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A geological snapshot from the front of the Northern Calcareous Alps: Well Obermoos TH-1, Salzburg, Austria

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Abstract

The deep thermal well Obermoos TH-1 (total depth 2468 m, year 1990) was drilled within the Upper Cretaceous Salzburg-Reichenhall basin of the Northern Calcareous Alps at the southwestern edge of Salzburg city, Austria. The lithologic log shows c. 200 m thick Quaternary sediments of the glacially overdeepened Salzach Valley above bedrock. The Quaternary infill is underlain by c. 250 m thick, almost horizontally lying coarse clastics and marls, which belong to the Upper Cretaceous Salzburg-Reichenhall Gosau basin. From 456 m to 2468 m, a steeply dipping, more or less continuous succession from Cenomanian strata to Upper Triassic Hauptdolomit was encountered. This succession is considered being part of the Bajuvaric nappe of the central Northern Calcareous Alps, which is entirely overridden by units of the Tyrolic arc in the study area. The new data from the deep drilling provides (i) new information on depth and filling of the deeper parts of the Pleistocene valley and (ii) new insights into the complex structure of the Bajuvaric nappe. We also discuss a potential fault crossing the Salzburg-Reichenhall basin being part of the Cenozoic Innsbruck-Salzburg-Amstetten fault system. On a larger scale, the Tyrolic unit exposed in the southern margin of the Salzburg-Reichenhall basin and potentially overlying the borehole section must be the same as in the flat-laying Tyrolic nappe found in two deep drill holes, 15 km southeast and 18 km east of the City of Salzburg (Vigaun 1 and Vordersee 1).

1. Introduction

The Northern Calcareous Alps (NCA) with Upper Carboniferous to Eocene successions of the Eastern Alps represent a classical fold-and-thrust belt, which formed by superimposed stages of mainly Early Cretaceous and Eocene to Miocene shortening (Tollmann, 1985; Linzer et al., 1997, 2002; Wessely and Wagner, 1993). These two stages of shortening are separated by a time of localized extension and associated basin formation during the Late Cretaceous to Early Eocene ("Gosau" basins; see, e.g., Faupl and Wagreich, 2000, Wagreich and Decker, 2001; for a different view for the western part of the NCA, see Ortner, 2007). Classically, the NCA are subdivided into four main units, which are from north to south, respectively from base to top, the Bajuvaric, Tyrolic and Lower and Upper Juvavic units, the latter two units forming tectonic klippen, e.g. in the SW of Salzburg ("Juvavum" was the Roman name of Salzburg). The structure of the northern margin of the Northern Calcareous Alps is complex because of significant structural changes along strike. The central NCA south of Salzburg contain only locally exposed occurrences of Bajuvaric units and the so-called Tyrolic arc with the mainly flat-lying Tyrolic nappe reaching the northern NCA margin (Figure 1a) in its eastern part, and the Gosau-type Salzburg-Reichenhall basin along its northern margin.

Here, we present new insights from data of the hitherto unpublished deep geothermal well Obermoos TH-1, which was drilled within the Salzburg-Reichenhall Gosau basin, and penetrated, unexpectedly, the nearly subvertical frontal part of NCA nappes. We propose an explanation for this peculiar structure. The Bajuvaric nappe now is proved in a more representative dimension in the subcrop below the Tyrolic arc as a steeply dipping slice in the front of the Tyrolic and Upper Juvavic nappes. The deep structure of the Tyrolic arc is mainly based on additional data from (i) two hydrocarbon exploration boreholes drilled by the Austrian oil company OMV (Vigaun 1, Kramer and Kröll, 1977) and Vordersee1 (Geutebrück et al., 1982) and (ii) few unpublished industrial seismic sections. Data from the well Obermoos TH-1 contributes also significantly to the knowledge of the poorly investigated Salzburg-Reichenhall Gosau basin (e.g. Wagreich, 2003a) as well as to the Quaternary overdeepening of the Salzach Valley basin (Brandecker, 1974; van Husen, 1979, 1980; Donadel et al., 2014).

2. Regional geological setting

As mentioned above, the classic structural division within the NCA defines the Bajuvaric, Tyrolic and Upper and Lower Juvavic nappe complexes (Tollmann, 1985, 1987 and references therein; Mandl, 2000; for a different view see Frisch and Gawlick, 2003) (Figure1a, b). The age of formations in the NCA ranges from Late Carboniferous or Early Permian to Early Eocene. The base comprises a Permian to Lower Triassic siliciclastic succession and the uppermost Permian evaporitic Haselgebirge Formation. Middle and Upper Triassic of the Upper Juvavic nappes consist mostly of reef- and peri-reefal carbonates, whereas the Tyrolic and Bajuvaric nappes include lagoonal carbonate facies types and

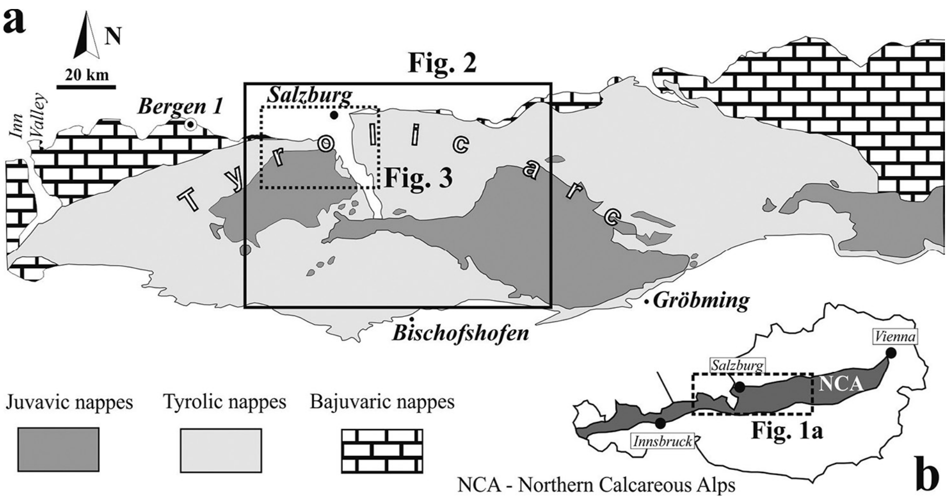

Figure 1. a: Overview on central Northern Calcareous Alps (NCA). b: Location of the study area within Austria.

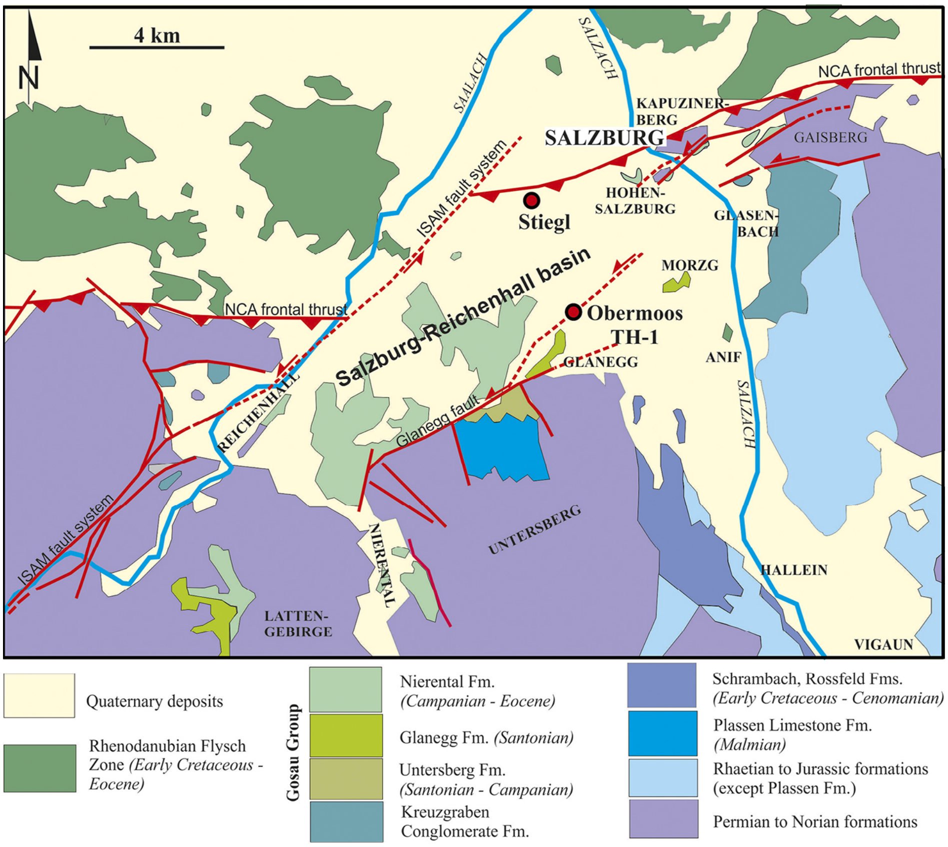

Figure 2. The central Northern Calcareous Alps with locations of wells mentioned in the text (modified after Braunstingl et al., 2005).

only subordinate reef limestones. The Middle and Upper Triassic formations of the Lower Juvavic nappe represent solely an outer shelf or a deep-sea carbonate facies type (Mandl, 2000). Sedimentation of the Lower Juvavic unit occurred in basins with basinal limestones (Pötschen Limestone) and on intrabasinal ridges, with reduced sedimentary thickness of an outer shelf (the pelagic Hallstatt Limestone) (Tollmann, 1985, 1987; Mandl, 2000). The ridges were suggested to relate to Triassic salt diapirism (Mandl, 1982, 2000; Plöchinger, 1984).

The westernmost part of the expanding late Middle Triassic to Late Triassic Tethys Ocean is called Hallstatt-Meliata Ocean, and comprises remnants of deep-sea successions in the eastern parts of the NCA (Kozur, 1992; Faupl and Wagreich, 2000; Neubauer et al., 2000 and references therein). The Permian/Middle Triassic to lower Upper Triassic succession is interpreted as the rift stage and passive margin formation and subsequent drift stage (Lein, 1987; Mandl, 2000). The Hallstatt-Meliata Ocean was considered as being subducted (e.g., Dallmeyer et al., 2008) and/or finally closed during the Late Jurassic (Missoni and Gawlick, 2011a, b; Gawlick and Missoni, 2015 and references therein). Coevally, the sea floor of the NCA subsided and reached considerable water depths with the formation of radiolarites. Gravitational sliding of large blocks and slices is reported from different places (e.g., Mandl, 1982; Plöchinger, 1990; Ortner et al., 2008) and this concept was developed until recent years arguing for a Late Jurassic age of shortening (Missoni and Gawlick, 2011a, b; Gawlick and Missoni, 2015 and references therein). During Early Cretaceous, nappe stacking of Austroalpine units started due to the subduction of Austroalpine continental crust. Thrusting prograded from S to N, respectively from ESE to WNW (Ratschbacher, 1986; Ratschbacher et al., 1989; Linzer et al., 1995; Mandl, 2000; Neubauer et al., 2000).

Several hypothesis and models were put forward for the mechanism and timing of emplacement of Juvavic units: i) both Lower and Upper Juvavic units took their position by means of thrust tectonics during the eo-Alpine deformational event (late Early to early Late Cretaceous) (Kober, 1955; Pichler, 1963; Schweigl and Neubauer, 1997; Mandl, 2000; Schorn and Neubauer, 2011; Schorn et al., 2013), ii), emplacement of all Juvavic units by gravity sliding respectively closure of the Neotethys ocean since Late Jurassic times, as evidenced by Juvavic clasts in Upper Jurassic to Lower Cretaceous Tyrolic formations (Missoni and Gawlick, 2011a, b; Gawlick and Missoni, 2015 and references therein; Krische et al., 2013, 2014; Ortner et al., 2008), or (iii), early Cretaceous Juvavic emplacement as a consequence of Late Jurassic strike-slip movements related to the opening of the Penninic Ocean (Frank and Schlager, 2006).

The Cretaceous-aged nappe stack within the NCA was transgressed and unconformably overlain by Upper Cretaceous to Eocene Gosau basins (e.g., Wagreich and Decker, 2001), which represent a sort of piggy-back basin subsiding due to subduction erosion (Wagreich, 1993, 1995) and/or extensional collapse basin formation (Neubauer et al., 1995; Wagreich and Decker, 2001). In the western part of the NCA, the Gosau basins formed in a purely compressional setting (Ortner et al., 2015a). The Salzburg-Reichenhall basin is part of these Gosau basins, which are distributed over nearly the entire length of NCA (Faupl and Wagreich, 1996, 2000).

In the Eocene, after subduction of the Penninic Ocean, the second paroxysm of the Alpine orogeny occurred, when the stable European continent basement was subducted below the NCA at the leading edge of the Austroalpine-Adriatic microcontinent (Faupl and Wagreich, 2000; Linzer et al., 2002 and references therein). The present NCA overthrust the Rhenodanubian Flysch (part of the Penninic Ocean fill) and Helvetic domain (part of the cover of the stable European continent) resulting in a wide thin-skinned tectonic nappe complex (Linzer et al., 1995; Mandl, 2000; Neubauer et al., 2000). The northern margin of the NCA is considered to be heavily affected by these Cenozoic deformation stages, since the detachment of the NCA domain occurred beneath the lowermost unit, the Bajuvaric nappe (Figure 2; Linzer et al., 1995, 1997; Peresson and Decker, 1997a, b). Deformation of the Upper Cretaceous to Eocene Gosau basin fill deposited on top of the uppermost nappes (Tyrolic and Juvavic nappes) suggests significant post-Gosau deformation in Late Eocene to Early Miocene times (Linzer et al., 1995, 1997; Peresson and Decker, 1997a, b).

The Salzburg-Reichenhall basin is located in the most external part of the central Northern Calcareous Alps of the Austroalpine nappe complex (Figs. 2, 3; e.g., Risch, 1988). The assembled NCA nappe stack including the Gosau basins was overthrusted onto the combined Rhenodanubian Flysch and Helvetic nappe complexes during late Eocene/early Oligocene, and, together with these, onto the Northern Molasse Basin as part of underthrusted European lithosphere during Oligocene and Early Miocene (Tollmann, 1985; Hinsch, 2013; Ortner et al., 2015b and references therein).

In the study area, the NCA form the so-called Tyrolic (structural) arc where the Tyrolic nappes almost completely override the Bajuvaric units to the very northern margin of the Northern Calcareous Alps (Figure 2; e.g., Plöchinger, 1955). The flat-lying Tyrolic Osterhorn nappe constitutes the eastern good of the study area. The Bajuvaric nappe system is local-

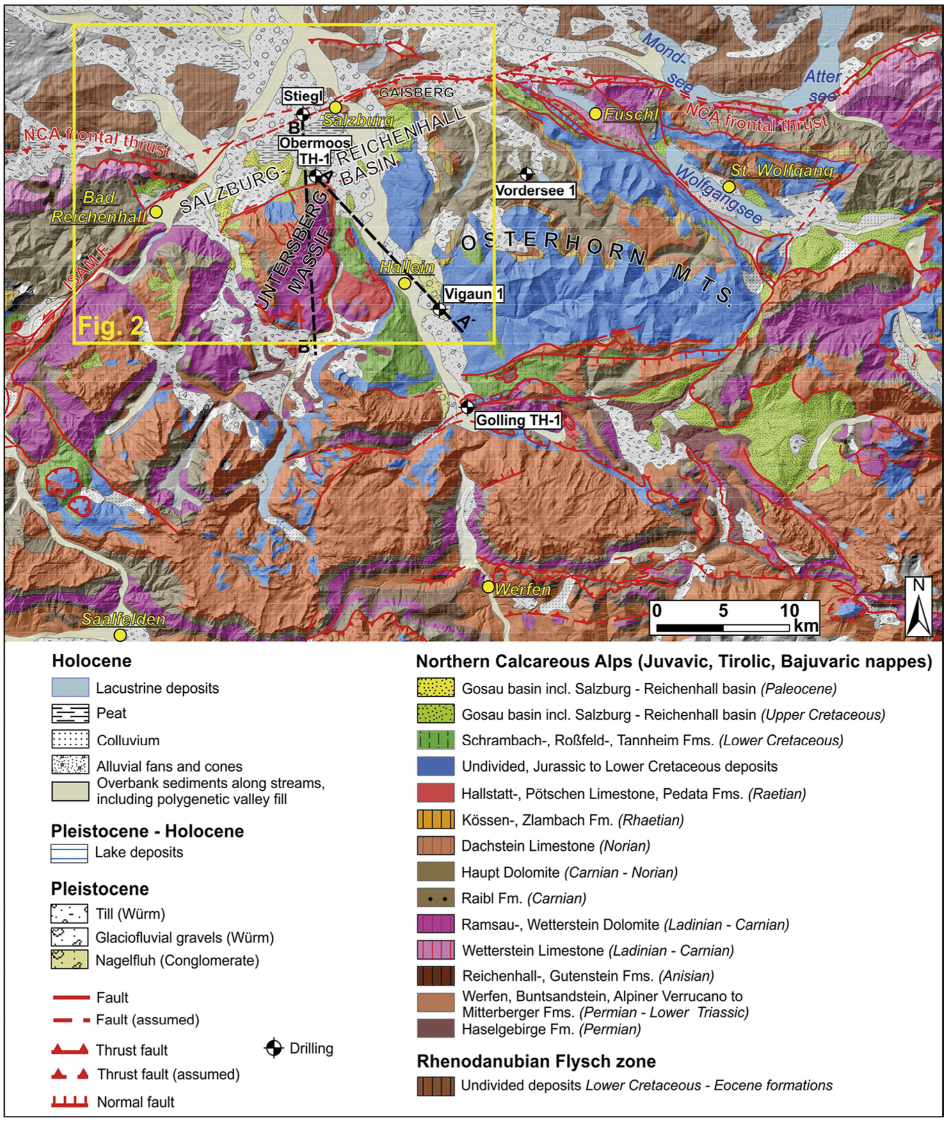

Figure 3. Overview on the Salzburg- Reichenhall Gosau basin with location of the well Obermoos TH-1 and other locations mentioned in the text (map compiled from Prey, 1969 and Egger and van Husen, 2009a and own observations).

ly exposed in small remnants along northern margins of the working area. However, herein we document the existence of Bajuvaric units in a more complete dimension as demonstrated by the well Obermoos TH-1.

The Salzburg-Reichenhall Gosau basin formed close to the northern margin of the Northern Calcareous Alps (for overview, see Leiss, 1988b; Herm, 1962; Faupl and Wagreich, 1996, 2000). Outcrop conditions are poor due to scattered and isolated exposure of Upper Cretaceous to Eocene strata within the glacially overdeepened Salzach and Saalach Valleys and along slopes of adjacent mountains (Figs. 2, 3). Cretaceous formations are exposed along eastern (Gaisberg), southern (Untersberg) and western (Reichenhall) margins of the basin (Plöchinger, 1990; Egger and van Husen, 2009a). Younger, Paleocene-Eocene formations are mainly exposed in the central sectors of the basin and some valleys at the western margin of the Untersberg massif and Gaisberg (Krenmayr, 1996; Egger et al., 1996, 2005; Egger and van Husen, 2009a). A complete Upper Cretaceous to Eocene section can be found in the SW, at the top of the Lattengebirge (Fig. 2).

Previous mapping of the Salzburg-Reichenhall Gosau basin distinguished a number of formations (Del Negro, 1979; Prey, 1980; Leiss 1989, 1990). The stratigraphy is based on work by Egger et al. (2005, 2013), Herm (1962), Herm et al. (1981) Leiss (1988a), von Hillebrandt (1962), Wagreich (2003a) and Weidich (1984a, 1984b). These include from bottom to top the following formations (Fig. 3): The Kreuzgraben Formation is exposed with an estimated thickness of several hundred meters at the western slope of the Gaisberg. It comprises reddish conglomerates with rare yellow-brownish carbonate sandstone intercalations and is supposed to be of Coniacian age (Del Negro, 1979; Leiss, 1989). The Untersberg Formation (also Untersberg "Marmor") is exposed at the northern slope of the Untersberg and comprises above a thin reddish lateritic breccia layer grayish conglomerate/breccia with a thickness of several tens of meters (Kieslinger, 1964; Leiss, 1989, 1990). This formation is well exposed in many quarries as the rock is poor in joints and therefore used as building stone and for sculptures. Bioclastic detritus include hippurites, radiolites, bryozoans, foraminifera and rhodophyta. The Coniacian-Santonian age is based on rare foraminifera (Leiss, 1989, 1990).

The Glanegg Formation is exposed in the northern foreland of the Untersberg and is separated by the Glanegg fault from the Untersberg massif (Figure 3). The Glanegg Formation (Grabenbach Formation of Wagreich, 2003a) of Coniacian to Late Santonian age includes shallow water limestones, which are overlain by grayish hemipelagic and bathyal marls with intercalations of sandstones and pebbly sandstones of the Morzg Formation (Höfling, 1985; Egger et al., 2013). An olistostrome bears numerous Triassic Hallstatt Limestone clasts and occurs in the southernmost Glanriedel (Höfling, 1985; Figure 3 for location). There, the age is based on foraminifera, and is Early Coniacian to Early Santonian (Höfling, 1985). The overlying formation above the Morzg Fm. is referred as Nierental Formation according to the type locality in the Nierental at the western slope of the Untersberg Mountain (Krenmayr, 1999). The Nierental Formation includes grey and red marls and marly limestones of Late Cretaceous age and grades upwards into

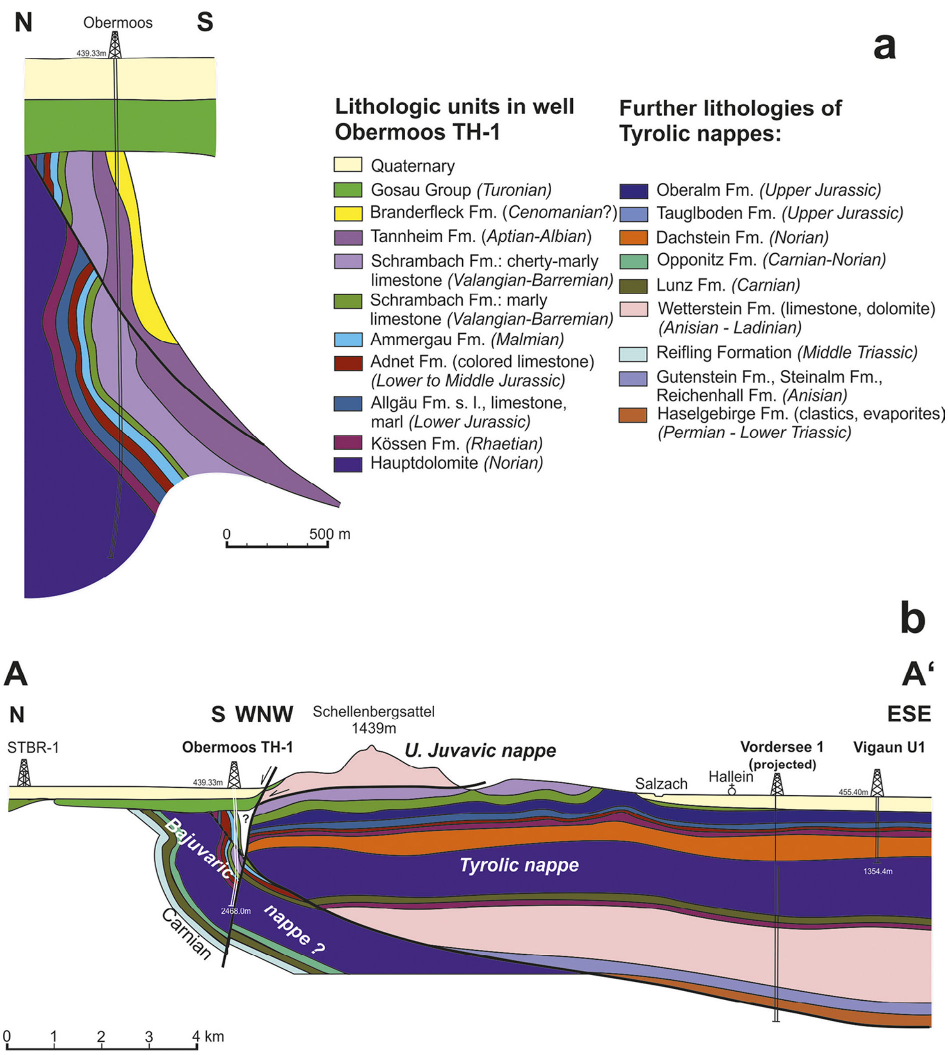

Figure 4. a: Section of well Obermoos TH-1. b: Structural interpretation of well Obermoos TH-1 in the frame of boreholes Vigaun and Hintersee.

decimeter-bedded Paleocene to Eocene turbidites with shale intercalations (Faupl and Wagreich, 1996). These levels also contain Late Paleocene bentonites (Egger et al., 1996, 2005).

In terms of the structure, the Salzburg-Reichenhall basin is located on top of the Tyrolic to Juvavic nappe boundary. The Berchtesgaden nappe with the Untersberg massif form the southern boundary separated by the Glanegg fault. There, the Upper Jurassic Plassen Formation unconformably overlies the Dachstein and Hierlatz limestones and a poorly investigated unconformity is in between these two stratigraphic units. Above, another, bauxite-bearing unconformity (Figure 4b), the Untersberg Formation follows, which dips moderately to the north. Separated by the E-W striking Glanegg fault, the Salzburg-Reichenhall basin follows in the north, in which, in the central part of the basin, most strata dip moderately to the north (Prey, 1969, 1980; Egger et al., 2013). Structural relationships indicate a sinistral oblique-slip, north-down displacement along the Glanegg fault. The northern margin of the Salzburg-Reichenhall basin is again a subvertical sinistral strike-slip fault, which separates the Salzburg-Reichenhall basin from the Upper Triassic limestones and dolomite forming the S-dipping wedge from Hohensalzburg – Kühberg – Nockstein representing part of the Tyrolic nappe (Figure 3). This fault may be part or a splay of the Innsbruck-Salzburg-Amstetten (ISAM) fault (Egger, 1997). The Upper Triassic carbonates overthrust thin Cenomanian marls of the Bajuvaric nappe (Prey, 1969, 1980). The whole NCA overthrust the Rhenodanubian Flysch zone.

The Quaternary Salzach Valley fill is known from several boreholes (Brandecker, 1974; Prey, 1959; Hell, 1963) and a lithotype distribution model was proposed by van Husen (1979, 1980). The so-called Salzburg lake mudstone ("Salzburger Seeton") was considered to represent Late Würmian deposition. Recently, Herbst and Riepler (2006) published a few ^{14}C ages arguing for a Middle Würmian age of upper portions of this mudstone. Ages of deeper mudstone levels which even exceed the last glacial period by far (>200 ka), were recently presented by Fiebig et al., 2014 from a small glacial branch basin of the Salzach Glacier, about 10 km NW of Well Obermoos.

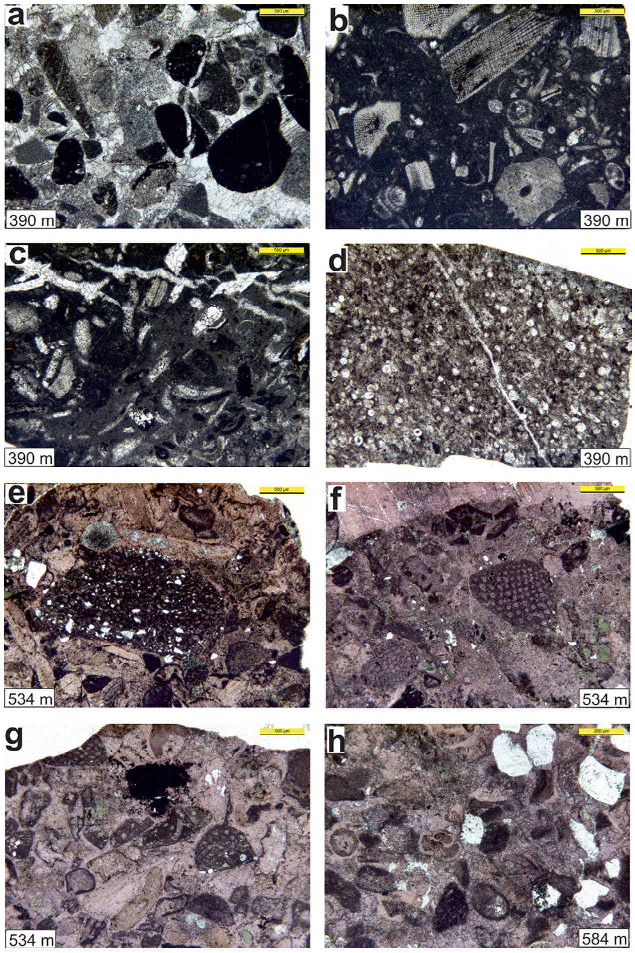

Figure 5. Microfacies of thin sections from the Gosau Group (Turonian-Coniacian?) of well Obermoos TH-1. Gosau Group (Turonian-Coniacian ?). a: Pebbles of Oxfordian radiolarite; b: limestone pebble of the Kössen Formation, rich in fragments of bivalves and crinoids; c: pebble of Lower Jurassic Adnet limestone; d: a radiolarian-rich component (with an origin from Northern Calcareous Alps) in the Gosau conglomerate. Microfacies of thin sections from the Branderfleck Formation (Cenomanian); e: bioclastite with orbitolinid foraminifera; f: bioclastite with corallinaceen algae, fragments of molluscs, and orbitolinid foraminifera; g: bioclastite with bryozoans, orbitolinid foraminifera; h: sandstone consisting of quartz and carbonate components, including planktic foraminifera (*Rotalipora* sp.?).

3. Well Obermoos TH-1

The well Obermoos TH-1 was aimed to produce thermal water and was drilled in 1990 within Salzburg town area at an elevation of 439.3 m above sea level (N47°45´09.1´´, E13°00´51.4´´). It reached a depth of 2468 m (for location, see Figure 2, 3). The following material is available and will be partly discussed here: (i) description of cuttings taken in intervals of 2-6 m, (ii) thin sections and microfacies analysis of thin sections from limestone, marly limestone and sandstone samples, (iii) micro- and nannofossil investigations on cuttings of marls, (iv) geophysical borehole data of selected intervals representing results of sonic, latero- and gamma-ray log measurement. For micropaleontological investigations, 51 marly microfossil samples were washed, and 18 samples for nannofossils were taken at appropriate intervals. Together 23 samples from both types of samples yield determinable calcareous micro- and nannofossils. Determinations were done by Mrs. Roswitha Braunstein during 1991 and 1992, and nannofossil taxonomy is updated using Burnett (1998). Microfacies is documented in Figures 5-8. The fossil data are shown in Tables 1 and 2 and their stratigraphic value is discussed in the main text below.

3.1 Geological section of the well Obermoos TH-1

In the following, we provide a rough description of the profile from top to the bottom of the borehole (Figure 4a). The profile includes:

0-206 m: 5 m of Holocene peat and clay are followed by 200 m of sandy gravel containing few thin mudstone intercalations.

206-456 m: Gosau Group, presumably Kreuzgraben-Formation, comprising reddish to yellow-brownish marls and breccia intercalations with predominant Jurassic and some Triassic clasts within an often reddish matrix (Figure 5a-c).

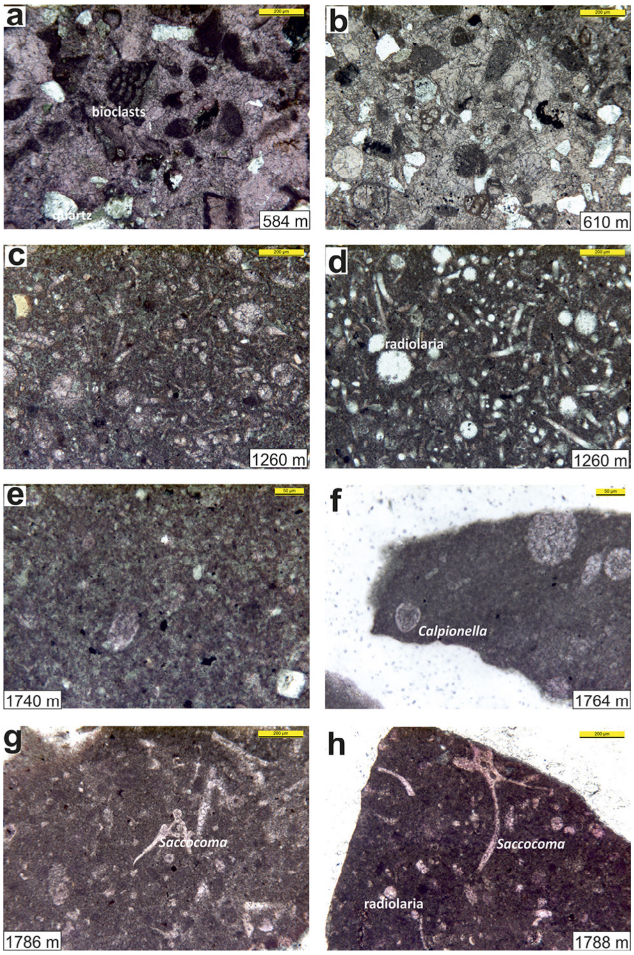

Figure 6. Branderfleck Formation (Cenomanian): a: sandstone consisting of quartz and carbonate components including carbonate bioclasts; microfacies of thin sections from the Aptian/Albian to Kimmeridgian formations. b: sandstone with quartz and carbonate components, *Hedbergella* sp.? Aptian/Albian; c: packstone with abundant spiculae of sponges and radiolarian; Valanginian-Barremian, higher part. d: mudstone, rare biodetritus, rare calpionellids; Valanginian-Barremian, lower part (Schrambach Formation); e: mudstone, rare biodetritus, rare calpionellids; f: mudstone with *Calpionella alpina*, radiolaria; Tithonian; g, h: Kimmeridgian; g: wackestone, *Saccocoma*, biodetritus; h: wackestone, Saccocoma, biodetritus, radiolaria.

The succession frequently contains re-deposited fauna and nannofossils of Early Cretaceous age (see section 3.2). At the base, a transition to grey marls can be observed.

456-601 m: Cenomanian of Branderfleck Fm., greyish biodetritic calcarenite with some quartz and glauconite grains (Figs. 5e-h, 6a-b).

601-1212 m: greyish Lower Aptian to Albian marl (presumably Tannheim Formation, e.g. Zacher, 1966) with few thin fine-grained beds of sandstone. Between 730 and 760 m, these marls are cataclastically deformed.

1212-1720 m: Higher "Neocomian" (Valanginian-Barremian, Schrambach Fm.) strata showing a radiolaria-spiculae microfacies comprising three subunits with chert-bearing greyish marly limestone (1212-1300 m, where chert nodules are particularly abundant at ca. 1270 m; Fig. 6c-d), grey detritic limestone, (1300-1388 m) and sandstone-bearing limy marl.

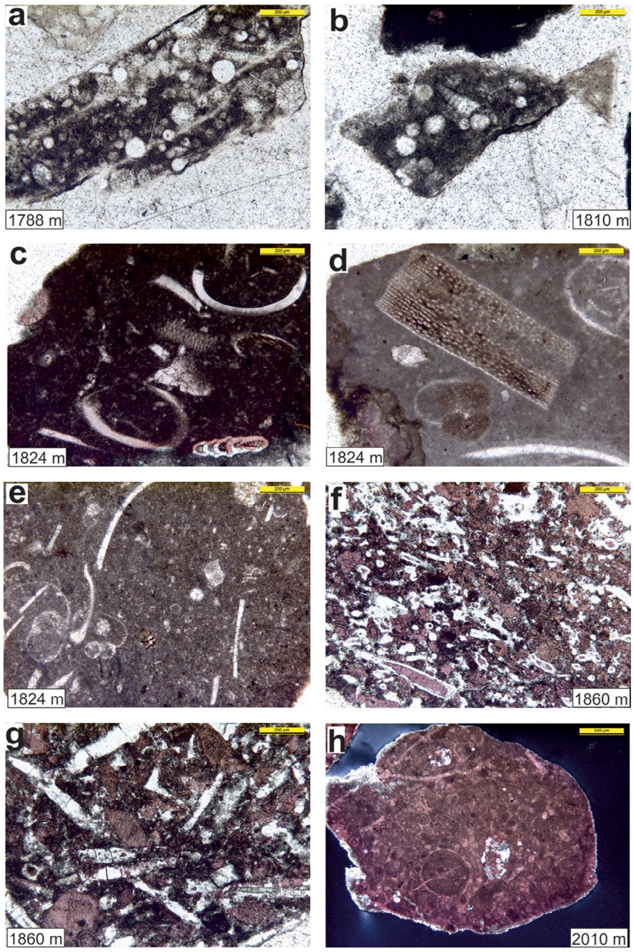

Figure 7. Microfacies of thin sections from the Oxfordian to Rhaetian. a and b: packstone, radiolarite, abundant radiolarians, in (b) also Nasselaria; Oxfordian; c-e: Lower Jurassic, Adnet Limestone; c: wackestone, large ostracods, remnants of crinoids, Frondicularia sp.; d: wackestone with a crinoid fragment and a juvenile gastropod; e: wackestone with juvenile ammonoidea and biodetritus. f-g: Lower Jurassic cherty limestone. f: packstone, abundant sponge spiculae; g: packstone with spiculae and crinoids remnants. h: packstone, biodetritus of bivalves, crinoids, foraminifers of the Rhaetian Kössen Formation.

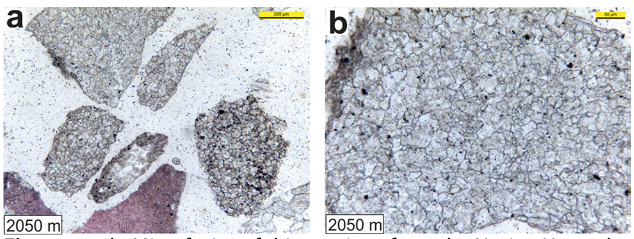

Figure 8 a, b. Microfacies of thin sections from the Norian Hauptdolomite. Dolosparite with some dots of pyrite.

1720-1756 m: greyish marly limestone of the Schrambach Formation of Valanginian-Barremian age (Fig. 6e).

1756-1784 m: greyish to greenish and violet Tithonian limestone with calpionellidae including *Calpionella alpina* (Figure 6f).

1784-1800 m: reddish Kimmeridgian limestone with abundant *Saccocoma* (Figs. 6g-h, 7a).

1800-1819 m: greenish-grey to reddish-grey and whitish radiolarite (Oxfordian Ruhpolding Formation) (Fig. 7b).

Table 1. Calcareous nannofossils

Borehole depth [m]	220	262	324	356	400	446	448	616	620	630	640	1146	1170	1190	1270	1310	1496	1600	1708	1740	1900
Conusphaera mexicana mexicana	x	x						x	x	x		x	x			x	x	x	x	x	
Nannoconus kamptneri kamptneri	x																x				
Nannoconus sp.	x						x	x													
Micrantholithus sp.	x					x															
Manivitella pemmatoidea	x							x			x		x	x	x	x	x	x	x	x	x
Watznaueria barnesae	x	x	x	x	x	x	x	x	x	x		x	x	x	x	x	x	x	x	x	x
Cyclagelosphaera margerelii	x		x	x		x	x	x	x	x	x		x		x	x	x	x	x	x	
Ellipsagelosphaera ovata							x	x			x									x	
Braarudosphaera regularis			x							x			x		x	x		x		x	
Parhabdolithus embergeri			x		x			x	x	x	x	x	x	x							
Micrantholithus hoschulzii					x			x	x	x	x	x	x		x	x	x		x	x	
Nannoconus colomii							x						x	x				x	x		
Conusphaera mexicana							x														x
Nannoconus bucheri								x	x	x	x		x		x	x		x		x	
Nannoconus circularis								x	x	x	x	x	x	x	x	x	x	x	x	x	x
Nannoconus truittii								x	x		x		x	x	x	x	x	x	x	x	x
Nannoconus kamptneri								x		x	x	x		x					x	x	x
Nannoconus steinmannii steinmannii								x		x	x		x				x		x		
Nannoconus quadriangulus								x	x				x							x	
Nannoconus inconspicuus								x					x	x	x	x				x	
Rhagodiscus asper								x	x	x	x	x	x	x	x	x	x			x	x
Rhagodiscus angustus								x	x	x		x	x	x	x	x				x	
Microstaurus chiastius								x	x	x			x			x		x		x	
Tegulalithus septentrionalis								x	x	x	x				x	x				x	
Stradneria crenulata								x					x			x				x	x
Cretarhabdus striatus								x													
Biscutum constans								x							x	x					
Ephrolithus antiquus								x	x	x	x		x								
Micrantholithus obtusus								x	x			x	x			x	x	x	x	x	x
Lithraphidites carniolensis carniolensis								x	x	x	x	x	x	x	x	x	x		x	x	
Nannoconus abundans									x	x					x	x	x	x	x	x	
Nannoconus globulus									x	x	x	x	x	x	x			x	x	x	
Ephrolithus floralis									x	x	x			x		x				x	
Sollastites horticus									x	x	x						x		x		
Vekshinella stradneri									x	x	x	x	x		x					x	
Micrantholithus sp. 1									x	x	x	x	x		x	x					
Cyclagelosphaera deflandrei									x	x	x		x	x		x					
Nannoconus elongatus										x	x	x	x	x	x	x	x		x	x	
Braarudosphaera africana										x			x		x						
Cretarhabdus conicus										x			x							x	
Cretarhabdus angustiforatus										x		x	x			x					
Calcicalathina oblongata										x						x				x	
Glauckonithus diplogrammus											x		x		x	x					
Tegumentum striatum											x				x					x x	
Zeugrhabdotus erectus											x				x	x					x
Watznaueria britannica											x								x	x	
Nannoconus bermudezii												x									
Tranolithus cf. phacelosus												x									
Braarudosphaera cf. africana												x									
Tranolithus phacelosus													x		x						
Ephrolithus cf. Floralis													x								
Lithraphidites praequadratus													x								
Nannoconus steinmannii															x	x				x	
Conusphaera rothii															x					x	
Cretarhabdus crenulatus															x	x					
Reinhardtites fenestratus															x					x	
Discorhabdus rotatorius															x						
Prediscosphaera columnata															x					x	
Prediscosphaera sp. (Stamm)															x						x
Zeugrhabdotus embergeri															x	x	x	x	x	x	
Ellipsagelosphaera britannica															x						
Cyclaglosphaera deflandrei															x						
Pervilithius varius															x	x				x	
Eiffelithus sp. 1																x					
Prediscosphaera sp.																x					
Octopodorhabdus sp. (? magnus)																x					
Ellipsagelosphaera fossacincta																x					
Nannoconus multicadus																	x		x		
Nannoconus borealis																	x	x	x		
Rhagodiscus sp.																	x				
Nannoconus boletus																		x			
Micrantolithus batilliformis																		x			
Creatarhabdus crenulatus																			x		
Coccosphären x																			x		
Octopodorhabdus magnus																				x	
Hayesites albiensis																				x	
Vekshinella quadriarcella																				x	
Ellipsagelosphaera aperta																					x
Lithraphidites alatus																					x
Lucianorhabdus carniolensis carniolensis																					x
Haquius circumradiatus																					x
Calcisphaerulidae																					x

Table 1. Nannofossils from borehole Obermoos TH-1 (determinations by Roswitha Braunstein; taxonomy emended according to Burnett, 1998).

Table 2. Obermoos Th 1, microfacies and microfauna. (s) rare, (h) common, (m) abundant.

Cenomanian Branderfleck Formation	*Orbitolina* sp., *Rotalipora*? Corallinacea, crinoids, bivalvae, *Textularia* sp., *Glomospira* sp., lagenids
Upper Aptian/ Albian Tannheim Fm	*Trochammina*, *Verneuillina* sp., *Textularia* sp., *Lenticulina* sp., *Globigerinelloides* algeriana, *Hedbergella* sp., *Discorbis* wassoevizi, *Epistomina* *charlottae, E*. sp., *E. polypioides*
Valanginian-Barremian? Schrambach Fm.?	*Spiculae*, radiolarians
Berriasian-Valanginian? Schrambach Fm.	*Calpionella* (s), radiolarians
Tithonian-Berriasian? Calpionella limestone (Ammergau Fm.)	*Calpionella* (h), radiolarians
Kimmeridge-Tithonian Saccocoma-limestone (Ammergau Fm.)	*Saccocoma* (h), radiolarians
Oxfordian Ruhpolding Radiolarite	Radiolaria div. sp. (m); Nasselaria
Lower Jurassic Adnet Limestone (Adnet Group)	Crinoids, *Nodosaria* sp., *Frondicularia* sp., ostracods, juvenile ammonites
Lower Jurassic Limestone with chert (Allgäu Fm.?)	Spiculae (m), crinoids
Upper Triassic Plattenkalk, Kössen Fm.	Bivalves (m), echinoderms, *Ammodiscus*, oo-/pelmicrite
Upper Triassic Hauptdolomit	Dolomicrite, dolosparite

Table 2. Microfacies types of all lithological units from the borehole Obermoos TH-1.

1819-1829 m: reddish Middle Jurassic limestone (Figure 7c-e).

1829-1873 m: light-greyish to light-greenish-reddish-grey limestone with chert and crinoids of Early Jurassic age (Fig. 7f-g).

1873-1905 m: fault zone with four subsections: (1) Lower Jurassic patchy marly limestone ("Fleckenmergel") (1873-1882 m), (2) light-greyish to reddish-greyish Lower Jurassic limestone with some chert lenses (1882-1886 m), (3) upper Lower Cretaceous purple to grey shale (1886-1905 m), which is likely a tectonic lens on a strike-slip fault, and (4) greyish Lower Jurassic limestone and marly limestone with a spiculae-radiolaria microfacies with few echinodermata and *Lenticulina*.

1905-2030 m: dark grey detritic-oolithic limestone (Figure 7h) with marly intercalations of the Kössen Formation (Rhaetian).

2030-2050 m: biodetritic limestone with dolomite and marl intercalations of the Rhaetian Plattenkalk (Kössen Formation).

2050-2468 m: light-greyish Norian Hauptdolomit (Figure 8a, b), a greyish dolomite with some dark-greyish-green to green slate intercalations between 2150 and 2168 m and 2206 and 2225 m. The dolomite is dark-greyish at 2186 m and dark- to medium-greyish at *c.* 2220 m.

3.2 Biostratigraphy

All nannofossils as determined by Mrs. Roswitha Braunstein are compiled in Table 1. According to the micro- and nannofossil contents, as well as microfacies, we distinguish several biostratigraphic levels (for details of biostratigraphy, see Tables 1 and 2). For the assignment of lithostratigraphic terms, we largely follow Piller et al. (2004) - problematic assignments are marked by question mark (see Table 2).

3.2.1 Gosau Group (206-456 m)

The uppermost part below Pleistocene comprises Gosau Group sedimentary rocks as conglomerates and variegated marls containing only redeposited fossils from older Cretaceous strata (Tab. 1): At depths 220 and 262 m, *Conusphaera mexicana mexicana* was found (stratigraphic range latest Kimmeridgian to Early Albian), and at levels 324 m, 400 m, 446 and 448 Early Cretaceous fossils such as Parhabdolithus embergeri are present.

3.2.2 Cenomanian Branderfleck Formation (456-601 m)

Between 456 and 601 m greyish biodetritic calcarenite with some quartz and glauconite occur with shallow water debris like corallinacea, bivalves, but also echinoderms and some orbitolinids. This facies can be compared to orbitolinid-bearing sandstones and detrital limestones from the Branderfleck Formation of the eastern part of the NCA (Wagreich, 2003b; Schlagintweit and Wagreich, 2005).

3.2.3 Grey Lower Aptian to Albian marl of the Tannheim Fm. (601-1212 m)

Between depths 601 and 1212 m, greyish Lower Aptian to Albian marls with few thin fine-grained sandstones intercalations were found. Between 730 and 760 m, these marls are cataclastically deformed. These marls can be assigned most probably to the Tannheim Formation, a typical lithological unit of the Bajuvaric nappes (e.g. Zacher, 1966; Wagreich, 2003c). At level 616 m, *Nannoconus quadriangulus and Rhagodiscus angustus* indicate a Late Aptian age of the Chiastozygus litterarius biozone (Aptian/Early Albian; CC7b). Nannofossils of samples from levels 620 m and 630 m indicate CC7b biozone (Aptian/Early Albian) of Perch-Nielsen (1985), whereas samples from levels 640 m and 1146 m suggest a Late Aptian/Early Albian age (CC 7 biozone; Perch-Nielsen, 1985). *Tranolithus phacelosus* of level 1170 m is likely a marker for the Prediscosphaera columnata Zone (CC 8) according to Perch-Nielsen (1985) although the zonal fossil *Prediscosphaera columnata* is missing. Fossils of level 1190 m indicate again the CC 7 biozone of Aptian/Early Albian age. The microfauna consists of a distinct typical assemblage, very often with arenaceous foraminifera like *Haplophragmoides* sp., *Cyclammina* sp., *Trochammina* sp., *Verneuillina* sp., but as leading elements *Globigerellinoides* ex gr. *algeriana*, *Epistomina charlottae* (very rare), *E. polypoides* and other Epistominas species, *Discorbis wassoevizi, Lenticulina* sp., and *Hedbergella* sp. Especially rich assemblages of these foraminifera were found at depths around 630 m and 660 m.

3.2.4 Higher "Neocomian" (Valanginian-Barremian) strata, probably Schrambach Formation (1212-1720 m)

Higher "Neocomian" (Valanginian-Barremian) strata of the interval 1212 to 1720 m show a radiolaria-spiculae microfacies and comprise three subunits with (1) a chert-bearing greyish marly limestone (1212-1300 m), where chert is abundant at c. 1270 m, (2) grey detrital limestone from 1300 to 1388 m and (3) sandstone-bearing and limy marls from 1388 to 1720 m.

The lithology including log information of this whole section is quite different from that of the Aptian/Albian interval and the microfacies is rather typical for a higher "Neocomian" (Valanginian-Barremian) stratigraphic position. These units resemble distal facies types of the Rossfeld Formation (e. g., Lukeneder, 2005) with gradual transitions into the Schrambach Formation (Rasser et al., 2003), and are known from northern parts of the Bajuvaric nappes further to the east (e.g. Decker et al., 1987).

However, the exact stratigraphic age of this units remains unclear, as the marly cuttings of the overlying Aptian/Albian tend very much for drilling contamination so that the following mentioned nannofossil assemblages seem to originate from higher drilling intervals, thus giving essentially the same age interpretation as recorded for the Tannheim Formation. The sample at level 1270 m indicates CC 8 biozone (Albian) of Perch-Nielsen (1985). At level 1310 m, the presence of *Eiffellithus* sp. 1, *Rhagodiscus angustus* and *Praediscosphaera* sp. give a Late Albian age (CC 8b), and samples at levels 1496 m, 1600 m and 1708 m indicate an Early Aptian age.

Based on the stratigraphic position and the oldest age of the overlying Tannheim Formation, we assign a Valanginian-Barremian age to this interval.

3.2.5 Schrambach Formation (Valanginian-Barremian; 1720-1756 m)

According to the lithology and the microfacies with radiolarias and a single *Calpionella* this interval represents a Valanginian section. For nannofossil biostratigraphy, drilling contamination is surely a problem because again only Aptian to earliest Albian marker fossils were found (e.g. nannofossil sample 1740 m with *Nannoconus quadriangulus*, zone CC 7). Nevertheless, we interpret this interval to represent the lower part of the Early Cretaceous (Berriasian-Valanginian), coeval to the Schrambach Formation.

3.2.6 Tithonian Limestone of the Ammergau Fm. (1756-1784 m)

Typical biostratigraphic elements in a mudstone microfacies are different species of radiolaria and frequent calpionellids, e.g. *Calpionella alpina* (Fig. 6f) indicating a late Tithonian-Berriasian age.

3.2.7 Kimmeridgian-Tithonian Limestone of the Ammergau Fm. (1784-1800 m)

This limestone is characterized by abundant fragments of *Saccocoma* in a mudstone microfacies.

3.2.8 Oxfordian Radiolarite of the Ruhpolding Formation (1800-1819 m)

Abundant radiolarians of different species occur in a mudstone microfacies. No sign of Middle Jurassic limestone could be identified.

3.2.9 Lower Jurassic red limestone of Adnet Formation (1819-1829 m)

Characteristic elements within a red packstone are juvenile ammonoids, crinoids, foraminifera like *Nodosaria* sp. and *Frondicularia* sp., large ostracods and fragments of bivalves.

3.2.10 Lower Jurassic cherty limestone of Allgäu Formation (1829-1980 m)

The main microfacial elements are siliceous spicules beside some crinoidal fragments, radiolarians and ostracods, at 1942 m a single *Involutina* sp..

3.2.11 Rhaetian Kössen Formation and Plattenkalk (1980-2050 m)

Frequent fragments of bivalves, echinoderms, and some foraminifera occur in mudstones and packstones, as well some ooliths and pelmicrites.

3.2.12 Upper Triassic Hauptdolomite

Rare ghosts of biogenic structures occur in the fine-grained dolomites, in coarse-grained dolosparites no biogenic remnants have been found (Figure 8a, b).

4. Discussion

The section of the well Obermoos TH-1 contributes to the knowledge of three distinct structural and lithostratigraphic levels as well as to the structure of the northern part of NCA.

4.1 Tectonic assignment and structure of the Bajuvaric nappe

The tectonic assignment of the drilling profile to Bajuvaric units is based on the presence of an adequate Jurassic-Barremian section and a well developed Aptian/Albian marly interval, the Tannheim Formation, covered by Cenomanian Branderfleck Formation. This combination is typical for the lower part of the Bajuvaric nappe system further to the west within the Northern Calcareous Alps and has, e.g. some similarities to the Carnian to Cenomanian section of the well Bergen 1 and its surroundings (Ganss, 1956) exposed c. 32 km WNW of the well Obermoos TH 1 (Fig. 1a). Here, it seems immediately overthrusted by the Tyrolic nappe system, which is again overridden by the Lower and Upper (Untersberg) Juvavic nappe (Figs. 1, 2, 9), which are exposed immediately to the south. Consequently, the Bajuvaric-type section in the basement of the Salzburg-Reichenhall

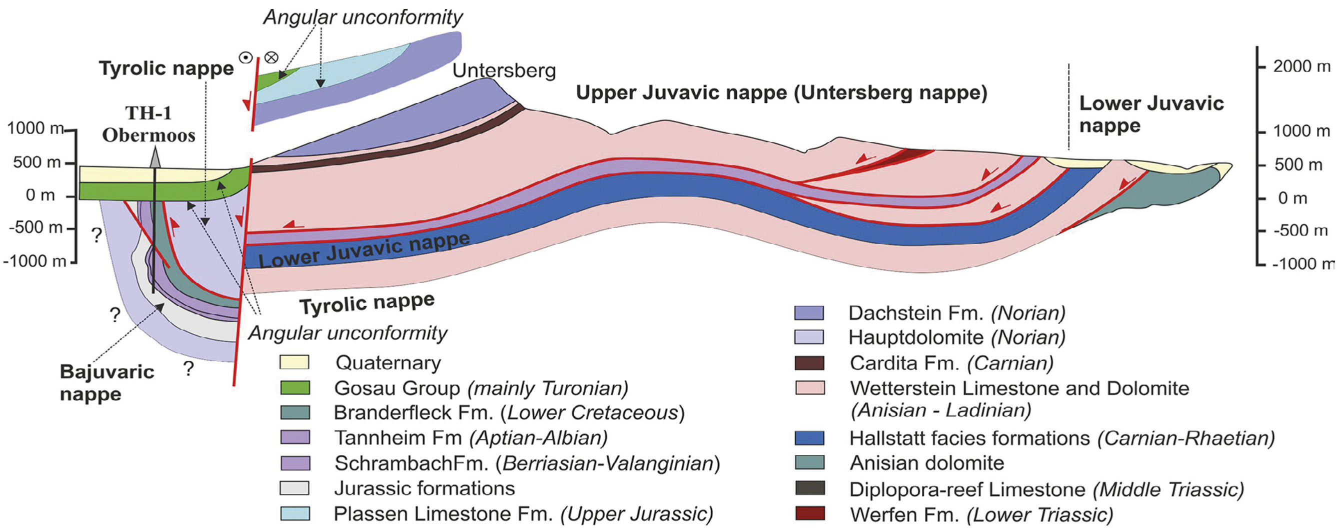

Figure 9. Interpretation of the large-scale structure along northern margin of central Northern Calcareous Alps.

basin is entirely surrounded by Tirolic and Upper Juvavic units (Figs. 1, 2). These relationships highlight the importance of the E-W trending Glanegg fault as a major strike-slip fault, which transported Bajuvaric units into this peculiar position.

The Norian to Cenomanian section in the borehole indicates steep-dipping units because thicknesses, exceed the usual values. Despite no dip logs have been run the results of the inclinometer log, which registers the deviation of the borehole, show that the bit drilled softly into the northern direction. This means, that the general dipping is directed to the South, because the bit runs automatically perpendicularly against bedding. The facies of the Jurassic section part and especially the existence of the Aptian and Albian formations covered by the Branderfleck Formation correspond to that of the Bajuvaric nappes (Leiss, 1990; Wagreich, 2003b), which is steeply dipping below the Tyrolic nappe. The Norian to Cenomanian succession in the borehole is not similar to that of the Tyrolic nappe exposed to the south respectively southeast. The succession could also not represent an extension of the Berchtesgaden nappe, in which Jurassic and Lower Cretaceous are either missing or bear different formations, e.g. the Upper Jurassic Plassen Formation (Schlager, 1930). As discussed above, the borehole section is likely part of a steeply dipping Bajuvaric nappe, which must be overridden by a Tyrolic nappe unit south of the borehole. This part potentially allows also a structural correlation with the flat-lying sections exposed in boreholes Vordersee 1 (Geutebrück et al., 1982) and Vigaun 1. The according section is shown in Figure 4b. The relationships allow draw an E-W section, which demonstrate the change of structural styles between the flat-laying Ostern Mts. and the steep northern NCA margin (see also Neubauer et al., 2003; Ortner et al., 2006).

In Figure 9, we show a tentative interpretation of the structures along the northern part of the NCA, especially the Juvavic units, which also includes the Untersberg in the south. There, the Upper Juvavic nappe with its Middle-Upper Triassic shallow water facies overrides the Lower Juvavic nappe with its Permian Haselgebirge and Middle-Upper Triassic Hallstatt facies and Lower Jurassic formations (Prey, 1969; Ganss, 1978), schematically indicated in Figure 9. The Lower Juvavic nappe lies above the Rossfeld Formation of the Tyrolic nappe. The only differences of our interpretation to a similar section of Missoni and Gawlick (2011a, b) are imbrications in the southern part of the Untersberg (visible in the map of Prey, 1969) and the deep, not outcropping part at the northern region of the Untersberg block. Missoni and Gawlick (2011a, b) assume the presence of an Eocene thrust transporting the Untersberg block (cutting its base) over the Salzburg-Reichenhall basin, whereas our interpretation assumes a major role of Late Cretaceous and Neogene sinistral oblique-slip motion along the Glanegg fault, superposing the contact between Bajuvaric and Juvavic units. From the map, it becomes clear that a major fault (Glanegg fault) separates the Upper Juvavic Untersberg nappe with transgressive Upper Cretaceous Gosau Group from mainly Eocene Nierental Formation in the north.

The Glanegg fault is interpreted to represent a sinistral strike-slip fault being part of a fault system forming a (potentially Late Cretaceous) pull-apart basin (Neubauer, in prep.). The fault section in the borehole is potentially part of the southernmost branch of the Oligocene to Neogene ENE-trending Innsbruck-Salzburg-Amstetten fault system (ISAM; Egger, 1997), which crosses the northern part of Salzburg-Reichenhall basin. This fault is tentatively correlated with unnamed E-W trending faults in the northwestern part of the Gaisberg region (Figure 3; Egger and van Husen, 2009a, b).

4.2 Salzburg-Reichenhall Gosau basin fill and structure

The drilled Gosau Group mainly contains the coarse clastics of the Kreuzgraben Formation forming the basal part of the Upper Cretaceous succession (Wagreich, 2003a). No marls resembling to the Morzg Fm. recently described by Egger et al. (2013) have been found. The section of the Obermoos borehole allows correlation with the conglomerates of the Gaisberg and Glasenbach gorge region in the east (Egger and van Husen, 2009a, b), which is in the eastern lateral extension of the borehole. No distinct non-NCA ("exotic") components could be found within the conglomerates, which show mainly local sources from the surrounding Bajuvaric formations. We interpret a major unconformity separating the flat-lying Gosau Group from the folded Branderfleck Formation and older strata that form a syncline that developed during the mid-Cretaceous.

4.3 Quaternary Salzach Valley basin infill

As the first c. 200 m of Quaternary valley fill was not a primary target of the drilling details provided by the drillers' lithological logs are very sparse. The sandy gravels below the thin Holocene peat layers do potentially record (glacio-)fluvial sediments, from near the northern margin of the Untersberg. We tentatively argue for a tributary of the paleo-Salzach river draining Alpine basin further to the north (Donadel et al., 2014). The encountered coarse-grained facies is very different from the common facies of the Salzach Valley fill near the city of Salzburg mainly comprising lacustrine fines/mudstones (Kramer and Kröll, 1977; Brandecker, 1974; van Husen, 1980; Preusser et al., 2010).

5. Conclusions

Description and interpretation of the well Obermoos TH-1 drilled close to the southern margin within the Salzburg-Reichenhall basin to a depth of 2468 meters allow the following major conclusions.

The section shows close similarities to an also steep section at the northern margin of the Northern Calcareous Alps in the well Bergen 1 drilled c. 32 km westnorthwest.

The tectonic assignment of the drilled Obermoos TH-1 section is founded on the presence of Upper Triassic Hauptdolomite at the base, Jurassic to Barremian strata, and Aptian/Albian marly Tannheim Formation covered by marls assigned to the Cenomanian Branderfleck Formation. The section thus has close similarities to successions of the Bajuvaric units exposed further to the west and east.

No Juvavic units were found in the drillhole although the downward projection of Juvavic units of the Untersberg would argue for such a section. Therefore, we conclude that a major strike-slip fault separates the Juvavic Untersberg Mountain from the Salzburg-Reichenhall Gosau basin.

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References

Brandecker, H., 1974. Hydrogeologie des Salzburger Beckens. Steirische Beiträge zur Hydrogeologie, 26, 5-39.

Braunstingl, R., Hejl, E. and Pestal, G., 2005. Geologie der österreichischen Bundesländer – Salzburg. Geologische Karte M 1:200.000. Geologische Bundesanstalt, Wien.

Burnett, J.A., 1998. Upper Cretaceous. In: Bown, P.R. (Ed.), Calcareous Nannofossil Biostratigraphy. British Micropalaeontological Society Publications Series, Chapman and Hall, London, pp. 132-199.

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

Decker, K., Faupl, P. and Müller, P., 1987. Synorogenic Sedimentation on the Northern Calcareous Alps during the Early Cretaceous. In: Flügel, H. W. and Faupl, P. (Eds.), Geodynamics of the Eastern Alps (1987). Deuticke, Wien, pp. 126-141.

Del-Negro, W., 1979. Der Bau der Gaisberggruppe. Mitteilung der Gesellschaft für Salzburger Landeskunde, 119, 325-350.

Donadel, A. K., Höfer-Öllinger, Frimmel, H. E. and Schrott, L., 2014. Evolution of Late- to Postglacial River Confluences in Overdeepened Alpine Valleys – Saalach and Königsseeache (Austria). Austrian Journal of Earth Sciences, 107/2, 60-73.

Egger, H., 1997. Das sinistrale Innsbruck-Salzburg-Amstetten-Blattverschiebungssystem: ein weiterer Beleg für die miozäne laterale Extrusion der Ostalpen. Jahrbuch der Geologischen Bundesanstalt, 140, 47-50.

Egger, H. and van Husen, D., 2009a. Geologische Karte von Österreich 1:50000, ÖK 64 Strasswalchen. Geologische Bundesanstalt, Wien.

Egger, H. and van Husen, D., 2009b. Geologische Karte der Republik Österreich 1:50000. Erläuterungen zu Blatt 64 Strasswalchen. Geologische Bundesanstalt, Wien, 87 pp.

Egger, H., Bichler, M., Homayoun, M., Kirchner, E. and Surenian, R., 1996. Spätpaleozäne Bentonite aus der Gosau-Gruppe des Untersberg-Vorlandes (Nördliche Kalkalpen, Salzburg). Jahrbuch der Geologischen Bundesanstalt [Wien], 139, 13-20.

Egger, H., Homayoun, M., Huber, H., Rögl, F. and Schmitz, B., 2005. Early Eocene climatic, volcanic, and biotic events in the northwestern Tethyan Untersberg section, Austria. Palaeogeography Palaeoclimatology Palaeoecology, 217, 243-264.

Egger, H., Mohamed, O. and Rögl, F., 2013. Plankton stratigraphy of the Santonian at Morzg, Salzburg (Gosau Group, Northern Calcareous Alps, Austria). Austrian Journal of Earth Sciences, 106/2, 98-114.

Faupl, P. and Wagreich, M., 1996. Basin analysis of the Gosau Group of the Northern Calcareous Alps (Turonian-Eocene, Eastern Alps). EAGE Special Publications, 5, 127-135.

Faupl, P. and Wagreich, M., 2000. Late Jurassic to Eocene Palaeogeography and geodynamic Evolution of the Eastern Alps. Mitteilungen der Österreichischen Geologischen Gesellschaft, 92 (1999), 79-94.

Fiebig, M., Herbst, P., Drescher-Schneider, R., Lüthgens, C., Lomax, J. and Doppler, G., 2014. Some remarks about a new

Last Glacial record from the western Salzach foreland glacier basin (Southern Germany). Quaternary International, 328-329, 107-119. http://dx.doi.org/10.1016/j.quaint.2013.12.048

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

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

Ganss, O., 1956. Geologie des Blattes Bergen mit einem Beitrag von I. de Klasz (Helvetische Zone), K. Götzinger (Bohrung Bergen 1) und F. Vogel (Bodenkundlicher Beitrag). Geologica Bavarica, 26, 1-164.

Ganss, O., 1978. Geologische Karte von Bayern 1:100.000, Blatt 667 Bad Reichenhall. Bayerisches Geologisches Landesamt, Munich, scale 1:100,000.

Gawlick, H-J. and Missoni, S., 2015. Middle Triassic radiolarite pebbles in the Middle Jurassic Hallstatt Mélange of the Eastern Alps: implications for Triassic-Jurassic geodynamic and paleogeographic reconstructions of the western Tethyan realm. Facies, 61, 13, 19 p, http://dx.doi.org/10.1007/s10347-015-0439-3.

Geutebrück, E., Klammer, W., Schimanek, K., Steiger, E., Ströbl, E., Winkler, G. and Zych, D., 1982. Oberflächengeophysikalische Verfahren im Rahmen der KW-Exploration der ÖMV. Erdöl und Erdgas, 100, 296-304.

Hell, M., 1963. Tiefbohrung inmitten des Salzburger Beckens durchfährt Grundgebirge. Mitteilungen der Gesellschaft für Salzburger Landeskunde,103, 135-140.

Herbst, P. and Riepler, F., 2006. ^{14}C evidence for an Early to Pre-Würmian age for parts of the Salzburger Seeton, Urstein, Salzach Valley, Austria. Austrian Journal of Earth Sciences, 99, 57-61.

Herm, D., 1962. Die Schichten der Oberkreide (Untere, Mittlere und Obere Gosau) im Becken von Reichenhall (Bayrische/Salzburger Alpen). Zeitschrift der deutschen geologischen Gesellschaft, 113, 320-337.

Herm, D., Hillebrandt, A. v. and Perch-Nielsen, K., 1981. Die Kreide/Tertiär-Grenze im Lattengebirge (Nördliche Kalkalpen) in mikropaläontologischer Sicht. Geologica Bavarica, 82, 319-344.

Hinsch, R., 2013. Laterally varying structure and kinematics of the Molasse fold and thrust belt of the Central Eastern Alps: Implications for exploration. American Association of Petroleum Geologists Bulletin, 97, 1805-1831, doi: 10.1306/04081312129.

Höfling, R., 1985. Faziesverteilung und Fossilvergesellschafttungen im karbonatischen Flachwasser-Milieu der alpinen Oberkreide (Gosau-Formation). Münchner Geowissenschaftliche Abhandlungen Reihe A, 3, 1-206.

Kieslinger, A., 1964. Die nutzbaren Gesteine Salzburgs. Das Bergland-Buch, Salzburg, pp. XI & 435.

Kober, L. 1955. Bau und Entstehung der Alpen. Second Ed., 379 p., Deuticke, Vienna.

Kozur, H., 1992. The evolution of the Meliata-Hallstatt ocean and its significance for the early evolution of the Eastern Alps and Western Carpathians. Palaeogeography Palaeoclimatology Palaeoecology, 87, 109-135.

Kramer, H. and Kröll, A., 1977. Die Untersuchungsbohrung Vigaun U 1 bei Hallein in den Salzburger Kalkalpen. Mitteilungen der Österreichischen Geologischen Gesellschaft, 70, 1-10.

Krenmayr, H.G., 1996. Hemipelagic and turbiditic mudstone facies associations in the Upper Cretaceous Gosau Group of the Northern Calcareous Alps (Austria). Sedimentary Geology, 101, 149-172.

Krenmayr, H. G., 1999. Die Nierental-Formation der Oberen Gosau Gruppe (Oberkreide-Paleozän, Nördliche Kalkalpen) in Berchtesgaden: Definition, Fazies und Environment. Jahrbuch der Geologischen Bundesanstalt, 141/4, 409-447.

Krische, O., Bujtor, L. and Gawlick, H-J., 2013. Calpionellid and ammonite biostratigraphy of uppermost Jurassic to Lower Cretaceous sedimentary rocks from the Leube quarry (Northern Calcareous Alps, Salzburg, Austria). Austrian Journal of Earth Sciences, 106/1, 26-45.

Krische, O., Goričan, Š. and Gawlick, H-J., 2014. Erosion of a Jurassic ophiolitic nappe-stack as indicated by exotic components in the Lower Cretaceous Rossfeld Formation of the Northern Calcareous Alps (Austria). Geologica Carpathica, 65, 3-24.

Lein, R., 1987. Evolution of the Northern Calcareous Alps during Triassic times. In: Flügel, H.W., Faupl, P. (Eds.), Geodynamics of the Eastern Alps. Franz Deuticke, Vienna, pp. 85-102.

Leiss, O., 1988a. Die Kontrolle des Sedimentationsgeschehens und der Biofacies durch evolutive orogenetische Prozesse in den Nördlichen Kalkalpen am Beispiel von Gosauvorkommen (Coniac-Santon). Documenta Naturae, 43, 1-95.

Leiss, O., 1988b. Die Stellung der Gosau (Coniac-Santon) im großtektonischen Rahmen (Lechtaler Alpen bis Salzkammergut, Österreich). Jahrbuch der Geologischen Bundesanstalt [Wien], 131, 609-636.

Leiss, O., 1989. Der Bauxit und die lateritisch-bauxitischen Ablagerungen der tiefen Gosau (Turon/Coniac) in den nördlichen Kalkalpen. Zeitschrift der Deutschen Geologischen Gesellschaft, 140, 137-150.

Leiss, O., 1990. Sedimentationsgeschehen und Biofazies innerhalb der Nördlichen Kalkalpen während der kretazischen Orogenese (Schwerpunkt: Gosau-Formation – Coniac/Santon). Mitteilungen der Gesellschaft der Geologie- und Bergbaustudenten Österreichs, 36, 39-85.

Linzer, H.G. Decker, K. Peresson, H., Dell´Mour, R. and Frisch, W., 2002. Balancing lateral orogenic float of the Eastern Alps. Tectonophysics, 354, 211-237.

Linzer, H. G., Moser, F., Nemes, F., Ratschbacher, L. and Sperner, B., 1997. Build-up and dismembering of a classical fold-thrust belt: from non-cylindrical stacking to lateral extrusion in the eastern Northern Calcareous Alps. Tectonophysics 272, 97-124.

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

Lukeneder A., 2005. Taphonomy and stratigraphy of Early Cretaceous ammonoid mass occurrences (Late Valanginian, Northern Calcareous Alps; Upper Austria). Austrian Journal of Earth Sciences, 98, 34-51.

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

Mandl, G.W., 2000. The Alpine sector of the Tethyan shelf – Examples pf Triassic to Jurassic sedimentation and deformation from the Northern Calcareous Alps. Mitteilungen der Österreichischen Geologischen Gesellschaft, 92(1999), 61-77.

Missoni, S. and Gawlick, H.-J., 2011a. Evidence for Jurassic subduction from the Northern Calcareous Alps (Berchtesgaden; Austoalpine, Germany). International Journal of Earth Sciences, 100, 1605-1631. http://dx.doi.org/10.1007/s00531-010-0552-z.

Missoni, S., Gawlick, H.-J., 2011b. Jurassic mountain building and Mesozoic-Cenozoic geodynamic evolution of the Northern Calcareous Alps as proven in the Berchtesgaden Alps (Germany). Facies, 57,137-186. http://dx.doi.org/10.1007/s10347-010-0225-1.

Neubauer, F., Dallmeyer, R.D., Dunkl, I. and Schirnik, D., 1995. Late Cretaceous exhumation of the metamorphic Gleinalm dome, Eastern Alps: kinematics, cooling history and sedimentary response in a sinistral wrench corridor. Tectonophysics, 242, 79-98

Neubauer, F., Genser, J. and Handler, R., 2000. The Eastern Alps: Result of a two-stage collision process. Mitteilungen der Österreichischen Geologischen Gesellschaft, 92, 117-134.

Neubauer, F., Kiss, A. and Tomek, C., 2003. Control of the collisional architecture by inherited, passive-margin structures: the European crust in the TRANSALP section compared with borehole and other seismic sections of the northern Eastern Alps. Memorie di Scienze Geologiche [Padova], 54, 185-188.

Ortner, H., 2007. Styles of soft-sediment deformation on top of a growing fold system in the Gosau Group at Muttekopf, Northern Calcareous Alps, Austria: Slumping versus tectonic deformation. Sedimentary Geology, 196, 99-118.

Ortner, H., Reiter, H. and Brandner, R., 2006. Kinematics of the Inntal shear zone-sub-Tauern ramp fault system and the interpretation of the TRANSALP seismic section, Eastern Alps, Austria. Tectonophysics, 414, 241-258.

Ortner, H., Kositz, A., Willingshofer, E. and Sokoutis, D., 2015a. Geometry of growth strata in a transpressive fold belt in field and analogue model: Gosau Group at Muttekopf, Northern Calcareous Alps, Austria. Basin Research. http://dx.doi.org/10.1111/bre.12129

Ortner, H., Aichholzer, S., Zerlauth, M., Pilser, R. and Fügenschuh, B., 2015b. Geometry, amount and sequence of thrusting in the Subalpine Molasse of Western Austria and Southern Germany, European Alps. Tectonics, 34, 1-30. http://dx.doi.org/10.1002/2014TC003550

Ortner, H., Ustaszewski, M. and Rittner, M., 2008. Late Jurassic tectonics and sedimentation: breccias in the Unken syncline, central Northern Calcareous Alps. Swiss Journal of Geosciences, 101, Suppl. 1, S55-S71.

Perch-Nielsen, K., 1985. Mesozoic calcareous nannofossils. In. Bolli, H.M., Saunders, J.B. and Perch-Nielsen, K. (eds.), Plankton Stratigraphy. Cambridge University Press, Cambridge, pp. 329-426.

Peresson, H. and Decker, K., 1997a. Far-field effects of Late Miocene subduction in the Eastern Carpathians: E-W compression and inversion of structures in the Alpine-Carpathian-Pannonian region. Tectonics, 16, 38-56.

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

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

Piller, W.E., Egger, H., Erhart, C.W., Gross, M., Harzhauser, M., Hubmann, B., Van Husen, D., Krenmayr, H.-G., Krystyn, L., Lein, R., Lukeneder, A., Mandl, G.W., Rögl, F., Roetzel, R., Rupp, C., Schnabel, W., Schönlaub, H.P., Summesberger, H., Wagreich, M. and Wessely, G., 2004. Die stratigraphische Tabelle von Österreich 2004 (sedimentäre Folgen). Kommission für die paläontologische und stratigraphische Erforschung Österreichs, Österreichische Akademie der Wissenschaften und Österreichische Stratigraphische Kommission, Wien.

Plöchinger, B., 1955. Zur Geologie des Kalkalpenabschnittes vom Torrener Joch zum Ostfuß des Untersberges, die Göllmasse und die Halleiner Hallstätter Zone. Jahrbuch der Geologischen Bundesanstalt [Wien], 98/1, 93-144.

Plöchinger, B., 1984. Zum Nachweis jurassischer-kretazischer Eingleitungen von Hallstätter Gesteinsmassen beiderseits des Salzach-Quertales (Salzburg). Geologische Rundschau, 73/1, 293-306.

Plöchinger, B. (with contributions by H. Brandecker, H.P. Leditzky, V. Maurin, G. Tichy, D. van Husen), 1990. Erläuterungen zu Blatt 94 Hallein. Geologische Bundesanstalt, Vienna, pp. 76.

Preusser, F., Reitner, J. M. and Schlüchter, C., 2010. Distribution, geometry, age and origin of overdeepened valleys and basins in the Alps and their foreland. Swiss Journal of Geosciences, 103, 407-426. http://dx.doi.org/10.1007/s00015-010-0044-y

Prey, S., 1959. Zwei Tiefbohrungen der Stieglbrauerei in Salzburg. Verhandlungen der Geologischen Bundesanstalt, Wien, 216-224.

Prey, S., 1969. Geologische Karte der Umgebung der Stadt Salzburg, 1:50:000. Geologische Bundesanstalt, Wien.

Prey, S., 1980. Erläuternde Beschreibung des Nordteiles der Geologischen Karte der Umgebung der Stadt Salzburg, 1:50.000. Flyschzone, Walserbergserie, Gosau im Nordrand der Kalkalpen und Quartär. Verhandlungen der Geologische Bundesanstalt [Wien], 1980, 3, 281-325.

Rasser, M.W., Vasicek, Z., Skupien, P., Lobitzer, H. and Boorová, D., 2003. Die Schrambach-Formation an ihrer Typuslokalität (Unter-Kreide, Nördliche Kalkalpen, Salzburg): Lithostratigraphische Formalisierung und „historische" Irrtümer. In: Piller, W.E. (Ed.), Stratigraphia Austriaca, Schriftenreihe der Erdwissenschaftlichen Kommissionen, 16, 193-216 (Österreichische Akademie der Wissenschaften).

Ratschbacher, L., 1986. Kinematics of Austro-Alpine cover nappes: changing translation path due to transpression. Tectonophysics, 125, 335-356.

Ratschbacher, L., Frisch, W., Neubauer, F., Schmid, S.M. and Neugebauer, J., 1989. Extension in compressional orogenic belts: The eastern Alps. Geology, 17, 404-407.

Risch, H., 1988. Zur Sedimentationsabfolge und Tektogenese der Gosaukreide im Reichenhaller Becken. Neues Jahrbuch für Geologie und Paläontologie Monatshefte, 1988, (5), 293-310.

Schlagintweit, F., Wagreich, M., 2005. Micropaleontology of „Orbitolina Beds" of Lower Austria (Branderfleck Formation, Lower Cenomanian). Jahrbuch der Geologischen Bundesanstalt, 145, 115-125.

Schlager, M., 1930. Zur Geologie des Untersberges bei Salzburg. Verhandlungen der Geologischen Bundesanstalt, 1930, 245-255.

Schorn, A. and Neubauer, F., 2011. Emplacement of an evaporitic melange nappe in central Northern Calcareous Alps: evidence from the Moosegg klippe (Austria). Journal of Austrian Earth Sciences, 104/2, 22-46.

Schorn, A., Neubauer, F., Genser, J. and Bernroider, M., 2013. The Haselgebirge evaporitic mélange in central Northern Calcareous Alps (Austria): part of the Permian to Lower Triassic rift of the Meliata ocean? Tectonophysics, 583, 28-48. http://dx.doi.org/10.1016/j.tecto.2012.10.016

Schweigl, J. and Neubauer, F., 1997. Structural development of the central Northern Calcareous Alps: Significance for the Jurassic to Tertiary geodynamics in the Alps. Eclogae Geologicae Helvetiae, 60, 303-323.

Tollmann, A., 1985. Geologie von Österreich, Band 2: Außerzentralalpiner Anteil. Deuticke, Vienna, 718 pp.

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

van Husen, D., 1979. Verbreitung, Ursachen und Füllung glazial übertiefter Talabschnitte an Beispielen in den Ostalpen. Eiszeitalter und Gegenwart, 29, 9-22.

van Husen, D., 1980. Geological Processes during the Quaternary. Mitteilungen der Österreichischen Geologischen Gesellschaft, 92, 135-157.

von Hillebrandt, A., 1962. Das Alttertiär im Becken von Reichenhall und Salzburg (Nördliche Kalkalpen). Zeitschrift der deutschen geologischen Gesellschaft, 113, 339—358.

Wagreich, M., 1993. Subcrustal tectonic erosion in orogenic belts – a model for the Late Cretaceous subsidence of the Northern Calcareous Alps (Austria). Geology, 21, 941-944.

Wagreich, M., 1995. Subduction tectonic erosion and Late Cretaceous subsidence along the northern Austroalpine margin (Eastern Alps, Austria). Tectonophysics, 242, 63-78.

Wagreich, M., 2003a. The Grabenbach Formation (Gosau Group, Santonian – Lower Campanian) in the Lattengebirge (Germany): lithostratigraphy, biostratigraphy and strontium isotope stratigraphy. Österreichische Akademie der Wissenschaften, Schriftenreihe der Erdwissenschaftlichen Kommissionen, 16, 141-150.

Wagreich, M., 2003b. Lithostratigraphie und Sedimentologie der Branderfleck-Formation (Cenomanium) in den niederösterreichischen Kalkvoralpen. In: Piller, W.E. (ed.), Stratigraphia Austriaca. Österreichische Akadademie der Wissenschaften, Schriftenreihe der Erdwissenschaftlichen Kommissionen, 16, 151-164.

Wagreich, M., 2003c. A slope-apron succession filling a piggyback basin: the Tannheim and Losenstein Formations (Aptian – Cenomanian) of the eastern part of the Northern Calcareous Alps (Austria). Mitteilungen der Österreichischen Geologischen Gesellschaft, 93 (2000), 31-54.

Wagreich, M. and Decker, K., 2001. Sedimentary tectonics and subsidence modeling of the type Upper Cretaceous Gosau basin (Northern Calcareous Alps, Austria). International Journal of Earth Sciences (Geologische Rundschau) 90, 714-726. http://dx.doi.org/10.1007/s005310000181

Weidich, K.F., 1984a. Über die Beziehungen des „Cenomans" zur Gosau in den Nördlichen Kalkalpen und ihre Auswirkungen auf die paläogeographischen und tektonischen Vorstellungen. Geologische Rundschau, 73, 517-566.

Weidich, K.F., 1984b. Feinstratigraphie, Taxonomie planktonischer Foraminiferen Palökologie der Foraminiferengesamtfauna der kalkalpinen tieferen Oberkreide (Untercenomen-Untercampan) der Bayrischen Alpen. Bayerische Akademie der Wissenschaften mathematisch-naturwissenschaftliche Klasse, 162, 1-151.

Wessely, G. and Wagner, L. 1993. Die Nordalpen. In: Brix, F. and Schultz, O. (Eds.), Erdöl und Erdgas in Österreich.Naturhistorisches Museum, Wien, pp. 360-371.

Zacher, W., 1966. Die kalkalpinen Kreideablagerungen in der Umgebung des Tannheimer Tales (Außerfern, Tirol). Mit einem mikropaläontologischen Beitrag von F. Bettenstaedt. Mitteilungen der Bayerischen Staatsammlung Paläontologie und Historische Geologie, 6, 213-228.

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