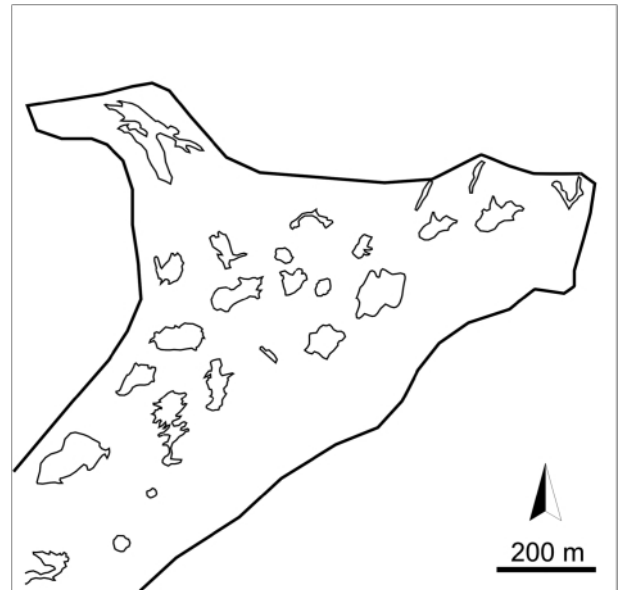


FIGURE 7: Bad Dürrenberg, Obersteinberg level, simplified, depth of caverns ca. 650–750 m a.s.l., no preferred orientation of shapes.

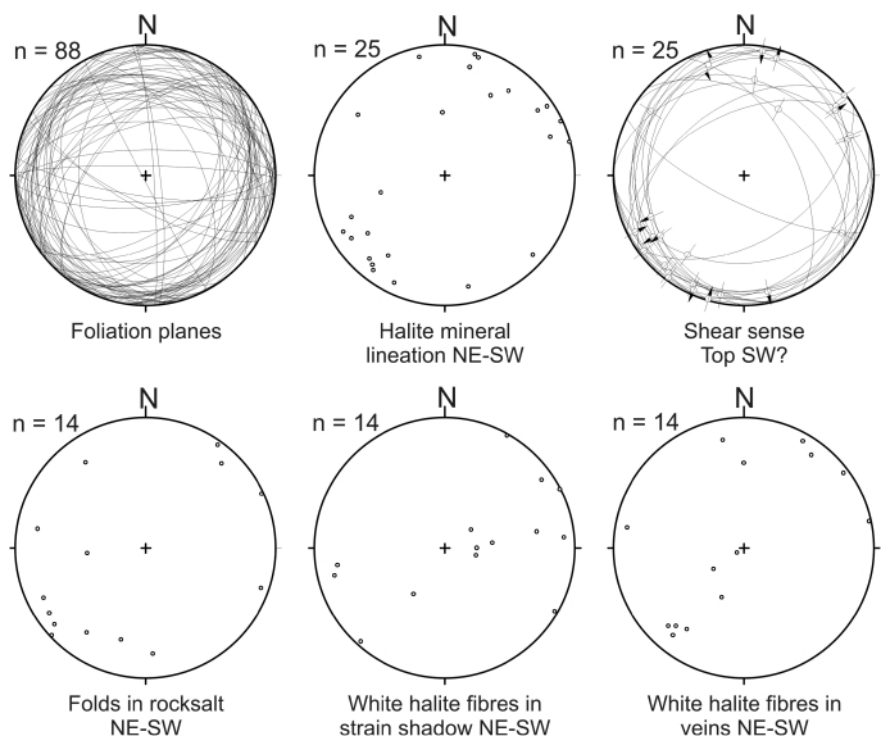


FIGURE 8: Bad Dürrenberg, orientation data of rocksalt (for explanation, see text). Equal area projection, lower hemisphere.

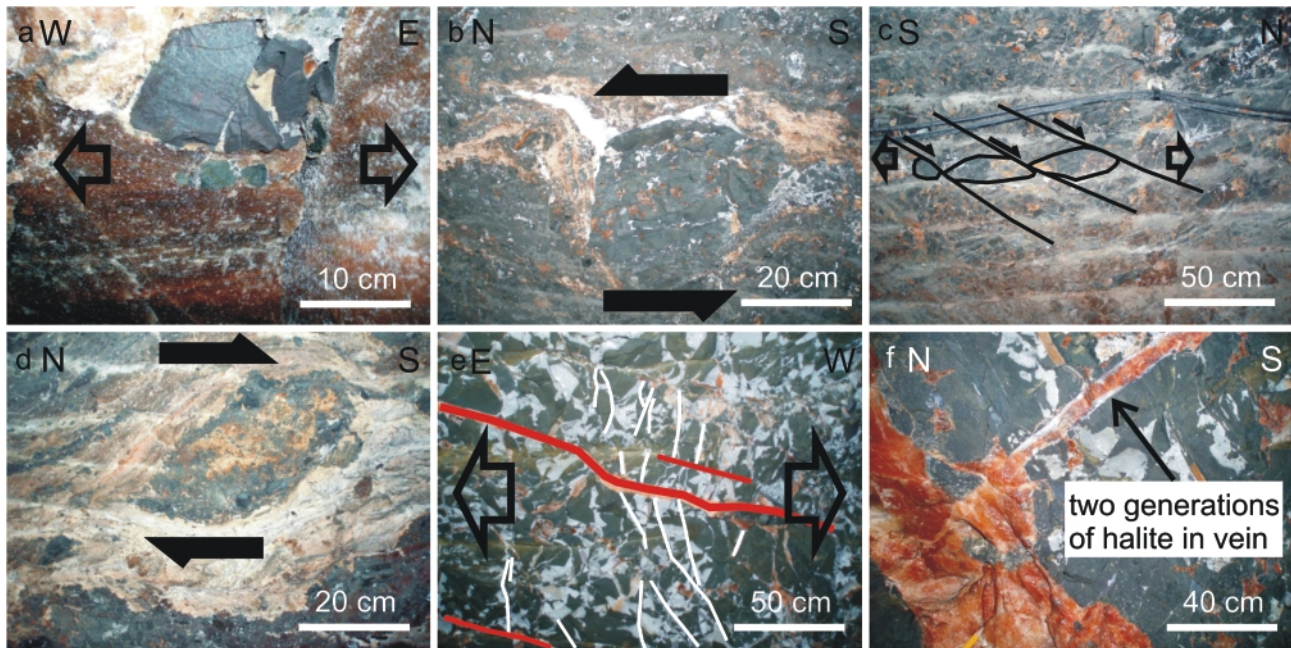


FIGURE 9: Bad Dürrenberg, photos illustrate flat orientation of foliation. (a) Clast in rocksalt breaks during non-rotational deformation. (b) δ -type porphyroclast with white halite in strain shadow. (c) Normal faulting due to extension. (d) σ -object consisting of mudrock. (e) Veins with white halite 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-

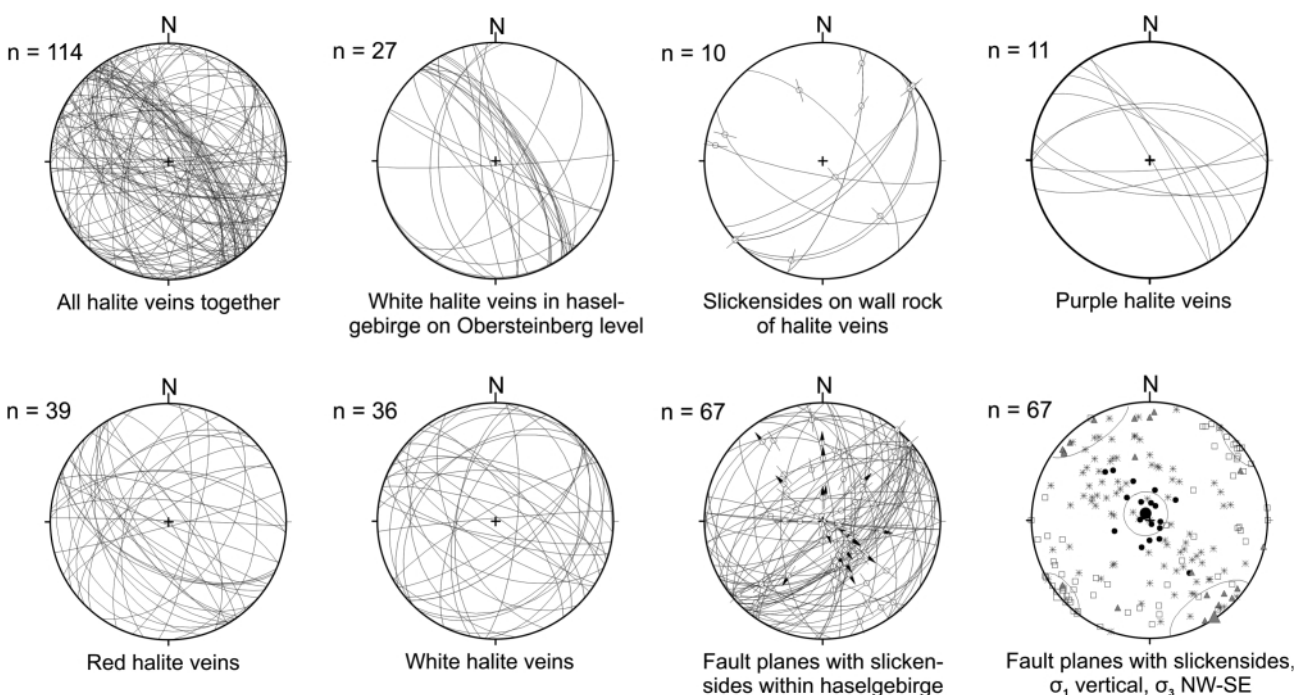


FIGURE 10: Bad Dürrenberg, orientation data of veins and fractures (for explanation, see text). Equal area projection, lower hemisphere.

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 Dürrenberg 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 ha-

selgebirge 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

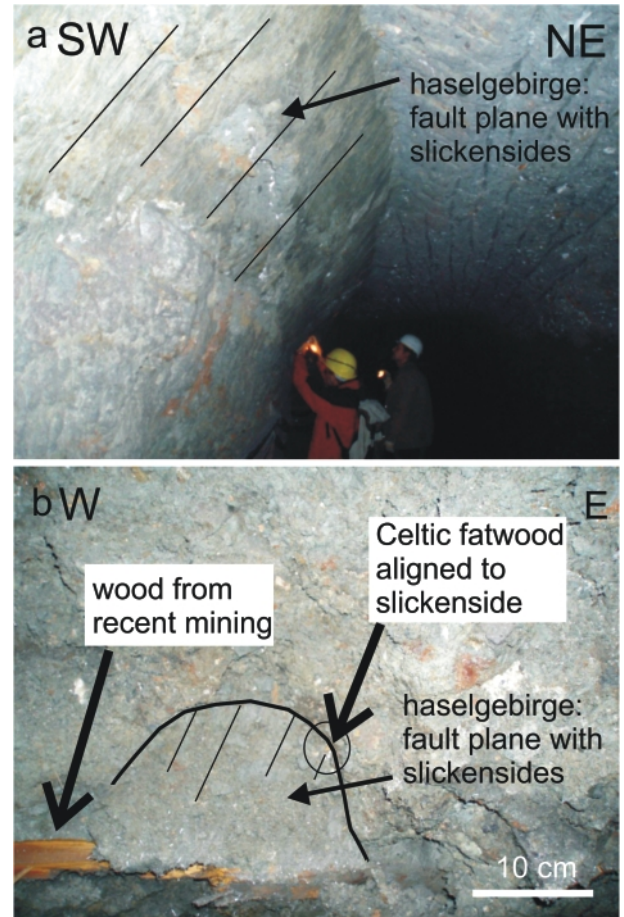


FIGURE 11: Bad Dürrenberg. (a) Normal faults in haselgebirge on Obersteinberg level, (b) younger than Celtic times.

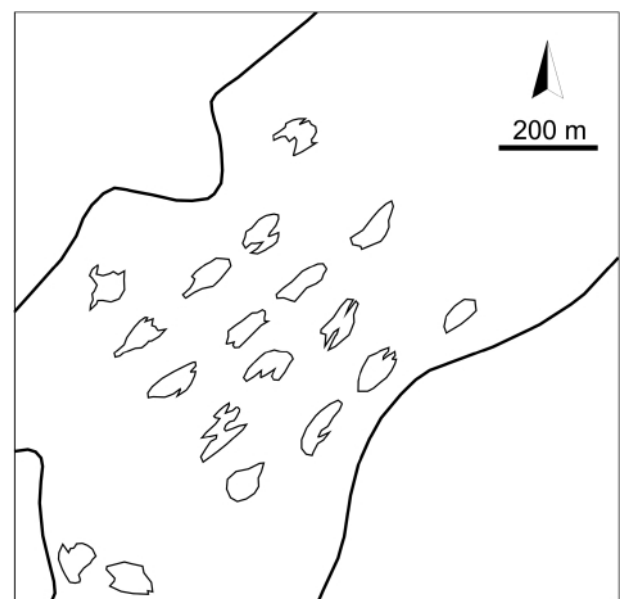


FIGURE 12: Berchtesgaden, level of Erste Tiefbausoehle, simplified, depth of caverns ca. 350–450 m a.s.l., shapes are elongated NE–SW.

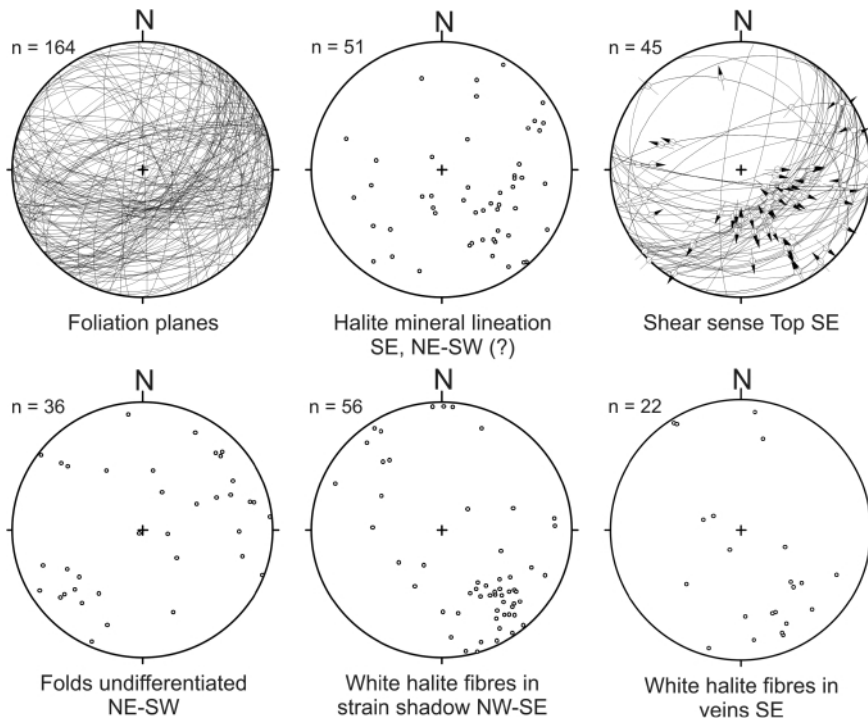


FIGURE 13: Berchtesgaden, orientation data of rocksalt (for explanation, see text). Equal area projection, lower hemisphere.

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 anhydrite 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 Dürrenberg 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-

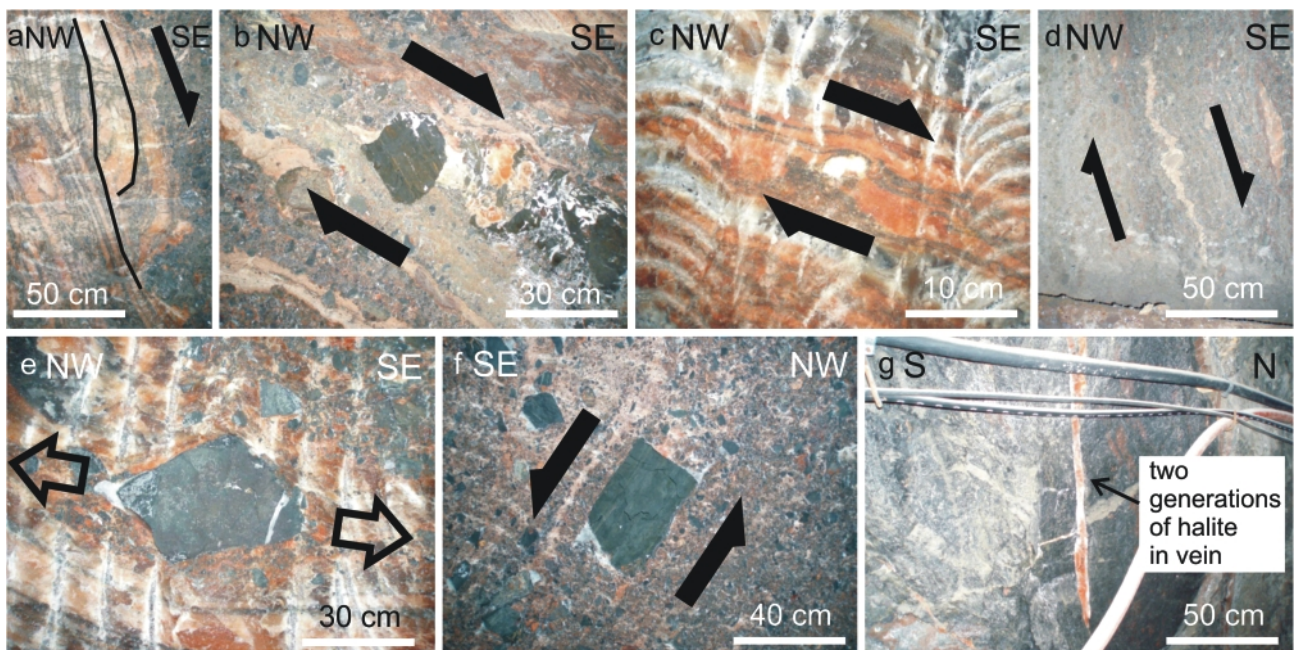


FIGURE 14: Berchtesgaden, photos illustrate normal fault orientation of the foliation. (a) Drag fold in rocksalt. (b) σ -clast with white halite fibres in strain shadows, country rock is haselgebirge. (c) Nodule of rigid non-halite salt (white clast) oblique to foliation circumfluent by rocksalt. (d) 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.

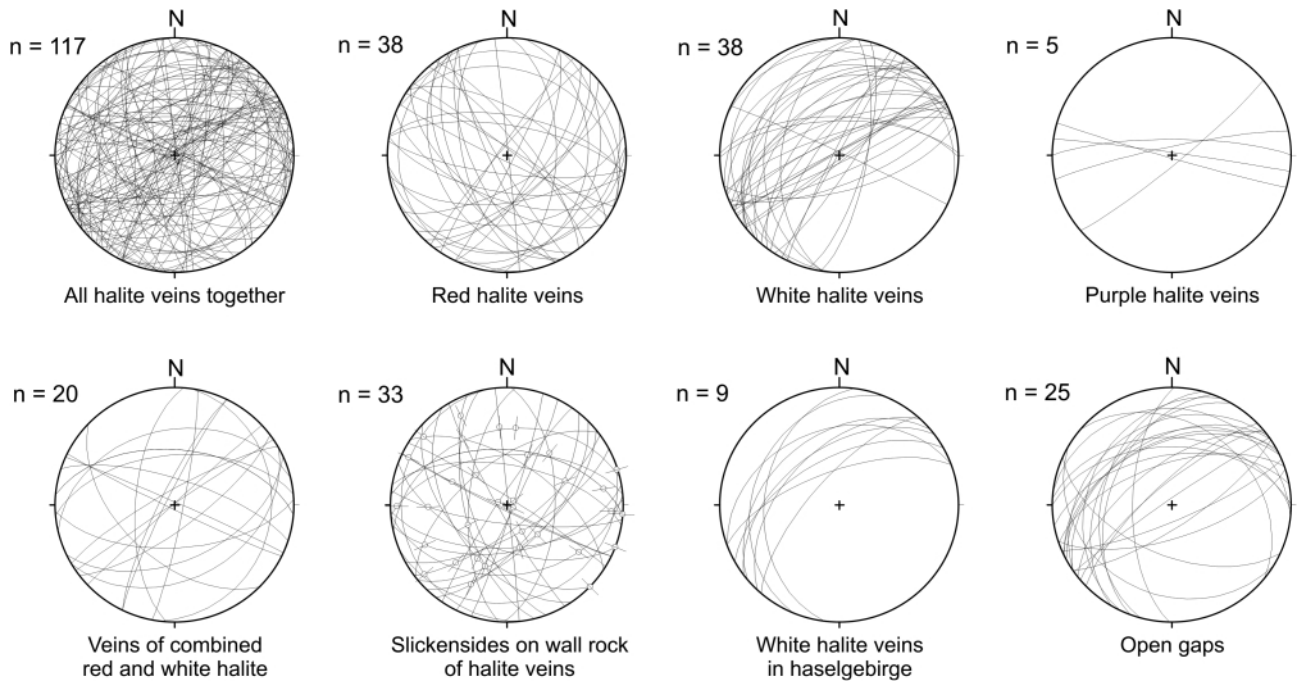


FIGURE 15: Berchtesgaden, orientation data of veins and fractures (for explanation, see text). Equal area projection, lower hemisphere.

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 from 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 Dürrenberg. 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 Dürrenberg, 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 (Plöching, 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-

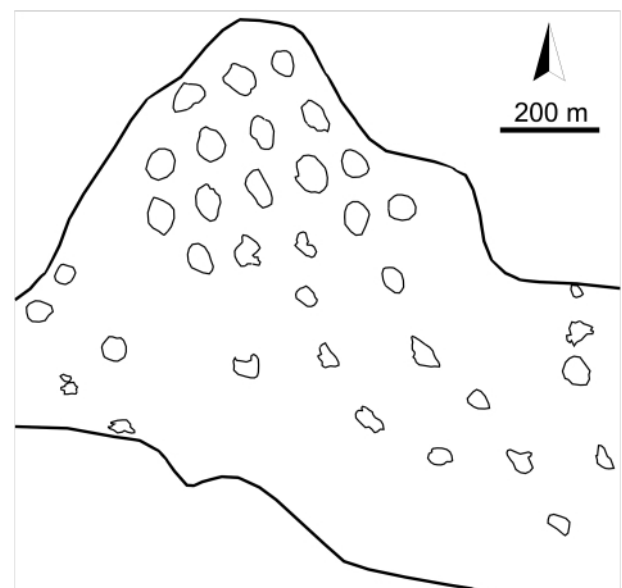


FIGURE 16: Altaussee, Franzberg level, simplified, depth of caverns ca. 820–900 m a.s.l., shapes are slightly elongated NW–SE.

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, Plasenkalk 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 (com-

pare 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 orientation 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

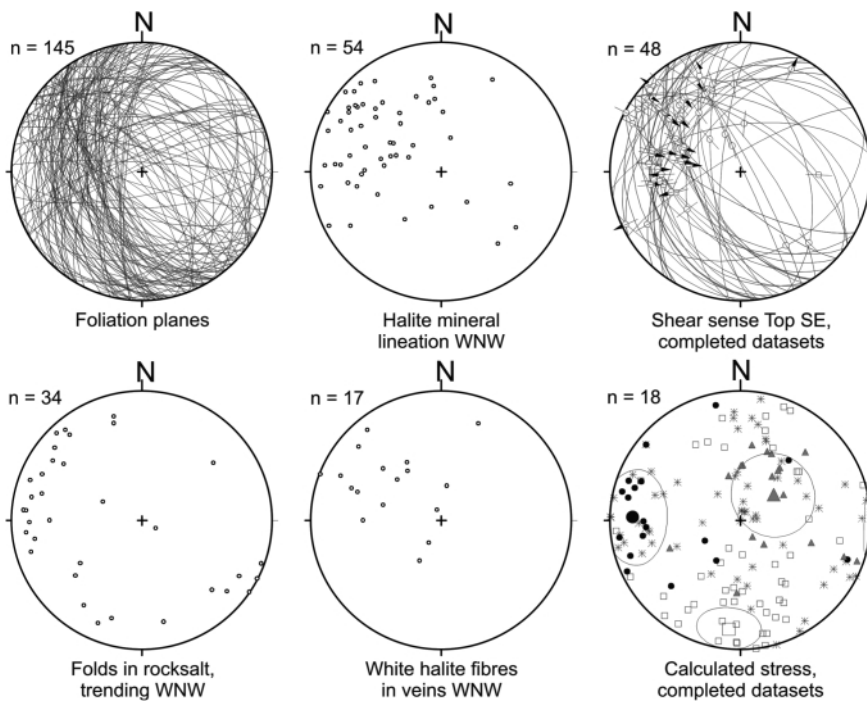


FIGURE 17: Altaussee, orientation data of rocksalt (for explanation, see text). Equal area projection, lower hemisphere.

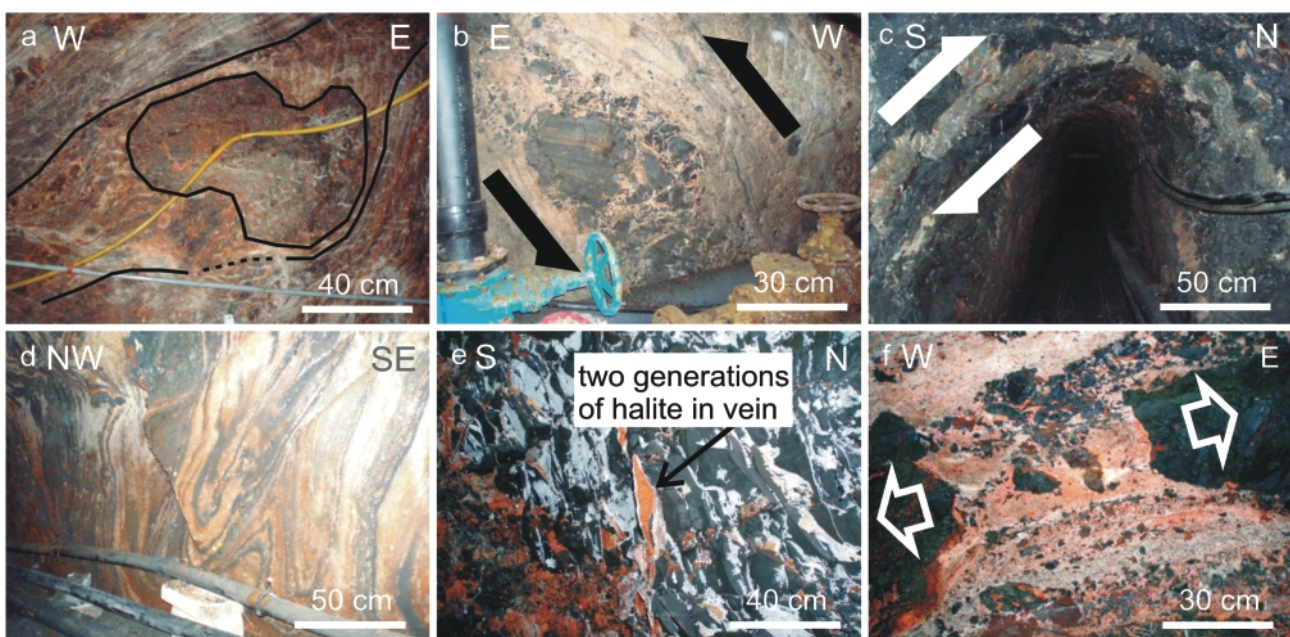


FIGURE 18: Altaussee, style of deformation and reverse faulting of foliation. (a) Stream line body around rigid object. (b) Circumfluent shale clast, folds in adjacent rocksalt. (c) View along gallery towards W. Layer of sandstone in mudrock matrix. (d) Isoclinal folds in rocksalt. (e) Veins in mudrock, 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. Kassembaum (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 overthrust breccia as Rossfeld Fm. with the help of nanofossils. 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.

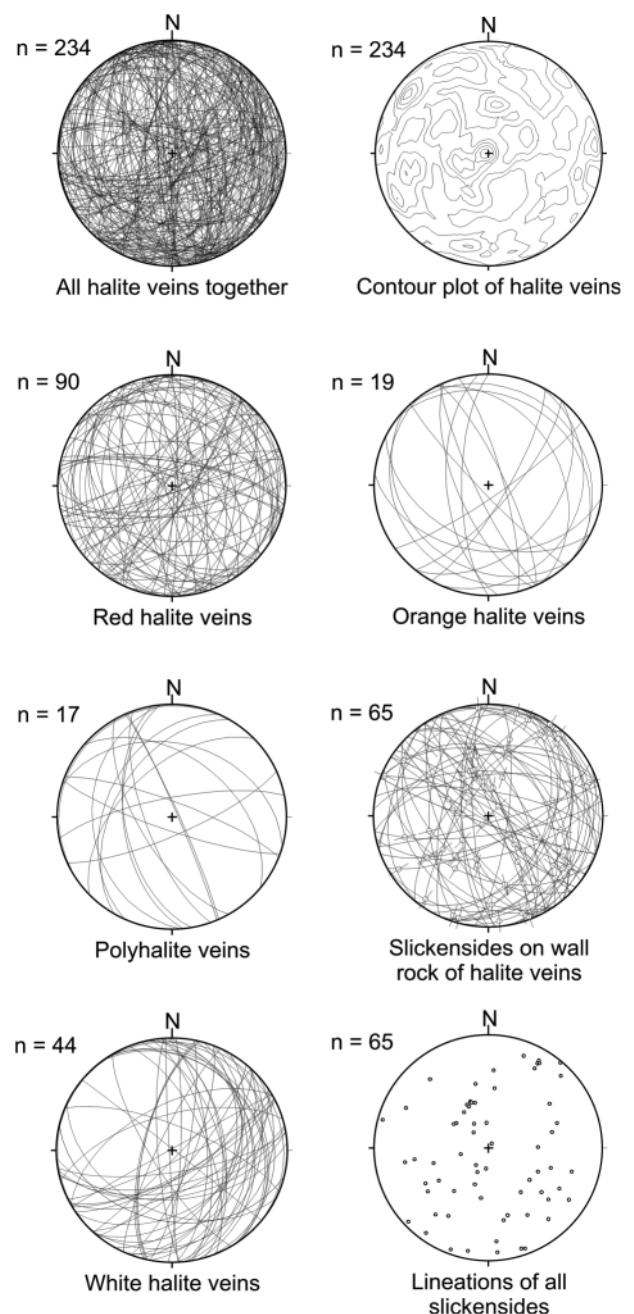


FIGURE 19: Altaussee, orientation data of veins and fractures (for explanation, see text). Equal area projection, lower hemisphere.

During Late Cretaceous to Paleogene 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 rock-salt 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.

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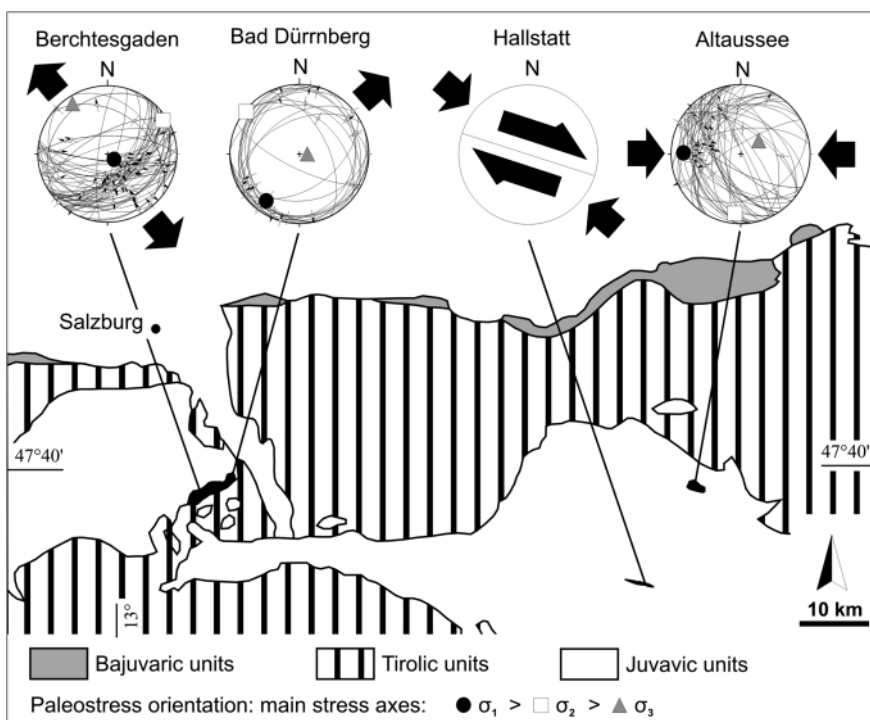


FIGURE 20: Palaeostress orientation within rocksalt deposits (for explanation see text).

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