**Abstract:** Polyhalite rocks of the evaporitic Haselgebirge Formation are emplaced within a rocksalt–mudrock tectonite. The rheologically weak series served as a major detachment level during nappe stacking of the Northern Calcareous Alps (Eastern Alps). To test the mineral polyhalite \([K_2Ca_2Mg(SO_4)_{4.2}H_2O]\) as a useful geochronometer for various diagenetic and deformation fabric types, \(^{40}\text{Ar}/^{39}\text{Ar}\) age dating was combined with microstructural analysis. Vein infills, polyhalite intergrown with anhydrite and polyhalite within mudrock, crystallized in several stages between c. 235 and 210 Ma. Mylonites of fine-grained polyhalite rock indicate subsequent stages of tectonothermal overprint between c. 155 and 105 Ma, which is roughly consistent with previously measured feldspar and muscovite \(^{40}\text{Ar}/^{39}\text{Ar}\) data from the region. Illite crystallinity points to temperatures of c. 200 °C. The peak temperature of overprint was at c. 180 °C in the Berchtesgaden mine (vitrinite reflectance, fluid inclusions) and c. 240 °C in the Altaussee mine (fluid inclusions). These temperatures are below the value of 255 °C, where polyhalite starts to dehydrate. Disturbed age spectra patterns result from multiphase polyhalite growth; however, single phases and completely recrystallized fabrics yield good results. As in the Alpine test case, polyhalite may characteristically serve as a geochronometer for diagenetic and very-low-grade metamorphic processes.

**Supplementary material:** A table of used materials and methods and the detailed \(^{40}\text{Ar}/^{39}\text{Ar}\) step-heating data for polyhalite are available at: www.geolsoc.org.uk/SUP18574

The mineral polyhalite \([K_2Ca_2Mg(SO_4)_{4.2}H_2O]\) often represents a constituent of K-bearing evaporites and can even constitute polyhalite rocks. The K-content makes the mineral interesting for possible dating of geological processes within evaporites by the \(^{40}\text{Ar}/^{39}\text{Ar}\) method. Polyhalite is a common mineral within the Permian–Lower Triassic evaporites of the Eastern Alps. It was first described from Bad Ischl (Stromeyer 1818) and the crystal structure was determined for the first time in Austria (Schlatti et al. 1970; Bindi 2005). Under laboratory conditions, using thermal analysis methods, Wollmann et al. (2008) found that the dehydration process of polyhalite starts at 255 °C and the dehydration reactions are completed at 343 °C. These temperature boundaries define the upper range of polyhalite as a geochronometer.

Rocksalt in diapirs or in detachment levels often incorporates sulphate rocks and other rocks (e.g. Prucha 1968; Schaubeger 1986; Schoenherr et al. 2009; Stern et al. 2011). In contrast to the rheologically weak salt (halite) rocks, the rheologically stiff enclaves of, for example, polyhalite rocks are assumed to preserve information from the times of diagenesis and intense deformation events. The tectonic mélangé of the Northern Calcareous Alps consists of rocksalt, mudrock, anhydrite and subordinate polyhalite rocks, the latter forming up to metre-sized lenses within the halite–mudrock matrix (Spötl 1989; Leitner et al. 2011).

Only a few attempts to date polyhalite have been made using the Rb–Sr, K–Ar and \(^{40}\text{Ar}/^{39}\text{Ar}\) methods. Polyhalites from the German Zechstein salt deposits using K–Ar age dating gave a wide range of ages of uncertain significance (Pilot & Blank 1967). The Permian Salado Formation in New Mexico, United States of America, was investigated using Rb–Sr and K–Ar methods (Brookins et al. 1980; Brookins 1986). There, various types of polyhalite rock were investigated (polyhalite from distorted evaporate beds, polyhalite intergrown with sylvinite and polyhalite from a location next to...
a lamprophyre dike). However, no macro- or microstructures were described. In a short note, one isochron age using $^{40}\text{Ar}/^{39}\text{Ar}$ dating methods was mentioned for dendritic polyhalite intergrown with halite (Onstott et al. 1995). Polyhalite from the Miocene Carpathian foredeep basin was investigated numerous times with the K–Ar method (Krushchov & Zaydis 1978; Halas et al. 1996; Peryt et al. 1996; Wójtowicz et al. 2003). Two polyhalite rock types are mentioned (polyhalite–anhydrite rock in salt-bearing breccias and polyhalite rock from within potash beds) by Wójtowicz et al. (2003); however, in combination with dating other evaporate minerals, the data allowed tectonic interpretations.

In the present study, $^{40}\text{Ar}/^{39}\text{Ar}$ age dating is applied to polyhalite using macro- and microfabrics for the first time in a systematic approach. Several new results are reported here and are discussed within the frame of companion work (Leitner et al. 2012). Vitrinite reflection measurements on altered plant remains from sandstone, fluid inclusions in anhydrite and the illite crystallinity of mudrock are used to estimate the peak temperature in the investigated locations. A wide range of temperatures and geochronological ages exist for the thermal overprint of the Northern Calcareous Alps in the literature, used for cross-checking our new data.

**Geological setting**

The Northern Calcareous Alps form a fold-and-thrust belt along the northern margin of the Eastern Alps. They are classically divided into the Bajuvaric, Tirolic and Juvavic nappe complexes (Fig. 1a–c). Thrusting prograded from south to north and then towards NW during the Early Cretaceous and Palaeogene (e.g. Linzer et al. 1995; Neubauer et al. 2000).

The stratigraphic age of formations in the Northern Calcareous Alps ranges from Late Carboniferous–Early Permian to Eocene times (Mandl 2000). Rocksalt deposits are mostly found in the Lower Juvavic unit (with formations of Late Permian–Early Jurassic times; Mandl 2000). The westernmost part of the expanding Middle Triassic Tethys Ocean is called Meliata Ocean, which comprises rare deep-sea sequences in the eastern parts of the Northern Calcareous Alps (Faupl & Wagreich 2000; Neubauer et al. 2000). A passive continental margin was formed during Middle and Late Triassic times, and evidence for strong tectonic subsidence due to thick shallow water deposits, onset of drifting and widespread SEDEX-type hydrothermal Pb-Zn mineralization is known from the Northern Calcareous Alps (Kozur 1991; Ebner et al. 2000; Mandl 2000; Neubauer et al. 2000). The Meliata Ocean was closed in Late Jurassic times (e.g. Dallmeyer et al. 2008). Coevally, the sea floor reached maximum water depths with the formation of radiolarites in the footwall plate of the Northern Calcareous Alps by means of thrust loading. At the transition from the Early to Late Cretaceous epoch, nappe stacking of Austroalpine units continued due to the subduction of Austroalpine continental crust. The classic hypothesis assumes that both Juvavic nappes took their final position during Late Jurassic–Early Cretaceous nappe tectonics (Mandl 2000). Lower Cretaceous nappe stacking was partly associated with very-low-grade metamorphism. Upper Cretaceous–Eocene Gosau basins seal some nappe contacts and post-date metamorphism. In a parautochthonous model, no distinction between Tirolic and Upper Juvavic units exists and only the rocks of the Lower Juvavic unit are considered allochthonous (Frisch & Gawlick 2003; Missoni & Gawlick 2011), taking their position in Late Jurassic. The presented polyhalite ages of this study contribute to the discussion of the polyphase orogenic history of the Northern Calcareous Alps.

The second stage of the Alpine orogeny took place during the Eocene, resulting in the collision of the stable European continent with the over-riding Austroalpine units. The Northern Calcareous Alps as we know them today were 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 occurred beneath the lowermost unit, the Bajuvaric nappe (Fig. 1b, c). Deformation of Upper Cretaceous–Middle Eocene Gosau basin deposits on uppermost nappes (Tirolic and Juvavic nappes) suggests significant post-Middle Eocene deformation.

The evaporites of the dominating Haselgebirge Formation were deposited during Late Permian–Early Triassic times (257 to c. 251 Ma) and the evaporites of the subordinate Reichenhall Formation at the Lower–Middle Triassic boundary (245–243 Ma) (Klaus 1965; Spötl & Pak 1996; Spötl 1988a, b). These evaporites served as one of the principal detachment levels during Jurassic–Cretaceous- and Palaeogene-aged nappe stacking (e.g. Linzer et al. 1995; Leitner & Neubauer 2011). Polyhalite rocks occur as decimetre- to metre-scaled tectonic lenses within a protomylonitic halite–mudrock matrix (Leitner et al. 2011).

**Saltmines of the Northern Calcareous Alps**

(Austria and Germany)

The underground mines of Berchtesgaden and Bad Dürnb erg are located in the same salt body (Fig. 1b). At the surface, the body extends for c. 7 km, is 0.5–2.0 km wide and at least 1000 m thick. The
Haselgebirge Formation body of Altaussee crops out around the mountain Sandling, comprising 2.3 km² on map view and is >1200 m thick (Fig. 1b). A detailed description of all mined salt bodies of the Northern Calcareous Alps covering the external shape, salt content, tectonic position and incorporated rocks is given in Leitner & Neubauer (2011).

Fig. 1. (a) Overview of the Eastern Alps and the Northern Calcareous Alps. Inset on the bottom right gives the position within Austria. (b) Main tectonic units and transect of the central Northern Calcareous Alps (modified after Schmid et al. 2004) with locations of the present study and former temperature and geochronological studies. (c) Metamorphic map of the Northern Calcareous Alps (modified after Frey et al. 1999).
Materials and methods

Rocksalt and its accompanying evaporites are accessible only in the mines of Hall in Tirol (Tyrol), Berchtesgaden (Bavaria, Germany), Bad Dürrnberg (Salzburg), Bad Ischl, Hallstatt (Upper Austria) and Altaussee (Styria). During this study, all mines were visited and representative samples of polyhalite rocks were investigated from the salt deposits of Altaussee (ALT), Berchtesgaden (BDG) and Bad Dürrnberg (DÜ).

We collected c. 45 specimen of polyhalite rocks from the salt mines for laboratory investigations: for thin sections analysis (31 samples with a total of 38 thin sections, 10 used in tables of this study); fluid inclusion study (3 samples); vitrinite reflectance (3 samples); illite crystallinity (3 samples); and \(^{40}\)Ar/\(^{39}\)Ar dating (12 samples).

\(^{40}\)Ar/\(^{39}\)Ar technique

Preparation of the samples before and after irradiation, \(^{40}\)Ar/\(^{39}\)Ar analyses and age calculations was carried out at the ARGONAUT (laboratory name) of the Department of Geography and Geology at the University of Salzburg. The samples were crushed carefully with a hammer and the fine and coarse fractions were removed by sieving. The material was washed with distilled water to dissolve halite, whose Cl-ions produce undesired Ar isotopes during irradiation, and dried with isopropanol. By comparison, the 200–250 μm fraction was separated under the microscope. Mineral concentrates were packed in aluminium foil and loaded in quartz vials. For calculation of the J-values, flux-monitors were placed between each 4–5 unknown samples.

Table 1. Overview of temperature and ages of the Lower Juvavic unit from the literature

| Temperature, age | Method          | Location       | Paper                                      |
|-----------------|-----------------|----------------|--------------------------------------------|
| c. 350 °C       | CAI             | Pailwand       | Gawlick et al. (1994)                      |
| >200 °C         | IC              | Berchtesgaden  | Kralik et al. (1987a)                      |
| 160–180 °C      | VR              | Hallstatt      | Spötl & Hasenhuittl (1998)                 |
| 150–300 °C      | FI              | Moosegg        | Wiesheu (1997)                            |
| >300 °C         | FI              | Bad Ischl      | Wiesheu (1997)                            |
| 220–260 °C      | FI              | Moosegg        | Spötl et al. (1998a)                      |
| 118–103 Ma      | K/Ar            | Webing         | Kirchner (1980)                           |
| 141–136 Ma, c. 120 Ma | K/Ar | Pailwand | Kralik et al. (1987a)                      |
| 155–139 Ma, 104–99 Ma | K/Ar | Pailwand | Kralik et al. (1987b)                      |
| 145–144 Ma      | \(^{40}\)Ar/\(^{39}\)Ar | Wienern       | Spötl et al. (1996)                      |
| 154–145 Ma      | \(^{40}\)Ar/\(^{39}\)Ar | Moosegg        | Spötl et al. (1998b)                      |
| c. 143 Ma       | Fission track   | Moosegg        | Hejkl & Grundmann (1989)                  |
| c. 44 Ma        | Fission track   | Moosegg        | Hejkl & Grundmann (1989)                  |
| 97–90 Ma        | \(^{40}\)Ar/\(^{39}\)Ar | Webing, Tragöß | Spötl et al. (1998b)                      |
| 120–114 Ma      | \(^{40}\)Ar/\(^{39}\)Ar | Pailwand       | Frank & Schlager (2006)                   |

Abbreviations: CAI – conodont alteration index; IC – illite crystallinity; VR – vitrinite reflectance; FI – fluid inclusions.
The sealed quartz vials were irradiated in the MTA (Magyar Tudományos Akadémia) reactor (Budapest, Hungary) for 16 hours. Correction factors for interfering isotopes were calculated from 45 analyses of co-irradiated Ca-glass samples and 70 analyses of K-glass samples: $^{36}\text{Ar}/^{37}\text{Ar}_{(\text{Ca})} = 0.000225$; $^{39}\text{Ar}/^{37}\text{Ar}_{(g)} = 0.000614$; $^{38}\text{Ar}/^{39}\text{Ar}_{(K)} = 0.0117$; and $^{40}\text{Ar}/^{39}\text{Ar}_{(K)} = 0.0266$. Variation in the flux of neutrons was monitored with the DRA1 sanidine standard for which a $^{40}\text{Ar}/^{39}\text{Ar}$ plateau age of 25.03 ± 0.05 Ma was originally reported (Wijbrans et al. 1995). Here we use the revised value of 25.26 ± 0.05 Ma (Hinsbergen et al. 2008). $^{40}\text{Ar}/^{39}\text{Ar}$ analyses were carried out using a UHV (ultra high vacuum) Ar-extraction line, equipped with a combined MERCHANTEK™ UV/IR laser system, and a VG-ISOTECH™ VG-3600 noble gas mass spectrometer. Stepwise heating analyses of samples were performed using a defocused (c. 1.5 mm diameter) 25 W CO$_2$-IR laser operating in TEM$_{00}$ mode at wavelengths between 10.57 and 10.63 µm. The position of the laser on the sample is monitored on the computer screen via a video camera in the optical axis of the laser beam through a double-vacuum window on the sample chamber. Gas clean-up was performed using one hot Zr-Al SAES™ getter. Gas admittance and pumping of the mass spectrometer and the Ar-extraction line are computer controlled using automatic valves. The VG-3600 is an 18 cm radius 60° extended geometry sector field mass analyser instrument, equipped with a bright Nier-type source operated at 4.5 kV. Measurements are performed on an axial electron multiplier in static mode; peak-jumping and stability of the magnet is controlled by a Hall-probe. For each laser power increment the intensities of $^{36}\text{Ar}$, $^{37}\text{Ar}$, $^{38}\text{Ar}$, $^{39}\text{Ar}$ and $^{40}\text{Ar}$ are measured and the baseline readings on mass 34.5 are automatically subtracted. Intensities of the peaks are back-extrapolated over 16 measured intensities to the time of gas admittance either by a straight line or a curved fit, depending on intensity and type of pattern of the evolving gas. Intensities are corrected for system blanks, background, post-irradiation decay of $^{37}\text{Ar}$ and interfering isotopes. Isotopic ratios, ages and errors for individual steps are calculated following suggestions by McDougall & Harrison (1999) and Scaillet (2000) using decay factors reported by Steiger & Jäger (1977). Definition and calculation of plateau ages were performed using ISOPLOT3.75 (Ludwig 2012).

Vitrinite reflection

Vitrinite reflectance measurements were performed at the Institute of Geology and Economic Geology, Mining University of Leoben. Values were measured on sections of sandstone with coal, polished under oil immersion in non-polarized light at a wavelength of 546 nm. The formula of Barker (1988) for the time-independent temperature regression gives an estimate of the temperature, within error limits of ± 20 °C.

Illicite crystallinity

Illicite crystallinity was determined at the Institute for Mineralogy and Petrology, University of Zagreb, Croatia. Mudrock was crushed and the <2 µm fraction was separated by centrifugation. Illicite crystallinity is given by the Kübler index (KI; Kübler 1967, 1968; Kübler & Jaboyedoff 2000). The KI values were calibrated to those of Küblers laboratory at Neuchatel with standard rock slab series.

Fluid inclusions

Microthermometrical measurements on anhydrite were carried out at the Institute for Mineralogy and Petrology, University of Zagreb. Measurements were performed at the Linkam THMS 600™ stage with fluid inclusion standards (SYN FLINCTM; pure H$_2$O, mixed H$_2$O-CO$_2$), using the FLUIDS computer program for aqueous solutions at low temperatures (Bakker 2003). Calculations are based on purely empirical best fits (Naden 1996). Isochores were calculated by use of the computer program ISOC (Bakker 2003) using the equation of state by Zhang & Frantz (1987).

Results

Macroscopic features of mudrock, anhydrite and polyhalite

Within undeformed mudrock, up to several centimetres thick veins with fibrous polyhalite crystals exist. In most cases, vein walls are parallel to the sedimentary layers and polyhalite crystals grew roughly perpendicular to the vein walls (Fig. 2a–c). In anhydrite rock, polyhalite layers mostly follow the foliation of anhydrite rock; sometimes they form parallel stripes (Fig. 2d–f). Occasionally, polyhalite layers were folded together with the hosting anhydrite rock. Gradual transitions exist between polyhalite in anhydrite and polyhalite in mudrock, depending on the primary intercalation of anhydrite (respectively, gypsum) and mudrock. Polyhalite layers and lenses within mudrock reach thicknesses of millimetres to decimetres, the latter representing massive layers. Layers are parallel to the sedimentary layering of the mudrock, and sometimes folded (Fig. 2g–i).
Polyhalite only occurs as a secondary mineral within the Alpine salt deposits. No sedimentary structures of polyhalite were found. Polyhalite crystallized and recrystallized with a variety of microfabric types. However, the subdivisions must be used with care since there exist variations in the amount of polyhalite–anhydrite–mudrock and the grade of deformation, particularly the distinction between sheared, partly sheared and non-sheared polyhalite rocks. An overview of the most common and characteristic microfabrics of the samples used for age dating is provided in Table 2; related microphotographs are shown in Figure 3.

**Fibrous polyhalite in veins (polyhalite rock type 1)**

The red-coloured fibrous polyhalite vein fillings in undeformed mudrock are up to several centimetres thick. Symmetrically arranged zones parallel to the wall rock indicate several stages of vein opening, according to an antitaxial crack-seal mechanism (Ramsay 1980). Under the microscope, fibres are oriented normal to the vein walls. The central median line comprises mudrock particles. The outer parts show neat fibres up to 7 mm in length with an extending shape towards the wall rock side, overgrowing neighbouring fibres (Fig. 3a). The lowest palaeo-stress orientation (σ3) during formation of the veins was subvertical (Leitner et al. 2012).

**Porphyroblasts of polyhalite in anhydrite (polyhalite rock type 2)**

**Round polyhalite blasts (polyhalite rock type 2A).** Polyhalite overgrew the anhydrite matrix, as polyhalite contains many inclusions of anhydrite. The shape of polyhalite grains is prismatic and the size is c. 3–5 mm. In well-preserved examples the centres of grains are colourless, whereas the rims are red (Figs 2f & 3b, c).

**Fibrous polyhalite blasts (polyhalite rock type 2B).** Single sheaf-shaped polyhalite fibres (up to 5 mm) or accumulations of polyhalite needles (c. 0.2–0.5 mm) often occur in the anhydrite matrix (Fig. 3d). The fibres are developed preferentially along contacts to mudrock and are euhedral at the contact to halite.
|                        | ALT-42A | BDG-37D | ALT-53B | ALT-11 | ALT-13 | ALT-35 | ALT-37B | DÜ-9 | BDG-92 | BDG-B4 |
|------------------------|---------|---------|---------|--------|--------|--------|---------|------|--------|--------|
| Grain size of polyh (mm) | 2–7     | 2–7     | 0.5–2.0 | 5–8    | 3–4    | 0.05–0.8 | 0.05–0.7 | 0.05–0.5 | 0.05–0.3 | 0.1–0.5 |
| Polyhalite core-rim | –       | –       | –       | –       | x      | –      | –       | –    | –      | –      |
| Polyhalite fibres | x       | x       | x       | x       | x      | –      | –       | x    | –      | x      |
| Polyhalite prismatic/twins | –     | –       | –       | (–)    | –       | x      | x       | x    | –      | (x)    |
| Polyhalite SPO | –       | –       | –       | –       | –       | x      | x       | –    | –      | –      |
| Large anhydrites | –       | –       | –       | –       | –       | –      | x       | –    | x      | x      |
| Tiny incl. in large anhy | –      | –       | –       | –       | –       | –      | x       | –    | x      | x      |
| Twinning of large anhy | –      | –       | –       | –       | –       | –      | –       | –    | x      | x      |
| Breaking up of large anhy | –   | –       | –       | –       | –       | –      | –       | –    | x      | x      |
| Small anhydrites | –       | –       | –       | –       | –       | –      | x       | –    | –      | –      |
| Paragenesis | P, A, M | P, M, H | P, A, M, O | P, A, M, H, O | P, A, M, H, O | P, A, M, H, O | P, A, M, H, O | P, A, M, H, O | P, A, M, H, O | P, A, M, H, O |
| Polyhalite type | 1       | 1       | 1       | 2       | 2       | 3      | 3       | 3    | 3      | 3      |

*Abbreviations: ALT – Altauśsee mine; BDG – Berchtesgaden mine; DÜ – Bad Dürrnberg mine; P – polyhalite; A – anhydrite; M – mudrock; H – halite; O – opaque minerals.*
Round porphyroblasts often include anhydrite matrix grains of straight grain boundaries, indicating a growth before major deformation. Fibrous porphyroblasts also occur within anhydrite matrix, where the grains expose lobate grain boundaries (from deformation) and no relative succession of growth stage types is obvious there.

Fig. 3. Microphotographs of polyhalite microfabric types, crossed polarizers: (a) fibrous polyhalite vein infill; (b) polyhalite porphyroblasts in anhydrite matrix; (c) large non-segregated polyhalite grain with core and rim structure; (d) fibres and needles of polyhalite within blocky anhydrite matrix; (e) mylonitic fine-grained polyhalite with areas of non-reduced grain size, extensive grain boundary migration; (f) foliated polyhalite rock with typical twins and shape-preferred orientation; (g) shear zones and relict sheared areas within polyhalite rock (small euohedral anhydrites, overgrowing shear zones, expose many polyhalite inclusions); (h) large anhydrite grain with strain shadow of polyhalite; (i) large anhydrite crystals, spicular polyhalite together with halite in gaps therein; (j) primary fluid inclusion bands and pressure twins of large anhydrite crystals, corroded by polyhalite; (k) anhydrite crystals with no preferred orientation from an isolated halite–anhydrite–polyhalite nodule within mudrock; anhydrite crystals corroded by polyhalite; and (l) polyhalite together with halite from a vein, without a preferred growth direction. All photographs with classification of polyhalite rock types (An: anhydrite; Ha: halite; Ph: polyhalite).
Dense polyhalite comprising corroded large anhydrite grains (polyhalite rock type 3)

Fine-grained, mylonitic polyhalite rock (polyhalite rock type 3A). The fine-grained and foliated polyhalite rock consists mainly of polyhalite. An intense foliation consists of regions with small grains (0.2 mm) to very small grains (<0.05 mm; Fig. 3e). Lobate grain boundaries indicate grain boundary migration as the dominating recrystallization mechanism. Domains of pre-shearing grown, coarse-grained, irregular polyhalite (0.1–0.3 mm) are circumfluent by the foliation. These grains often expose a prismatic habit with characteristic symmetrical twins (Fig. 3f). Large euhedral anhydrite grains (15–20 mm) comprise tiny inclusions of polyhalite and are corroded by polyhalite. They sometimes expose strain shadows of polyhalite (Fig. 3g).

Non-foliated polyhalite rock with local shear zones (polyhalite rock type 3B) which records partial overprint. Growth stages of sample ALT-35 are shown in Figure 4. Circa 0.2–0.4 mm large polyhalite grains occur in irregular patches with a tendency to fibrous growth (stage 2 in Fig. 4), and grains become euhedral in close proximity to halite. Some of the up to over 40 mm large anhydrite grains contain parallel zones of primary fluid and solid inclusions (Fig. 3i–j). The tiny solid inclusions are polyhalite (polyhalite stage 1 in Fig. 4). The large anhydrite crystals are corroded by the surrounding fibrous polyhalite, typically rectangular to their surface (Fig. 3j–k). In many cases, the crystals are broken and filled with xenomorphic halite and spicular polyhalite (Fig. 3j). Local thin shear bands of small polyhalite grains can be traced through the rock (stage 4 in Figs 3g & 4).

Non-foliated polyhalite rock (polyhalite rock type 3C). Purely irregular types are rarely identified, since all polyhalite rocks show some kind of shape-preferred orientation. One rock with a non-foliated microfabric of polyhalite is composed of halite–anhydrite–polyhalite nodules isolated within mudrock. Nodules are up to c. 15 cm length. Euhedral lath-shaped anhydrite crystals (up to 15 mm) are found within a matrix of xenomorphic halite. The large anhydrite crystals comprise tiny solid inclusions of polyhalite and are corroded by small polyhalite grains (c. 0.1 mm; Fig. 3i).

Polyhalite rock types 3A, 3B and 3C are all dense polyhalite rock comprising corroded large anhydrite grains, but differ in their grade of shearing: sheared, partly sheared and non-sheared, respectively.

Abundance of polyhalite types within the deposits

Polyhalite in veins (polyhalite rock type 1) were found in the Altaussee and Berchtesgaden-Bad Dürnberg mines, making up only c. 5%. The well-developed round polyhalite blasts (type 2A) have so far only been observed in the Altaussee mine. The fibrous type (type 2B) is common in both deposits and makes up c. 25% of all polyhalite rocks. Dense polyhalite (polyhalite rock type 3) is the dominating type in Altaussee and Berchtesgaden-Bad Dürnberg mines. It makes up c. 70% of all polyhalite rocks and needs further specification and subdivision.

Results of laboratory measurements

$^{40}\text{Ar}/^{39}\text{Ar}$ age dating results

Total-fusion and step-heating $^{40}\text{Ar}/^{39}\text{Ar}$ dating has been performed on single grains, pieces of single grains and/or polygrains, usually of the 200–250 μm fraction. Errors of ratios, J-values and ages are reported at the 1σ level (=standard deviation; 68.3% confidence level). Several experiments are reported as preliminary results in companion papers (Leitner et al. 2012). For the $^{40}\text{Ar}/^{39}\text{Ar}$ analytical results presented here, an overview is given in Table 3 and the age spectra are depicted in Figure 5. In general, the argon release of polyhalite was limited to a narrow range of laser power

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**Fig. 4.** Polyhalite growth stages in sample ALT-35.
| Sample         | Grains | Steps | Isochron age (ISO) | MSWD (ISO) | Initial $^{39}$Ar/$^{40}$Ar (ISO) | Total gas age, plateau age | MSWD/ | $^{39}$Ar (PA) | Oldest significant age | Step (o) | $^{39}$Ar (o) | Youngest significant age | step (y) | $^{39}$Ar (y) | Comment |
|---------------|--------|-------|-------------------|------------|-----------------------------------|--------------------------|--------|----------------|----------------------|----------|----------------|------------------------|----------|----------------|---------|
| ALT-53B       | 5      | 11    | 211 ± 10          | 10.0       | 280 ± 230                         | 221.3 ± 0.6              | 11     | 15.2           | 204.0 ± 0.8            | 3        | 2.5            | –                     |          |                |         |
| ALT-13 (622)* | 1      | 6     | –                 | –          | –                                 | 204.1 ± 1.0              | 6      | 20.5           | 178.4 ± 1.0            | 3        | 14.5           | –                     |          |                |         |
| ALT-13 (731)* | 5      | 12    | –                 | –          | –                                 | 209.9 ± 1.1              | 11     | 27.0           | 185.0 ± 1.0            | 4        | 9.3            | 27% $^{39}$Ar in step 11 |          |                |         |
| DÜ-9          | 5      | 7     | 207.3 ± 0.9       | 11.1       | 731 ± 1300                        | 231.3 ± 0.6              | 3      | 14.3           | 194.0 ± 0.6            | 7        | 7.3            | –                     |          |                |         |
| BDG-92 (638)  | 5      | 10    | 143 ± 13          | 87         | 380 ± 100                         | 218.0 ± 9.8              | 10     | 1.8            | 132.4 ± 0.5            | 7        | 11.1           | 85% $^{39}$Ar till step 7 |          |                |         |
| BDG-92 (618)  | 1      | 11    | 131.2 ± 1.4       | 0.44       | 312 ± 220                         | PA 131.3 ± 0.5           | 0.28/0.89 | 74.1         | 194.4 ± 3.2            | 9        | 13.0           | 38.5 all steps 3–7     |          |                |         |
| BDG-B4        | 8      | 5     | –                 | –          | –                                 | –                        | –      | –              | 183.7 ± 1.6            | 1        | 55.0           | –                     |          |                |         |
| ALT-35        | 5      | 7     | 172 ± 16          | 57         | 212 ± 110                         | 185.7 ± 0.5              | 7      | 19.6           | 158.5 ± 0.4            | 3        | 9.0            | –                     |          |                |         |
| ALT-37 (561)* | 1      | 8     | –                 | –          | –                                 | –                        | –      | –              | 156.6 ± 2.1            | 8        | 4.9            | –                     |          |                |         |
| ALT-37 (403)* | 1      | 4     | 166.7 ± 5.2       | 0.084      | 4160 ± 1300                       | 156.7 ± 0.8              | 4      | 65.1           | 119.6 ± 0.8            | 2        | 15.8           | 65% $^{39}$Ar in step 4 |          |                |         |
| ALT-37 (766)* | 5      | 16    | –                 | –          | –                                 | 152.3 ± 0.9              | 16     | 6.0            | 118.5 ± 0.9            | 6        | 3.4            | –                     |          |                |         |
| ALT-28 (098)* | 1      | 8     | 234.1 ± 3.2       | 2.7        | 415 ± 20                          | PA 234.6 ± 1.0           | 1.00/0.42 | 98.3         | –                    | –        | –              | –                     |          |                |         |
| ALT-28 (099)* | 5      | 9     | 235.2 ± 2.5       | 6.1        | 489 ± 290                         | PA 235.5 ± 1.0           | 0.77/0.61 | 71.8         | –                    | –        | –              | –                     |          |                |         |
| BDG-12 (089)* | 1      | 7     | 231.9 ± 1.5       | 5.9        | –                                 | TGA 230.2 ± 0.8          | –      | –              | –                    | –        | –              | –                     |          |                |         |
| BDG-12 (073)* | 5      | 11    | 218.3 ± 1.4       | 22         | 1175 ± 2200                       | TGA 220.1 ± 0.7          | –      | –              | –                    | –        | –              | –                     |          |                |         |
| ALT-42A*†     | 1      | 3     | –                 | –          | –                                 | –                        | –      | –              | –                    | –        | –              | –                     |          |                |         |
| BDG-37D*      | 7      | 4     | 232.6 ± 1.0       | 3.4        | 780 ± 2300                        | TGA 234.2 ± 0.5          | –      | –              | 235.4 ± 0.5            | 4        | 46.1           | 232.0 ± 0.6            | 1        | 24.4           | 46% $^{39}$Ar in step 4 |          |                |         |
| ALT-11 core*  | 1      | 9     | 224.7 ± 1.0       | 1.0        | –                                 | 229.0 ± 0.6              | 4      | 12.2           | 215.5 ± 0.6            | 6        | 5.3            | –                     |          |                |         |
| ALT-11 rim*   | 4      | 11    | 208.1 ± 1.7       | 24         | 1228 ± 1800                       | TGA 211.9 ± 0.5          | –      | 18.3           | 203.6 ± 1.1            | 3        | 2.5            | –                     |          |                |         |
| ALT-37 (562)* | 1      | 5     | –                 | –          | –                                 | 113.2 ± 1.0              | 4      | 25.8           | 44.3 ± 9.4             | 1        | 2.8            | 26% $^{39}$Ar in step 4 |          |                |         |

*Preliminary results in companion papers (Leitner et al. a, b).
†Time between irradiation and measurement was more than 10 times the half-life of $^{37}$Ar, so no correction for Ca-derived $^{36}$Ar and $^{39}$Ar could be applied.

Abbreviations: ICA – isotope correlation age; PA – plateau age; TGA – total gas age; MSWD – mean square of weighted deviates.
and between 4 and 16 steps were measured. $^{38}\text{Ar}/^{39}\text{Ar}$ ratios are the same as for K-glass monitors ($= 0.0117$), proving that no significant Cl-concentrations were present in the samples. Therefore, no corrections for Cl-derived $^{36}\text{Ar}$ were applied. For some samples, the time between irradiation and measurement was more than 10 times the half-life of $^{37}\text{Ar}$, so no correction for Ca-derived $^{36}\text{Ar}$ and $^{39}\text{Ar}$ were applied either. Chemical analysis with EDX proved that their composition is that of pure polyhalite. For a characteristic value of $^{37}\text{Ar}/^{39}\text{Ar}$ of 0.48 for pure polyhalite,
the age without these corrections will be c. 0.5 Ma too young. This age difference is still within the error of the ages of our samples.

The chemical composition of polyhalite of various microfabric types was investigated by electron microprobe analysis, but no significant chemical differences were detected. To plot the range of scattering data, the ages of the oldest and youngest significant step (containing several percent of $^{39}$Ar released) were plotted in Figure 6. Some samples show the presence of inhomogeneous extraneous argon by giving older apparent ages for low-temperature release steps. The amount of extraneous argon cannot be quantified from the isochron plots because of the very low $^{36}$Ar/$^{40}$Ar ratios. These steps were ignored in the interpretation for these samples (ALT-13(731), ALT-53B, ALT-35 and ALT-37B(766)).

One sample of vein-type polyhalite (polyhalite type 1) was measured. The pieces were taken from large crystals, where the overprint was low according to thin section observations (Table 2). Single-grain and polygrain measurements yield similar argon release patterns. For sample ALT-53B, an age of $211 \pm 10$ Ma was calculated from the intercept on the inverse isochron plot.

In sample ALT-13 (polyhalite type 2), the single-grain and the polygrain measurement show roughly similar ages for the oldest and the youngest significant age. In both experiments of ALT-13, the measured $^{37}$Ar concentration was nearly the same as background due to a long time span between irradiation and measurement. The proper age should therefore be c. 0.5 Ma older.

Sample DÜ-9 (polyhalite type 3) yields a disturbed scattered argon release pattern, but an isochron age of $207.3 \pm 0.9$ Ma could be calculated (in fact, an errorchron age due to the excessive scatter of points in the isochron plot). The oldest significant age of DÜ-9 is $231.3 \pm 0.6$ Ma. Two measurements of sample BDG-92 (polyhalite type 3) yield similar youngest significant ages (the youngest age of experiment no. 638 is $132.4 \pm 0.5$ Ma and that of experiment no. 618 is $131.0 \pm 0.5$ Ma) and a similar argon release pattern. Large amounts of $^{39}$Ar were released first with low and constant $^{40}$Ar/$^{39}$Ar, and large amounts of $^{40}$Ar relative to $^{39}$Ar were released at high laser powers. Both measurements of BDG-92 show elevated $^{38}$Ar/$^{39}$Ar ratios in their last steps, which must come from the presence of chlorine. Additionally, the $^{37}$Ar/$^{39}$Ar ratio increased during step heating in experiment no. 638. It is interpreted that a second Ca-rich mineral started to degas at higher temperatures than polyhalite. The apparent age of $150.4 \pm 0.4$ Ma for the first step of experiment no. 638 contains an uncertain amount of excess argon; however, also the following steps released only low amounts of $^{40}$Ar relative to $^{39}$Ar (85% $^{39}$Ar till step 7). The plateau age $131.3 \pm 0.5$ Ma of experiment no. 618 comprises steps 3–7 (74% $^{39}$Ar released). Of the two experiments of sample BDG-92, only the single-grain measurement gave a plateau age which can be considered as a valid geological age, whereas the polygrain experiment gave scattered age steps. Sample BDG-B4 (polyhalite type 3) yields a disturbed age pattern with only 4 steps which are useful for interpretation. Additionally,
the Ca/K ratio was elevated, indicating that the sample was not pure polyhalite. This sample also showed an elevated $^{38}\text{Ar}/^{39}\text{Ar}$ ratio. The error from Cl for the first significant step is estimated to be c. 2 Ma. The $^{39}\text{Ar}/^{39}\text{Ar}$ ratio also increased during the experiment, which is again interpreted as resulting from the presence of a Ca-rich phase.

Two very-fine-grained samples of polyhalite were measured (polyhalite type 3). Because of its fine grain size, all measurements of samples ALT-35 and ALT-37B have to be treated as polygrain measurements. Three polygrain experiments of sample ALT-37B are reported here. Except at its start, experiment no. 403 yielded a nice staircase pattern with an oldest age at 156.7 $\pm$ 1.0 Ma (65% $^{39}\text{Ar}$ released in this step). For experiment no. 561 and 766, the measured Ca/K ratio was again nearly zero and therefore the proper ages should be c. 0.5 Ma older than the calculated ages without the correction for Ca-derived argon.

Vitrinite reflection, illite crystallinity and fluid inclusions

Samples for VR (sandstone with pieces of coal) exposed no polyhalite. The coal-bearing sandstones are incorporated into the tectonic mélange and experienced the same overprinting conditions as polyhalite–anhdyrite mudrocks. However, samples for IC (mudrock) and FI (anhdyrite) were taken from polyhalite–anhdyrite–mudrock agglomerates.

All three methods revealed similar temperatures of c. 200°C (Table 4). The temperature estimates of this study correlate well with the temperature estimates of the Northern Calcareous Alps as compiled in Table 1.

The fluid inclusions were all measured in large anhydrite crystals of polyhalite type 2; we thereby found primary and secondary fluid inclusions. The primary fluid inclusions are 5–15 $\mu$m in size, and are primary according to their petrography (Roedder 1984). Under transmitted light, anhydrite crystals are dark from the numerous inclusions. Many of them contained unpropotionally large halite and sylvite daughter minerals that dissolute 100–200 $\mu$m ice (up to 90 vol.%), defined as secondary in origin. Fluid inclusions have negative crystal forms and sometimes occupy distinct zones or planes. Their size varies from 10 to 150 $\mu$m. In some cases, these liquid-rich inclusions contain a small halite solid (up to 5 vol.%), which dissolves coevally with the disappearance of the vapour bubble, or several degrees below the total homogenization to liquid. A homogeneous trapping mode is assumed for these inclusions, and these secondary fluid inclusions were therefore used for pressure, temperature and composition estimates.

The minimum pressure conditions at the total homogenization temperature are c. 202°C at 13.1 bar to 222°C at 20.4 bar for the Altaussee mine and c. 150°C at 4.9 bar to 198°C at 12.1 bar for the Berchtesgaden mine, but trapping of the fluids

### Table 4. Vitrinite reflectance (VR), illite crystallinity (IC) and fluid inclusion (FI) data

| Sample  | Measured | Method related items | VR (%) mean value | VR standard deviation | T (°C) |
|---------|----------|----------------------|------------------|----------------------|--------|
| BDG-17  | 44       |                      | 1.43             | 0.15                 | 185 ± 20 |
| BDG-41  | 50       |                      | 1.45             | 0.17                 | 187 ± 20 |
| BDG-76  | 15       |                      | 1.47             | 0.10                 | 188 ± 20 |

| Sample  | Method related items | VR (%) mean value | VR standard deviation | T (°C) |
|---------|----------------------|------------------|----------------------|--------|
| BDG-28  |                      | 0.401            | 0.01                | 0.451  |
| ALT-35  |                      | 0.387            | 0.02                | 0.447  |
| DU-38   |                      | 0.398            | 0.02                | 0.449  |

| Sample  | Method related items | VR (%) mean value | VR standard deviation | T (°C) |
|---------|----------------------|------------------|----------------------|--------|
| ALT-11E |                      | 24.7–28.5        | –65 to −51           | –6.5 to 8.1 |
| ALT-78  |                      | 24.6–28.6        | –70 to −56           | –6.5 to −0.7 |
| BDG-37B |                      | 26.7–34.6        | –65 to −51           | –10.1 to 19.2 |

**Abbreviations:** FI – fluid inclusion; T – temperature; $T_e$ – eutecticum temperature; $T_{\text{m ice}}$ – ice melting temperature; $T_{\text{m hyd}}$ – hydrohalite melting temperature; $T_{\text{h hal}}$ – halite melting temperature; $T_{\text{h tot}}$ – temperature of total homogenization; L – liquid; V – vapour; $S_H$ – solid halite.

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could have occurred anywhere inside the isochore fields (Fig. 7). Using the independent geothermometers IC and VR, the maximum trapping pressure would be 1 kbar (= 100 MPa) for the Berchtesgaden mine. For the Altaussee mine, the pressure remains uncertain.

Discussion

Polyhalite rocks occur as decimetre- to metre-scaled tectonic lenses within a protocataclastic halite–mudrock matrix (Leitner et al. 2011). Polyhalite rock samples for $^{40}\text{Ar}/^{39}\text{Ar}$ age dating were selected according to their microfabrics. However, separation of growth stages in thin section was not accomplished in this study due to the complicated interlocking of growth stages. In the following, the exemplarily growth stages in ALT-35 were correlated with age dating measurements where possible.

Several experiments are reported as preliminary results in companion papers (Leitner et al. 2012). The discussion here presents a collective view of the results and the success of $^{40}\text{Ar}/^{39}\text{Ar}$ Ar age dating of polyhalite would not be intelligible without these data. Therefore, results of all $^{40}\text{Ar}/^{39}\text{Ar}$ Ar age data for this project are plotted in Figure 6. One microfabric type of polyhalite which occurs only subordinately in the salt deposits (pseudomorphic replacement of halite hopper crystals in undestroyed mudrock) yields plateau ages of 235.5 ± 0.9 Ma and 234.6 ± 0.9 Ma. Disturbed age spectra of the measurements presented here are probably the result of multiphase polyhalite growth and were used only for limited interpretation (Fig. 5).

Large fibrous polyhalite grains from veins (polyhalite type 1, Fig. 6) and large polyhalite porphyroblasts in anhydrite (polyhalite type 2) yield similar ages in the range c. 235–210 Ma (growth stages 2–3 in Fig. 4). Age spectra with ages of c. 225 Ma obtained for the core and c. 208 Ma obtained for pieces of the rim are interpreted to reflect multiple stages of fluid migration rather than $^{40}\text{Ar}$ loss (Table 3). However, argon loss or partial recrystallization by Alpine thermal overprint may be a reason for the disturbed age patterns, for example in ALT-53B. A coarse-grained polyhalite from a mudstone (sample DU9, polyhalite type 3) also shows this old age. As seen in thin sections, polyhalite inclusions within large anhydrite indicate simultaneous crystallization of polyhalite and anhydrite from the assemblage (Fig. 3 h–k). After a peak in development of these euhedral anhydrite crystals, they were broken and intensely corroded by the surrounding polyhalite grains (Fig. 3i–k). Their mechanical and chemical destruction is interpreted to be at least in part as old as the first growth of polyhalite during c. 235–210 Ma, because no major tectonic deformation was observed (diagenetic growth stages). This age is clearly younger than the suggested age of deposition of the dominating Haselgebirge Formation (257 to c. 251 Ma). Most polyhalite veins formed subparallel to sedimentary layers. The lowest stress orientation was therefore vertical, a phenomenon which was described in terms of force of crystallization for different minerals (Hilgers & Urai 2005). From that time (Middle Triassic) on, the passive continental margin of the Meliata Ocean developed and the dated diagenetic polyhalite growth likely reflects processes associated with the formation of the passive continental margin.

In the thin section of sample ALT-37B, various stages of grain size reduction were reached during tectonic mylonitization. The small grains (0.05–0.1 mm) show a shape-preferred orientation and extensive grain boundary migration. In between, regions of blocky coarse grains (0.1–0.3 mm) show no preferred orientation and only subordinate grain boundary migration. These regions represent relics of the diagenetic fabric. Sample ALT-37B was measured in four experiments, whereby the age spectra are disturbed and differ significantly from each other (Fig. 5). The measurements show oldest significant ages between c. 158 and 152 Ma (deformation growth stages 4–6 in Fig. 4). These apparent ages correlate well with age dates from Wienern and Moosegg gypsum quarries, where authigenic feldspar was dated at c. 154–145 Ma (Spötl et al. 1996, 1998b). At this time the Meliata Ocean was closed, possibly with the beginning of Alpine nappe stacking (Missoni & Gawlick 2011). Within the fine-grained rock (sample ALT-37B, polyhalite type 3), only ages between c. 118 and c. 105 occurred (deformation growth stages 4–6 in Fig. 4). These apparent ages are consistent with previously measured $^{40}\text{Ar}/^{39}\text{Ar}$ white mica ages of
c. 120–114 Ma from the southern margin of the Northern Calcareous Alps (Frank & Schlager 2006). During the Early Cretaceous, nappes of the Northern Calcareous Alps were thrust as continental crust was subducted (‘eo-Alpine’ stage, e.g. Neubauer et al. 2000). In this study, it was unfortunately not possible from thin section analysis to fix our measured temperatures from IC, VR and FI to a certain age. According to current knowledge from literature, the temperature peak was reached during Late Jurassic–Early Cretaceous times (Table 1). A last significant apparent age was found at c. 44 Ma. This is consistent with an apatite fission track study (Hejl & Grundmann 1989) and regional remagnetization data (Pueyo et al. 2007).

Together, the first polyhalite age data from the Upper Permian to Lower Triassic Haselgebirge Formation of the Eastern Alps, the type locality of polyhalite, yield meaningful geochronological results which are similar for two salt deposits c. 60 km apart. Grains from relic fabrics which were saved from mechanical destruction yield the best results (e.g. pseudomorphic polyhalite in nodules of undestroyed mudrock, Leitner et al. 2012). Grains from other relic fabrics (polyhalite vein, core and rim structure in anhydrite rock) and also pieces from completely recrystallized fabrics (ALT-37B, experiment no. 562) yield good results. Disturbed age spectra result from multiphase polyhalite growth in accordance with thin section analysis. Fine-grained shear zones exist in coarse-grained fabrics and fine-grained foliated rocks expose coarse-grained non-foliated relic areas. Since the thermal behaviour of polyhalite is widely unknown, argon loss by diffusion also cannot be excluded. The low temperature stability of 255 °C (to maximum 353 °C) of polyhalite precludes diffusion experiments to experimentally determine the diffusion constants. More work is needed, for example, with furnace experiments to find out reasons for complex degassing behaviour as found in some experiments. However, the preservation of a post-depositional age of c. 235 Ma in coarse polyhalite shows that in large crystals subsequent thermal effects of c. 200 °C have a negligible influence. 38Ar/39Ar ratios show that Cl did not contribute significantly to age reduction. 37Ar/39Ar ratios were constant at a characteristic value of 0.48 for pure polyhalite samples. Polyhalite can be used as practical geochronometer close to its thermal stability boundary. The dehydration starts at c. 255 °C and the dehydration reactions are completed at 343 °C (Wollmann et al. 2008). A challenge for the future could be to date specific growth stages of polyhalite by microsampling. In summary, polyhalite may characteristically serve as a geochronometer for diagenetic and very-low-grade metamorphic processes.

Conclusions

From our study, the following major conclusions can be made.

(1) Polyhalite only occurs as a secondary mineral within the Alpine salt deposits. No sedimentary structures of polyhalite were found. Polyhalite clearly grew after the sedimentation as is evidenced, for instance, by the formation of polyhalite veins. It crystallized with a wide variety of fabric types.

(2) The microfabric characterization of polyhalite in this study follows the mesoscale categories. The main groups are (1) fibrous polyhalite in veins, (2) polyhalite as blasts and fibres in an anhydrite matrix, and (3) dense polyhalite in mudrock with large anhydrites, which revealed foliated and subordinately non-foliated microfabrics under the microscope.

(3) Secondary polyhalite originated as early as c. 235–210 Ma (Middle–Late Triassic times). Samples from all main types – fibrous polyhalite in veins, polyhalite blasts in anhydrite and dense polyhalite with large corroded anhydrite crystals – show these early ages. Mineral structures were preserved during the Alpine tectono-thermal overprint. Partial recrystallization is the proposed reasons for the disturbed age spectra.

(4) A thermal overprint was recorded in large anhydrite crystals. Based on fluid inclusions, a peak temperature of c. 200 °C was reached in the salt deposits of Altaussee and Berchtesgaden-Bad Dürrnberg. However, it is not possible from our data to exactly date the age of the main thermal overprint stage.

(5) Mylonitic samples revealed significantly younger ages than the other fabric types. The microfabric developed by grain size reduction and extensive grain boundary migration. Jurassic apparent ages can be interpreted as the minimum age of an old recrystallization and Cretaceous apparent ages (c. 118–105 Ma) as the minimum age of the overprinting recrystallization. Although a last major overprint was thus clearly in the Cretaceous period, earlier stages of overprint may have affected the Haselgebirge Formation. The results of this study favour the classic model with Late Jurassic–Early Cretaceous nappe tectonics.

(6) Relic fabrics, mainly from large crystals, and completely recrystallized fine-grained fabrics yield good age dating results. Polyhalite may characteristically serve as a geochronometer for diagenetic and very-low-grade metamorphic processes of evaporites, for example in diapirs and evaporite thrust sheets.
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