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Field Guide

to the pre-conference excursion

Paleogeographic and tectonic evolution of the Salzburg-Reichenhall basin in Eastern Alps and its Neogene-Quaternary overprint

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Aim of the excursion

Based on new data, the excursion provides an integrated overview on the pull-apart-type formation of the Salzburg-Reichenhall basin containing the Gosau and Inntal Groups, redefinition of some of its lithostratigraphic units and provenance analysis. Further highlights are the detection of Neogene conglomerates with far-distant transport with nearly exclusive metamorphic components, its provenance analysis and the assessment of deformation structures in Quaternary conglomerates, the later allowing to redefine the landscape evolution and Quaternary kinematics of northern parts of Eastern Alps.

Abstract

The Eastern Alps include the remnants of two continent-continent collisional orogens, which are superimposed to each other. The earlier orogen formed at about the Early to Late Cretaceous boundary (Early Alpine orogeny) and represents, after the closure of the Penninic oceanic basin, the overriding plate of the second Eocene–Early Miocene orogen. In terms of the paleogeographic and tectonic evolution of the Eastern Alps, the Late Cretaceous to early Middle Eocene time represents a transitional stage between these two paroxysmal orogenic events, and Gosau basins were deposited as a sort of collapse basins following the Early Alpine orogeny at the late Early to early Late Cretaceous boundary.

This study and excursion provides new paleogeographic and structural data from Late Cretaceous to Eocene Salzburg-Reichenhall basin, which is exposed at the northern leading edge of the Northern Calcareous Alps (NCA) overlying the Cretaceous Austroalpine nappe complex. The Salzburg-Reichenhall basin is interpreted to have initially formed as Upper Cretaceous pull-apart- or strike-slip type collapse basin on an overstep within a regional ENE-trending wrench fault system crossing Salzburg city and overstepping the folded Permian to Lower Cretaceous NCA succession. The Late Cretaceous stage is governed by longitudinal infilling, from E to SE, and steep lateral basin margins in the south and west. Later, during Santonian to Paleogene, marl deposition suggests loss of the pronounced paleo-topography and is considered to and represents a tectonically quiet period. Relief reappears with siliciclastic turbidites of Late Paleocene/Eocene age. The overlying Middle to Upper Eocene Inntal Group is an intramontane molasse basin related via the Oberaudorf basin to the Eocene-Oligocene Unterinntal basin, which is later disrupted by the sinistral Saalach fault (Fig. 1b). Furthermore, on overlying Pleistocene Mönchsberg Nagelfluh deformation structures are found, too, implying still ongoing neotectonic activity in the Salzach Valley Graben.

1. Introduction

The Gosau basins, a common feature characterizing the uppermost tectonic units of the Austroalpine mega-unit in Eastern Alps, Carpathians and similar basins in Southeast European mountain belts like Dinarides (Willingshofer, 2000), are basins, which are post-tectonic to the plate collision after closure of the oceanic Meliata basin. In Eastern Alps, these basins Early Alpine metamorphism (Hoinkes et al., 1999). This sequence of deformation stages is commonly known as „Austrian" tectonic phase (Tollmann, 1976, 1985 and references therein). Most Gosau basins in Eastern Alps formed after this deformation phase following a phase of erosion (e.g., Faupl and Wagreich, 2000). Generally, a terrestrial to shallow marine Lower Gosau Subgroup is distinguished from a deep marine Upper Gosau Subgroup starting mostly with Campanian (Wagreich and Faupl, 1994). Gosau basins are always isolated and scattered in the NCA and the central part of the Austroalpine mega-unit (Fig. 1a).

Many models have been proposed to explain formation of collapse basins within mountain belts, which develop within and along margins of growing mountain belts after collision during late orogenic stages. Such basins form after plate collision, when the overthickened orogenic wedge starts to extend (e.g., Selverstone, 2005). An often-observed feature is the linkage of intramontane basins with major strike-slip faults, which result from partitioning of oblique convergence into orogen-parallel strike-slip and orthogonal thrust motion (e.g., Ratschbacher et al., 1989, 1991). In Eastern Alps and in adjacent Carpathians and Dinarides, typical examples for such collapse-type basins are the Late Cretaceous to Eocene so-called Gosau basins (Fig. 1a), which play a significant role for unraveling of the tectonic history of the Eastern Alpine orogen. As known since a long time, these basins formed on the Austroalpine nappe stack and postdate Early Cretaceous shortening, nappe stacking and peak metamorphism within the Austroalpine nappe stack (e.g., Ratschbacher et al., 1989; Neubauer et al., 2000; Schmid et al., 2004). Several models have been postulated for the tectonic evolution of the Gosau basins, mostly based on detailed investigation of specific, isolated basins. These models include:

1. Basin formation in terms of combined piggy-back mechanisms, subcrustal erosion and trench-ward tilting of the Austroalpine orogenic wedge (Wagreich, 1993a, 1995).
2. Formation as collapse basin due to synorogenic collapse contemporaneous with shortening at depth due to oblique shortening a plate convergence (Neubauer et al., 1995). Both sinistral (Neubauer et al., 1995) and dextral (Wagreich and Decker, 2001), orogen-parallel ca. E- to NE-trending wrench corridors have been postulated.
3. This type of basin grades into extensional basins, which resulted from ca. orogen-parallel extension and in which strike-slip deformation and wrenching play a minor role (e.g., the Krappfeld and Kainach Gosau basins; Neubauer et al., 1995; Koroknai et al., 1999; Willingshofer et al., 1999).
4. On the northwestern NCA syntectonic compressional Gosau basins (Ortner et al., 2016), which are Santonian in age, and there the onset of basin subsidence is younger than in other Gosau basins. An often-neglected characteristic is that these are synchronous with synmetamorphic thrusting in Lower Austroalpine units at ca. 84–78 Ma (Neubauer, 1994; Dallmeyer et al., 1998).

Here, we report paleogeographic, petrographic and structural data from the Salzburg-Reichenhall Gosau basin, which is located along northern margins of the central Northern Calcareous Alps (NCA). We show its potential Late Cretaceous formation mechanisms, the basin fills and its overprint by Neogene strike-slip faulting.

2. Geological setting

The Eastern Alps include from N to S, and from the northern base to its central axis, the uppermost Eocene to Miocene Molasse basin on the European basement, thin Jurassic-Eocene slices of Helvetic passive margin detached from the European basement, the Rhenodanubian Flysch zone with Cretaceous to Eocene turbidites being part of the Mesozoic, partly oceanic Penninic units, the Austroalpine nappe stack with a widely exposed polymetamorphic basement in the central, mostly metamorphosed axis and Permian to Eocene cover successions (Fig. 1a). The cover successions are prominently exposed in the Northern Calcareous Alps (NCA). Along the central axis of Eastern Alps, Penninic units are exposed in several windows, from which the Tauern window is the most prominent one. The sub-Penninic units include basement-cover successions derived from the southern extension

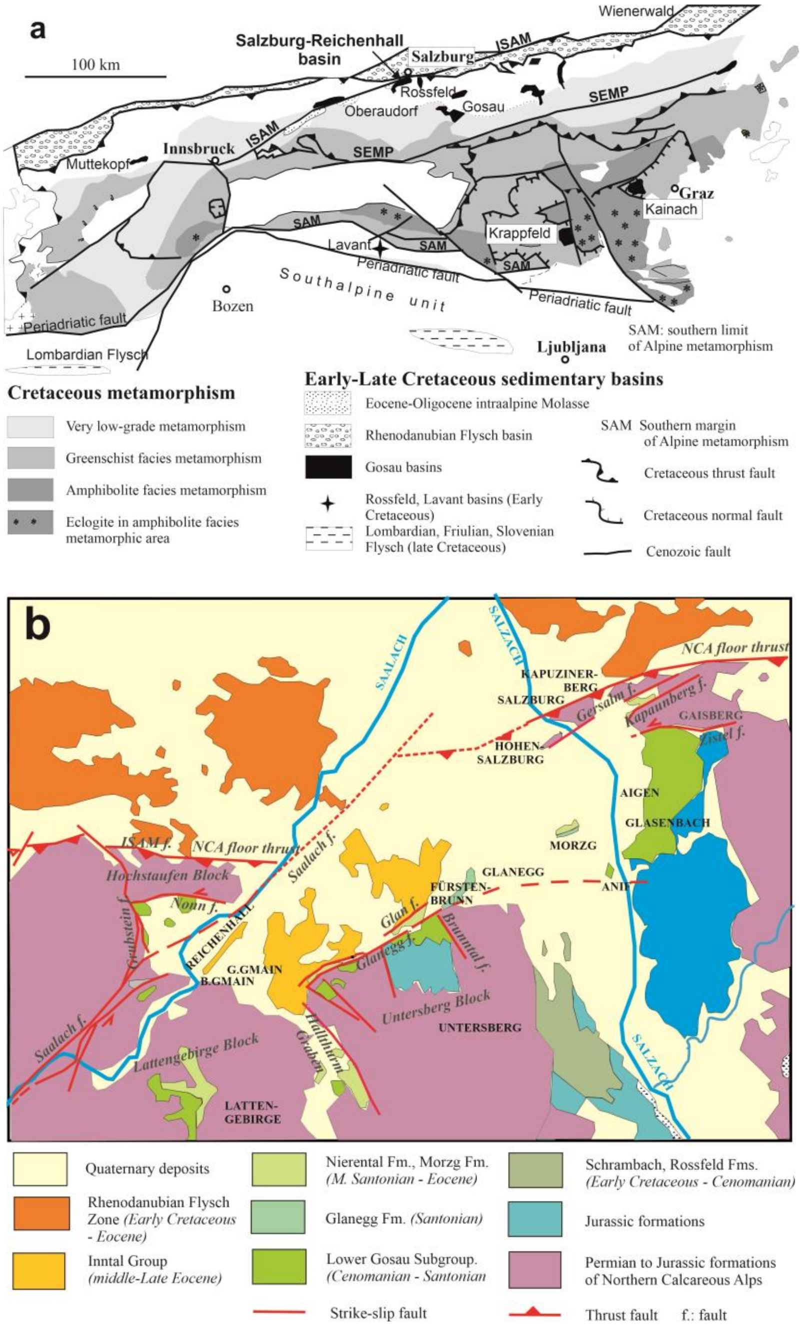

Fig. 1. (a) Simplified geological map of the Eastern Alps and location of various Gosau basins. (b) Simplified geological map of the framework of the Salzburg-Reichenhall Gosau basin. Based on Prey et al. (1969), Egger and van Husen (2003), Egger et al. (2017).

of the stable European crust, and the Glockner nappe, which represents the Mesozoic infill of the Piemontais-Ligurian Ocean (Schmid et al., 2004).

The Salzburg-Reichenhall Gosau basin is in the central part of NCA (Fig. 1a, b). As an example, the NCA stratigraphy southeast of the Salzburg-Reichenhall Gosau basin is shown in Fig. 2. The NCA represent the passive margin succession at the northern margin (in present-day coordinates) of the oceanic Meliata basin. The rift stage includes Permian to Lower Triassic terrestrial and shallow marine clastic rocks with evaporites (Haselgebirge Fm.) at the uppermost Permian–Lower Triassic boundary. Lower Triassic clastic rocks were replaced by 2 – 3 km thick shallow marine Middle and Upper Triassic carbonates laterally replaced by pelagic limestones (Mandl, 2000; Neubauer et al., 2000, Schmid et al., 2004; Fernandez et al., 2024). The drift stage started with Late Ladinian. A further Early Jurassic rift stage due to the opening of the Penninic Ocean resulted in drowning of the reefs and deepening of the depositional basins during Early Jurassic times. During Oxfordian, radiolarites were deposited followed by thick alternations of olistostromic limestone/marl succession (Oberalm Fm.) deposited at the aragonite compensation depth, which were replaced by marls and then by mixed siliciclastic/carbonatic flysch-like deposits in the Lower Cretaceous Rossfeld Fm. (Faupl and Tollmann, 1978; Eynatten et al., 1996; Eynatten and Gaupp, 1999; Krische et al., 2015). The flysch occurs only on the lower nappe, the Osterhorn nappe, which is part of the Staufen-Höllengebirge nappe. On the structurally higher Upper Juvavic nappe (also termed Berchtesgaden nappe) Upper Jurassic to Berriasian shallow water carbonates of the Plassen Fm. were deposited on the higher nappe, which are the source of the Oberalm olistostromic beds in the basin mentioned above. Shortening by folding and nappe stacking occurred at the Early/Late Cretaceous boundary (e.g., Schorn et al., 2013; Krische et al., 2015). The basic structure with Staufen-Höllengebirge, Lower Juvavic and Upper Juvavic nappes underneath the Salzburg-Reichenhall basin was formed after Rossfeld deposition and prior to the Gosau deposition. This deformation phase is followed by a phase of erosion under subtropical conditions, which denuded the section down to Upper Jurassic levels. Bauxites were locally deposited on the karstified relief.

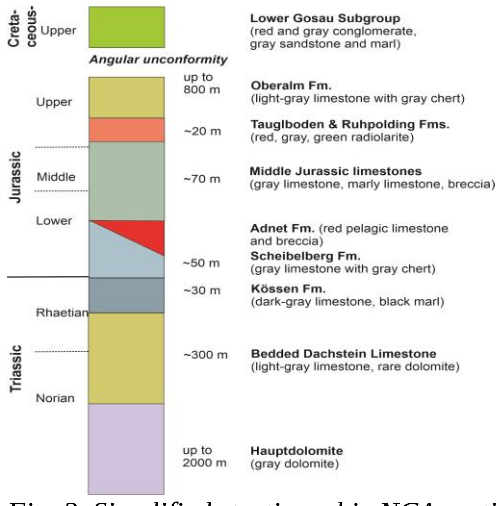

Fig. 2. Simplified stratigraphic NCA sections southeast and south of the eastern termination of the Salzburg-Reichenhall basin.

3. Salzburg-Reichenhall Gosau basin

The Salzburg-Reichenhall basin is exposed near to the northern boundary of the NCA and exhibits a basin fill ranging from Coniacian to Eocene (Egger and van Husen, 2009). Previous work concentrated on litho- and biostratigraphy (Plöchinger and Oberhauser, 1957; Papp, 1959; Hillebrandt et al., 1962; Herm, 1962; Herm et al., 1981a, b; Höfling, 1985; Leiss, 1990; Krenmayr, 1996, 1999; Egger et al., 2000, 2005, 2013, 2017). Egger et al. (2017) proposed the separation of the Upper Cretaceous to Middle Eocene Gosau Group from the overlying Middle-Upper Eocene to Oligocene Inntal Group. Structural studies were largely missing except a proposal for a pull-apart-type formation mechanism (Neubauer, 2002a).

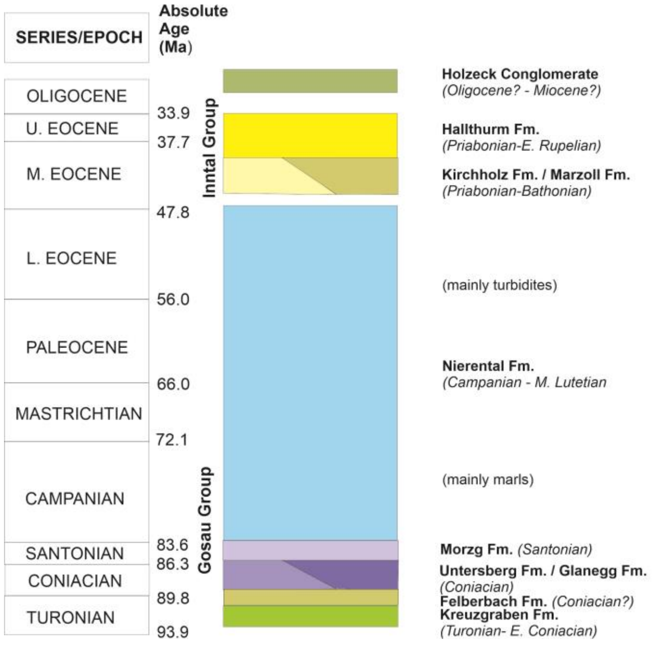

Fig. 3. Simplified stratigraphic section of the Salzburg-Reichenhall Gosau basin. Based on references mentioned in the text and new observations.

Outcrop conditions within the Salzburg-Reichenhall basin are poor due to scattered and isolated exposure of Late Cretaceous to Eocene successions deposits within the glacially over-deepened Salzach-Saalach valleys, which have their confluent to the north of the city of Salzburg (Fig. 1b). Several boreholes penetrated Gosau Group rocks underneath the Quaternary Valley fill (Hell, 1963; Del Negro 1979 and references therein; Wessely et al., 2016; Egger et al., 2024). Exposures are better along slopes of adjacent mountains (Fig. 1b) and the Lower Gosau Gosau Subgroup formations are exposed along eastern (Gaisberg) and western (Reichenhall) margins on the Staufen-Höllengebirge nappe and along the southern margin, on Untersberg and Lattengebirge blocks, which are separated by the Hallthurm graben. In the Hallthurm graben, the oldest strata are deposited on the Lattengebirge block representing a halfgraben, like the halfgraben on the Lattengebirge itself (Fig. 1b).

Younger, Eocene-Oligocene formations of the Inntal Group are exposed in the central and western sectors of the Salzburg-Reichenhall basin as well as within the Hallthurm graben and in some brooks at the western margin of the Untersberg massif like the Hallthurm valley south of Großgmain (G. Gmain in Fig. 1b).

4. Stratigraphy of the Salzburg-Reichenhall basin

A simplified composite Upper Cretaceous to Eocene Gosau Group section is shown in Figure 3, and important facies types are shown in Figure 4 for illustration. In the following, formations are described from bottom to top following the proposal of Egger et al. (2017) separating the Gosau Group from the overlying Inntal Group.

After a long-lasting period of erosion, during which bauxite and laterite were deposited both on the Staufen-Höllengebirge and Berchtesgaden nappes. The bauxite is well preserved and has been even mined, at the northeastern and northwestern base of the Untersberg (Günther and Tichy, 1979) and is enriched in some elements like Cr and Ni (Schroll and Sauer, 1964), potentially indicating an ophiolite detritus. After a pronounced angular unconformity (see Stop 1), the Kreuzgraben Formation Fm. (Coniacian?) is exposed with an estimated thickness of 50 to maximum 200 m at the western slope southern ridge of the Gaisberg to Elsbethen. It comprises reddish conglomerates and rare yellow-brownish carbonate sandstone intercalations. The conglomerate contains mostly well rounded, grain-supported carbonate pebbles with average diameters of 4 – 25 centimeters, and a component spectrum typical for the NCA (Fig. 4a, b). Few recent excavations for new buildings east of Glas quarter exposed well bedded half to several meter thick layers of conglomerate, red sandstone of subordinate reddish mudstone and yellowish marly siltstones (Fig. 4c, d). Conglomerates are polymictic and clasts reach max. 5 cm in size and are subrounded in shape (Fig. 4b). This lithofacies is termed as reddish sandstone-conglomerate lithofacies (Neubauer, in prep.). The conglomerates of the Lower Gosau Group form erosion-resistant ridges (Fig. 5a, b). In a recent study, two new lithostratigraphic entities were separated, the Felberbach Marl Fm. (Fig. 4e) and the overlying Aigen Conglomerate Fm. (Neubauer, in prep.). Their age is constrained by *Conchylia* (Tausch, 1886) and plant fossils (Ettingshausen, 1853). The Felberbach Marl Fm. is poorly exposed at the surface but was well described from abandoned coal exploration gallery (Fugger and Kastner, 1883), where it reaches a thickness of ca. 120 m (Fig. 6). The marls are overlain by well sorted conglomerates of the Aigen Conglomerate Fm. Both Kreuzgraben and Aigen Fms. contain exclusively clasts from the NCA, down to Lower Jurassic Adnet limestone and Norian Dachstein Limestone levels (Figs. 2, 6). The composition of conglomerates of the Lower Subgroup within the eastern Salzburg-Reichenhall basin testifies increasing compositional maturity as cherts represent a high proportion (Fig. 7). Two stages of the sedimentary evolution can be envisaged. In an early stage, fluvial deposits of a torrent in a subtropical climate were deposited (Fig. 8a). The environment gradually changed to lower energy, with increasing deposition of red mudstone in the reddish sandstone-conglomerate lithofacies representing fluvial plane deposits. Then, an aquatic, obviously cyclic, lacustrine or more likely marine, environment developed. Cyclicity is not uncommon in early Late Cretaceous (Hames et al., 2020; Sames et al., 2020). A similarity to brackish to non-marine aquatic deposits in the Tiefenbachgraben east of the Wolfgangsee seems likely (Ösi et al., 2001).

The Untersberg Fm. (Untersberg "Marmor") is exposed at the northern slope of the Untersberg, is deposited on the late Kimmeridgian-Berriasian Plassen Limestone above a thin reddish lateritic breccia and comprises above layer of a grayish conglomerate/breccia with a thickness of several tens of meters (ca. 40 m) (Kieslinger, 1964; Leiss, 1988). (Fig. 4f). This formation is well exposed in several quarries as the rock is poor in joints and therefore used as building and decoration stone and for sculptures (Kieslinger, 1964). Bioclastic detritus include hippurites, radiolites, bryozoans, foraminifera and rhodophyta (Leiss, 1988a and references therein). The Coniacian age is mainly based on foraminifera. Overlying grayish marls are rich in foraminifera and are Upper Coniacian to Lower Santonian in age, although no continuous section is known except in the Kühlbach area. On the northeastern Lattengebirge block, a hippurite reef, locally called the Krönner reef, is exposed (Höfling, 1985). Similar reefs are considered as the source for the bioclasts in breccias of the Untersberg Fm. (e.g., Risch, 1988; Leiss, 1988a).

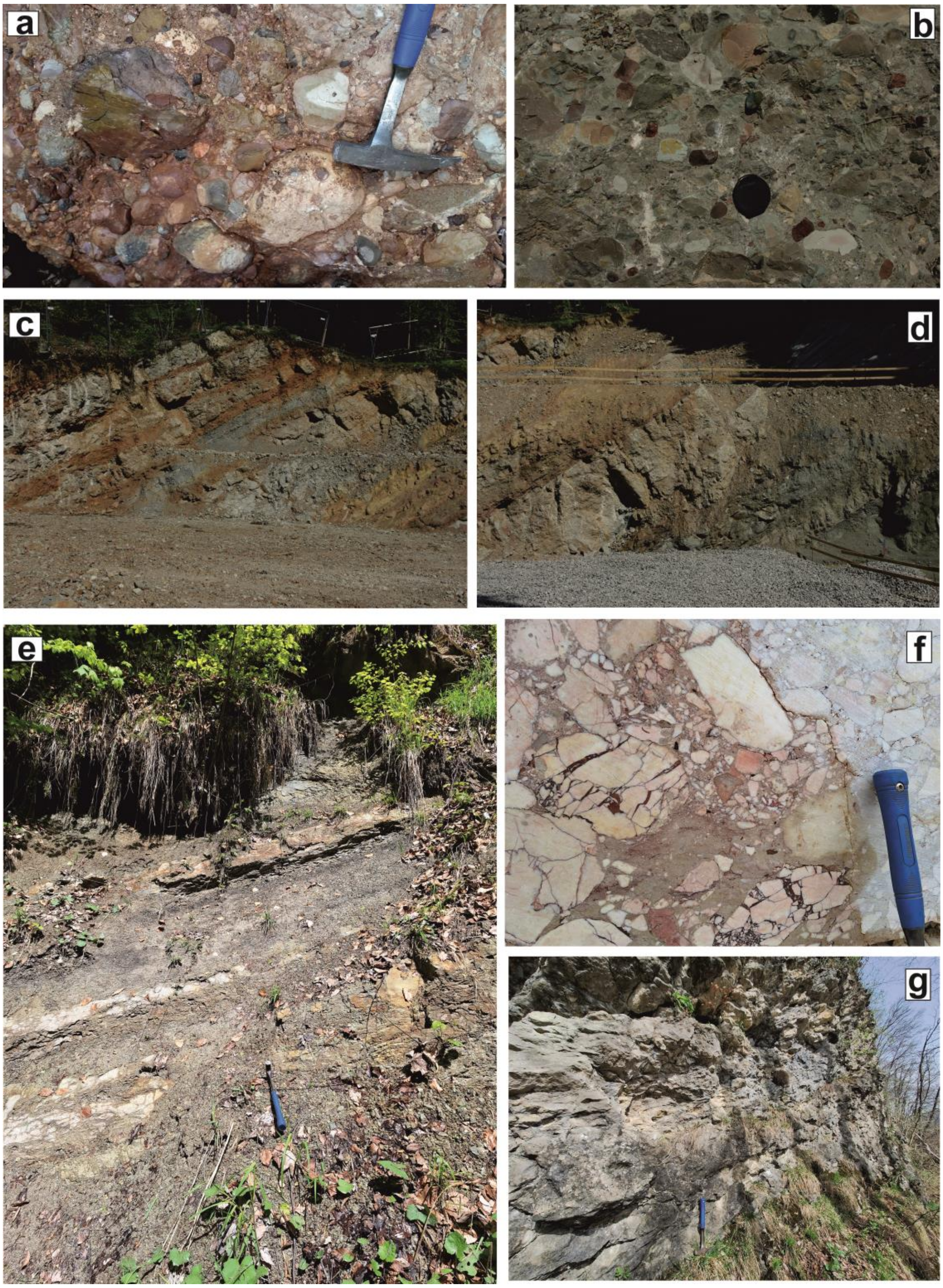

Fig. 4. Photographs of lithologies and outcrop-scale sedimentary structures of various lithofacies types of the Gosau Group exposed within the Salzburg-Reichenhall Gosau basin. (a) Basal conglomerate. (b) Well sorted polymictic conglomerate bed of the reddish sandstone-conglomerate lithofacies. (c) and (d) Excavation due to constructions exposed the reddish sandstone-conglomerate lithofacies in Glas (not accessible anymore). (e) Marl of the Feldberbach Fm. (exposure M-2 in Fig. 5b). (f) Breccia of the Untersberg Fm. in the Kiefer quarry. (g) Bedded limestones of the Glanegg Fm. (Morzg).

Fig. 5. Digital terrain models (DTM) showing the distribution of lithologically strong ridges of conglomerate/sandstone and weak lithologies, the later interpreted as marls. (a) Rauchbühel area. Most ridges are discontinuous representing the infill of a broad valley with an anastomosing or meandering river. Note the subparallel continuous ridges R11–R14, which are explained as shore facies. (b) DTM of the Felberbach catchment. Note weak lithologies in the underground interpreted as marls (Felberbach Fm.) M – major marl exposure along the Felberbach. Also note also that the supposed stratigraphic base of marls is a quartet of four subparallel ridges interpreted as shore facies or delta plane.

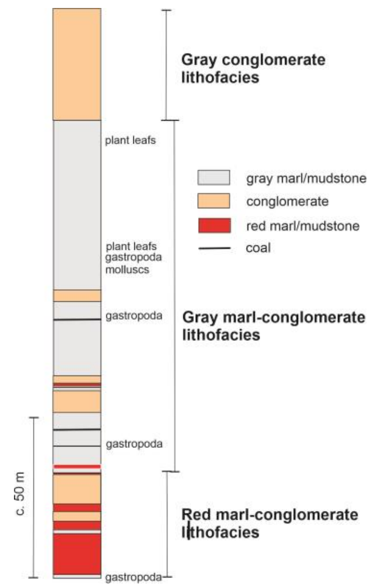

Fig. 6. Reconstructed section of the Gänsbrunn gallery using the well described gallery section of Fugger and Kastner (1883). For the location of the gallery, see Fig. 5b.

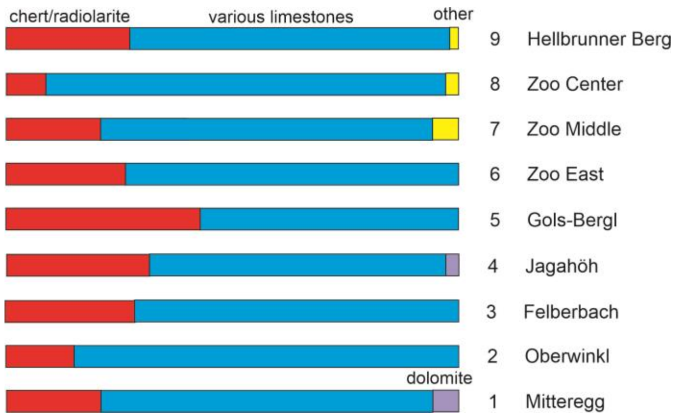

Fig. 7. Composition of conglomerates of the Lower Gosau Group in the eastern part of the Salzburg-Reichenhall basin. The sequence is in the lithostratigraphic order (top to base).

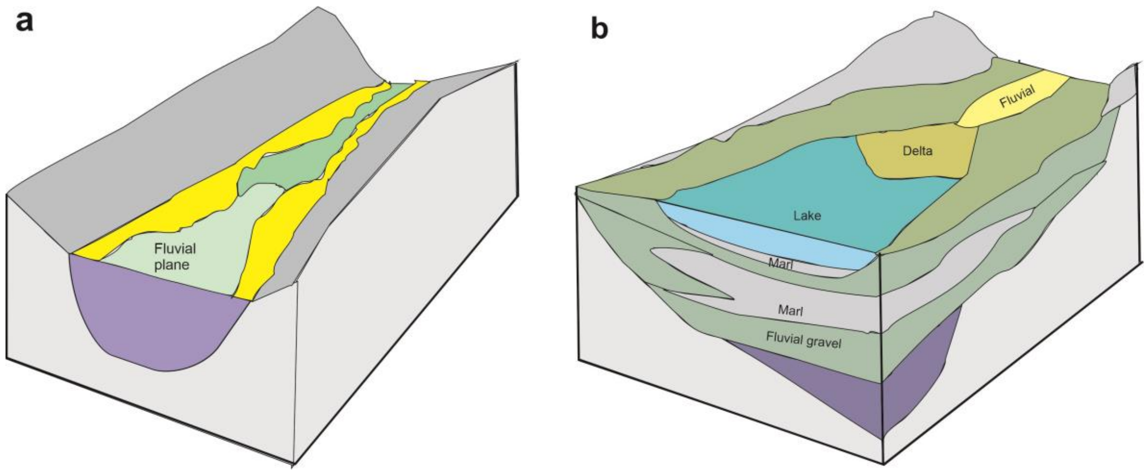

Fig. 8. Sedimentary models of basal formations at the western Gaisberg slope. (a) Initial stage with deposition of coarse conglomerates in a torrent. (b) Later stage with cyclic deposition of marine(?) marls and terrestrial conglomerates implying climate-modulated cyclicity.

The Glanegg Formation (Lower Coniacian to Lower Santonian) is exposed in the northern foreland of the Untersberg and is separated by the Glanegg fault from the Untersberg massif (Fig. 1a). The Glanegg Formation includes from base to the top: grayish hemipelagic marls with intercalations of sandstones and pebbly sandstones and Coniacian neritic limestone (Fig. 4g) (Egger et al. 2013). An olistostrome bears Triassic Hallstatt Limestone clasts and occurs in the southernmost Glanriedel (E of Fürstenbrunn). Macrofossils include bivalvia, gastropoda, and especially inoceramen. The shallow water deposits are overlain by bathyal marls of the Morzg Fm., which is defined by Egger et al. (2013). The marls of the Morzg Fm. include planktonic assemblages with foraminifera, calcareous nannoplankton and dinoflagellate cysts with middle-late Santonian age.

The overlying formation is referred as Nierental Fm. according to the type locality in the Nierental in the Hallthurm graben at the western slope of the Untersberg massif (Fig. 1b). The Nierental Fm. includes greenish-reddish marls of Late Cretaceous age and grades upwards into marls with decimeter-bedded Paleocene to Eocene turbidites with shale intercalations (Krenmayr, 1996, 1999). The Paleocene level also contains Late Paleocene bentonites (Egger et al., 1995, 2005, 2009; Egger and Uchmann, 2018).

Overlying the Nierental Fm., all further strata were recently compiled as Inntal Group (Egger et al., 2017), which seems to be separated by a disconformity and break in sedimentation from the underlying Gosau Group. The Inntal Group includes the Marzoll, Kirchholz and Hallthurm formations and range in age from Bartonian to Priabonian. Some representative lithologies are shown in Fig. 9. The Marzoll Fm. is overlying the Nierental Fm. and represents a deep-water succession with turbiditic siltstone and sandstone, gray colored mud flow and debris flow deposits (Egger et al., 2017) (Fig. 9a, b). In terms of fossils, substantial reworking of Early Cretaceous to Lutetian planktonic assemblages with the youngest one with calcareous nannoplankton diagnostic for the Bartonian and Priabonian (Egger et al., 2017). The Kirchholz Fm. include detrital limestone with corals and oysters with a marlstone layer planktonic foraminifera of a lower to middle Lutetian age and is interpreted as a reef-lagoon depositional system (Fig. 9c, d) (Hillebrandt 1962; Darga, 1990, 1992; Zágoršek and Darga, 2004). The Kirchholz Fm. is overlying Upper Cretaceous red marlstone.

According to Egger et al. (2017), the overlying Hallthurm Fm. includes limestone containing small quartz pebbles and a siliciclastic sand fraction, siliciclastic sandstone beds are interspersed within the limestone representing mixed carbonatic-siliciclastic facies.

Fig. 9. Photographs of outcrop-scale sedimentary structures of various lithofacies types of the Inntal Group exposed within the Salzburg-Reichenhall basin. (a) Dark mudstone and (b) carbonatic sandstones in the Marzoll Fm., Kohlgraben. (c) Nummulite sandstone of the Kirchholz Fm., Großgmain. (d) Rudstone with bryozoa and corals of the Kirchholz Fm., Eisenrichterstein.

The Holzeck Conglomerate, a new formation, is exposed west of Fürstenbrunn and is here assigned as uppermost part of the Inntal Group. Previously, it was mapped by Seefeldner (1957) and Prey et al. (1969, as “Interglacial conglomerate” and the richness of metamorphic rocks was already recognized. The conglomerate is fully lithified. Clasts show a very good roundness, foliated metamorphic clasts are often elongated. The largest boulders reach ~30 cm, the average grainsize is between 6 – 8 cm, nearly all clasts are larger than 1 cm. The matrix is sand-grained, although difficult to find in outcrops. These types of clasts are likely sourced in the Ötztal and Silvretta basement complexes.

5. Sandstone composition

The sandstone composition was studied in a number of samples from Kreuzgraben, Glanegg and Nierental Formations using the Dickinson-Gazzi method (Fig. 10 for typical sandstones of the turbiditic Nierental Fm.). All are hybrid sandstones, with dominating carbonate clasts and with a carbonate cement.

Thin sandstones intercalated in thick conglomerates of the Kreuzgraben Fm. comprise nearly exclusively carbonate framework constituents in a calcite cement. Carbonate clasts include micritic limestone, calcite monocrystalline calcite grains and carbonate bioclasts. The siliciclastic content of framework constituents varies from ca. 1 to maximum 20 percent. These include metamorphic polycrystalline quartz, chert, subordinate monocrystalline quartz grains, shale-type lithic clasts and volcanic clasts, comprising vitric chards and microcrystalline clasts. Opaque minerals, tourmaline and brownish amphibole as heavy minerals. One outcrop on the road ca. 1 km east of Glasenbach contains serpentinite clasts, brownish spinel, plagioclase, white mica, greenish amphibole and chlorite grains, as well as phyllite and siltstone clasts (see also Wagreich et al., 1995).

Sandstones of the Glanegg Fm. contain similar carbonate clast-rich sandstones with a calcitic matrix. The carbonate framework constituents include again micritic limestone, calcite monocrystalline calcite grains and carbonate bioclasts. The siliciclastic content is maximum ca. 5 percent and includes monocrystalline quartz grains, chert and polycrystalline quartz. Further rare components comprise white mica, K-feldspar, opaque minerals, and tourmaline. Volcanic clasts occur in few samples with (i) doleritic fabrics and (ii) angular chards with micro-crystalline quartz/feldspar. These fragile angular chards argue for contemporaneous volcanism.

Sandstones from the Eocene formations of the Inntal Group similarly comprise the same carbonate-rich framework constituents and a carbonate matrix, with contents of siliciclastic components of 5 to 30 percent. The bioclastic components are mainly echinoderm remainders and few gastropods. The siliciclastic contents are mostly subangular and are dominated by monocrystalline and polycrystalline quartz, some plagioclase and K-feldspar, white mica, rare biotite, chlorite, rutile, opaque, tourmaline grains and volcanic clasts. The latter comprise such with a doleritic fabric and such with a microcrystalline quartz/feldspar-rich fabric.

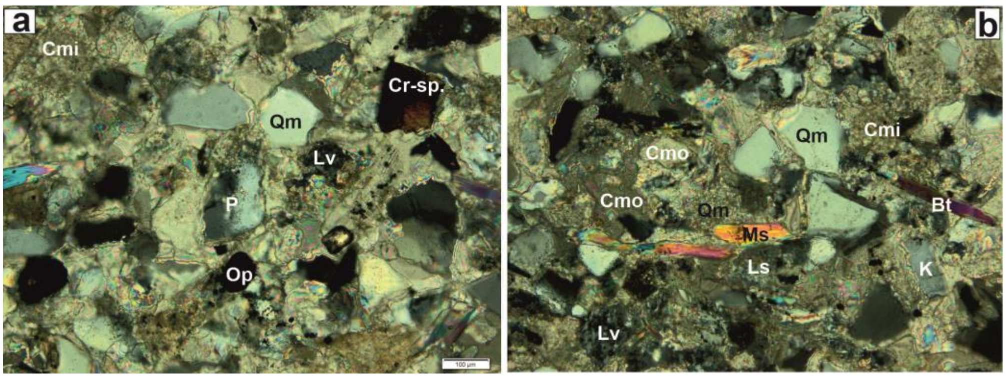

Fig. 10. Microphotographs of turbiditic sandstones of Paleocene-Eocene Nierental Fm. of the Salzburg-Reichenhall Gosau basin. Bt – biotite, Cmi – micritic carbonate, Cmo – monocrystalline, Cr-Sp – Cr-spinel, K – K-feldspar, Ls – sedimentary lithoclast, Lv –volcanic lithoclast, Ms – muscovite, Op – opaque mineral, P – plagioclase, Qm – monocrystalline quartz.

Detrital white mica from a sandstone sample of the Paleogene part of the Marzoll Fm. was studied. Six single-grain total fusion ages ($^{40}Ar/^{39}Ar$) range from 86 to 104 Ma, and two are older and include 151±1 and 186±Ma. The Cretaceous ages indicate that mainly amphibolite facies-grade metamorphic units of the exhuming Cretaceous orogenic wedge contributed to the basin fill. The two older ages (151±1 and 186±Ma) may represent so-called mixed ages.

6. Structure

The northern margin of the NCA is a thrust fault, which stretches E–W north of the Hohenstaufen, and likely corresponds to the ISAM fault (unclear course in this area), is then displaced by the Saalach fault with a sinistral displacement of ca. 5.5 km and continues then ENE on the northern side of the city hills (Hohensalzburg. Kapuzinerberg and Kühberg) of Salzburg (Fig. 1b). As already mentioned, the formation of the nappe boundary of the Staufen-Höllengebirge and Berchtesgaden nappe must be prior to the deposition of the Salzburg-Reichenhall basin. In the following, the principal structures delimiting the Salzburg-Reichenhall basin are strike-slip and normal faults along margins (Fig. 1b) and are described from north to south.

On the northern side of the Salzburg-Reichenhall basin, several ENE-WSW striking steep strike-slip faults are exposed (Fig. 1b). Two E-trending faults creates a graben structure mainly filled with marls of the Nierental Fm. and conglomerates of the Kreuzgraben Fm. at the northwestern slope of Gaisberg. Together with the thrust fault along the northern base at the structural base of the Northern Calcareous Alps, the Gersalm fault creates a small ridge of massive Triassic limestone and dolomite successions. The northern fault (Gersalm fault) continues to the southern slope of the Kapuzinerberg, where it also juxtaposes Triassic (N) versus Gosau (S) sediments. Recently, Egger et al. (2024) found Campanian marls of the Nierental Fm. in recent boreholes at Nonntal south of this fault. The area with Nierental Fm. in the underground extends from Hohensalzburg via Kapuzinerberg and Kühberg to Nockstein (Fig. 1b). The southern, Kapaunberg fault has a major N-directed reverse component. The poorly exposed steeply S-dipping and E–W trending Zistel fault shows a sinistral strike-slip and a top-S normal component of displacement.

Close to the southern margin of the basin, Egger et al. (2017) introduced the Glan fault separating the Nierental Fm. from the Inntal Group. Locally, evaporites of the Haselgebirge Fm. are exposed along this fault underlining its importance. Although poorly exposed, a significant strike-slip component and N-down components could be deduced from the map-scale structure and fault-striae data. Further south, the ENE-trending Glanegg fault separates the Untersberg massif with the Untersberg Fm. from other formations of the Gosau Group exposed to the north. The sense of displacement includes an apparent normal component as the fault juxtaposes the Coniacian Untersberg Formation against the mostly S-dipping Santonian-Eocene Nierental Formation. A major apparent sinistral strike-slip component is deduced, too, also based on fault-striae data. The Glanegg fault has no obvious extension to the east of the Salzach valley as N–S striking Triassic and Jurassic successions do not show any significant offset in the supposed lateral extension of the Glanegg fault (Fig. 1b) (see also maps of Egger and van Husen, 2003; Plöchinger, 1987).

On the Untersberg and Lattengebirge blocks, several further faults with an entirely different orientation are exposed. These include from east to west (Fig. 1b): On the Untersberg block, the NNW–SSE trending Brunntal fault separates massive Dachstein Limestone from the Plassen Limestone and overlying Untersberg Fm. The apparent offset is W-down and/or sinistral displacement. The Klingeralm fault has a similar orientation and shows an E-down and/or a dextral apparent displacement. The NW–SE trending Hirschangerkopf fault juxtaposes massive Dachstein Limestone from Plassen Limestone/Gosau Fm. with an apparent NE-down displacement. The Untersberg block is juxtaposed from the Hallthurm halfgraben by the East Hallthurm fault with a likely superposed displacement with several displacement stages. In the present stage, it juxtaposes the massive

Dachstein Limestone in the NE to the Eocene Inntal Group, whereas, on the western margin of the Hallthurm Halfgraben, the Coniacian Krönner reef is onlapping on the Lattengebirge Block.

On the central Lattengebirge block, the Lower Gosau Group is onlapping, whereas on the eastern side two major subvertical normal faults juxtapose the Gosau Group to the massive Dachstein Limestone. Two segments can be distinguished: (1) an apparently older N-S trending one in the southern part, and (2) NNW-SSE trending one in the northern part. Both segments show apparent W-down displacement.

An important N-S trending fault is exposed east of the Listsee and Grubstein NW of Bad Reichenhall and separate NCA basement rocks from poorly exposed breccia and conglomerate of the Kreuzgraben Fm. This fault is here termed Grubstein fault and interpreted as a synsedimentary normal fault and rocks as escarpment breccia. The Grubstein fault seems to delimit the E-trending, here termed Nonn fault, which separates the Hochstaufen Block from breccias of the Salzburg-Reichenhall basin (Fig. 1b). This fault seems to be a steep strike-slip fault although a major normal offset cannot be excluded.

In the Salzburg-Reichenhall basin, several distinct areas with distinct dip of strata can be distinguished. In the Gaisberg area, Kreuzgraben to Aigen formations dip generally to the W to NW. The main part Upper Cretaceous Gosau Group in the central part of the basin, dip generally to the N or NNW, with the Nierental Fm. in the northern part up to the Gersalm fault. The area between Glanegg and Glan faults is composed of marls of the Nierental Fm. and in its eastern part, these dip to the south, here interpreted as the relic of the halfgraben infill.

There are not many other outcrop-scale structures within the Gosau basin fill beside fault and striae, mainly along faults (Fig. 11b, c). The Inntal Group is affected by gentle folding around an ENE-trending fold axis, the main part between B.Gmein and Fürstenbrunn, the Inntal group strata form WSW-ESE syncline. Mesoscale folds are rare ((Fig. 11a). The Hallthurm graben represents a NW plunging syncline, too, delimited in the northeast by the mentioned inverted East Hallthurm fault, which was first a normal, then a reverse fault. In a few cases, evaporitic Haselgebirge is observed along faults (Fig. 11d), but it is also underlying the southwestern Salzburg-Reichenhall basin (Schauberger et al., 1976).

Further structures include pressure solution seams and calcite filled, steep extension veins. Bauxite and laterite filled extension veins are oriented E–W indicating N–S extension. Subvertical calcite-filled extension veins show a preferred orientation over the area. In the Gaisberg area, two sets can be distinguished: steeply NNE trending and steeply WNW-trending ones. These shows two post-depositional compression directions, NNE–SSW and WNW–ESE. The earlier set with ca. N-trending extension veins is also common in the Glanegg Formation. The Eocene successions east of Großgmain comprises two sets: dominant NW-trending and subordinate NE-trending ones. The well exposed Untersberg Fm. show three sets of extension veins: NE-trending, E-trending and NW-trending ones.

Fig. 11. Photographs of outcrop-scale tectonic structures within the Salzburg-Reichenhall Gosau basin. (a) Example of a rare recumbent fold with subhorizontal axial plane fractures (Eitelbach). (b) Normal fault in Nierental Fm. (c) Strong cataclastic overprint in the Nierental Fm. with superimposed fault sets (Eitelbach). (d) Evaporitic Haselgebirge Fm. along the Glanegg or Glan fault (Eitelbach). For the widespread distribution of the Haselgebirge Fm. in the Reichenhall area, see Schauberger et al. (1976).

7. Deformation stages based on map-scale structures and paleostress patterns

Map-scale faults are evaluated from existing maps (Egger and van Husen, 2003; Prey et al., 1969; Pavlik, 2009). In addition, slickenside and striation data were collected at ca. 50 stations between the western Osterhorn Mts. and Reichenhall, respectively in the Lattengebirge. In several outcrops, superimposed sets of slickensides and striations indicate a polyphase reactivation of these faults. The relative sequence is based on overprint, which is well observed in several key outcrops. These include:

Deformation stage D_1 is represented bauxite-bearing dykes/veins indicating N–S extension.

Deformation stage D_2 is represented by ENE–WSW extension along the numerous NNW–SSE trending normal faults indicating and considered as an initial stage of Gosau basin formation. Some of these faults, e.g., East Hallthurm and Grubstein faults, are likely associated with escarpment breccias although the field relationships are poorly exposed. It seems that this system is also associated with steep ENE- to E-trending oblique-slip faults showing the transtensional nature of this system. Fault-striae data in Triassic-Jurassic country rocks often show rather the conjugate fault rather than the main fault system. In any case, this is likely the main fault system responsible for the pull-apart type opening of the Salzburg-Reichenhall basin.

Deformation stage D_3 is based on fault and striae data and map-scale faults, mainly are NNW- and SSE-dipping normal faults showing a clear NNW–SSE extensional paleostress tensor. This stage is considered as an advanced stage of the Gosau basin formation responsible for the widening and subsidence, e.g., during the deposition of Morzg and Nierental formations.

Deformation stage D_4 includes N–S and E–W trending conjugate strike-slip faults due to NE–SW transpressional compression. Associated slickensides are spectacularly exposed along southern slope of the Kapuzinerberg within Salzburg city. A later, subordinate overprint is dextral, and later sinistral again and are related to Oligocene-Miocene overprint. **Deformation stage D_5** includes numerous NW- and NE-trending conjugate faults and are explained to result from ca. N–S to NNW–SSE transpressive compression.

Deformation stage D_6 includes many late-stage steep strike-slip faults are due E–W transpressive compression.

Few further faults record ca. ENE–WSW extension, respectively NW–SE transpressional strike-slip paleostress tensors and are uncertain in the assignment. The orientation data of deformation stages D_4 to D_6 are similar in orientation to proposed by Peresson and Decker (1997), Schweigl and Neubauer (1998) and Schorn and Neubauer (2012) in the wider surroundings.

8. Mönchsberg Conglomerate

Recently, the Nagelfluh conglomerate in Salzburg center as exposed on Mönchsberg and within the Salzach Valley in the south was formalized as Mönchsberg Conglomerate or Mönchsberg Nagelfluh (van Husen and Reitner in Piller et al., 2022). The well lithified and thick-bedded conglomerates dip with 20–30° towards W to NW, and conglomerates contain thin layers of grit. The conglomerates interpreted as foreset-beds of a Gilbert-Type delta deposit, which formed in a glacial lake at the end of the Mindel glaciation (Termination V) (van Husen and Reitner in Piller et al., 2022). Other hills within the Salzach valley, like the Hellbrunnerberg, expose similar deposits of Mönchsberg Conglomerate. Detailed studies in several outcrops, e.g., at the Hellbrunnerberg, show that fault structures affected the Mönchsberg Conglomerate implying Quaternary tectonic deformation (see, e.g., Stop 5, Steintheater).

9. Discussion

9.1. Development of the Salzburg-Reichenhall basin

Separated by an angular unconformity and bauxite lenses, the Upper Jurassic Plassen Limestone is overlain by Upper Cretaceous strata of the Gosau Group. These relationships indicate a significant pre-Gosau northward tilting of Jurassic strata at the Untersberg and terrestrial erosion, following the pre-Gosau, Austrian tectonic phase. Furthermore, sedimentary structures like bauxite-filled dykes and structural evidence argue for ca. N–S extension during the initial stage of the Gosau basin subsidence. Upper Cretaceous Gosau strata are dominated by carbonate detritus derived from underlying Mesozoic strata implying a carbonate source in the south of a marine basin with hippurite reefs in the south. In addition, lateral fluvial inflow is coming from the east and southeast (model in Fig. 8). The Glanegg Fm. is interpreted as a shallow marine environment, which deepens to the north, where the Morzg Fm. was deposited. During Campanian, basin deepening occurred in the Nierental Fm., and this depositional environment prevailed until the Early Eocene, over a long indicating long-lasting tectonic quiescence. The mostly southward or subhorizontal dip of Glanegg and Nierental Formations also indicates a halfgraben-like tilting of Santonian-Eocene strata to the S to SW, towards the Triassic and Jurassic strata, and the presence of a normal or sinistral transtensional fault in between. After a sedimentary break from late Lutetian to early Bartonian, the Inntal Group was deposited, which is sourced again by Austroalpine basement area, which was largely overprinted by Cretaceous metamorphism as detrital white mica with Cretaceous ages indicate an Austroalpine basement source. Transport indicators in siliciclastic turbiditic sandstones argue for SW-directed sediment transport during Eocene. Interestingly, although close to the northern margin of the NCA thrust front, the internal deformation of the Inntal Group strata is weak.

The question arises whether the Salzburg and Reichenhall basins have relationships to other Upper Cretaceous to Eocene-early Oligocene basins. The northern part is affected by the Oligocene-Miocene Innsbruck-Salzburg-Amstetten (ISAM) fault named and proposed by Egger (1997) and Laubscher (1996). Ortner et al. (2006) proposed a 40 km sinistral offset along the ISAM fault although the exact course is uncertain between Oberaudorf and W of Salzburg. The ISAM fault is displaced by the Saalach fault, which enters the Salzburg-Reichenhall basin SW of Bad Reichenhall and potentially diverges to several branches. The main branch of the Saalach faults delimits the Inntal Group to the NW. The ISAM fault is on the northern side of the Kapuzinerberg, and the Gersalm, Kapaunberg and Glan faults represent further strike-slip dominated faults along the ISAM fault system. Assuming that the Inntal Group within the Salzburg-Reichenhall basin is an extension of the Oberaudorf basin, the branching ISAM strike-slip system explains the relationship with the Oberaudorf basin. This would also explain the stratigraphic relationships of the Inntal Group in the Salzburg-Reichenhall basin with Oberaudorf basin (see Ortner and Stingl, 2001; Egger et al., 2017). Both on the southern and northern side of the Eocene-Oligocene Oberaudorf basin, Gosau deposits occurs. From the northern side the Kössen Gosau is that part, which could have been displaced by the sinistral ISAM fault from the northern side of the Salzburg-Reichenhall basin to the southwest.

9.2. Structural model

The data presented above reveals that formation of the Salzburg-Reichenhall Gosau basin can be explained as a result from a fault overstep in a strike-slip fault system respectively wrench corridor. The leading faults are ENE–WSW trending master faults along northern and southern margins (Nonn and Glanegg faults), and normal faults in the western margin and in Untersberg and Hallthurm blocks and in the Hallthurm Graben. Upper Cretaceous stratigraphic sequences are exposed along western, eastern and southern margins, Paleocene-Eocene sequences in southern center. This suggests that initial subsidence was more strongly in the west than in the east, and a sort of roll-over structure has been formed in western sectors of the basin. We interpret the Salzburg-Reichenhall basin as pull-apart basin that opened along a left-hand overstep along a sinistral master fault system during the Late Cretaceous. Although partly obscured by Miocene reactivation, the Glanegg fault is a sinistral strike-slip fault in the North of the Untersberg Block and the Nonn and Gersalm faults may represent this overstep system.

9.3. Source of the ophiolite detritus

The ophiolite detritus preserved in sandstones of the Glasenbach Conglomerate suggests the presence of a nearby source as their volcanic components are fragile and would decompose during a long transport. Similarly, serpentinite clasts and abundant chromian spinel have been described by Wagreich et al. (1995) and Wagreich (1993b) from this and other Gosau-type basins. The presence of such detritus and the Cr-Ni enrichment in bauxite suggest a nearby ophiolitic source, which should have been located to the east or southeast of the Salzburg-Reichenhall basin.

9.4. Source of volcanic components

Rare volcanic detritus occur in several stratigraphic levels within the Salzburg-Reichenhall basin. Fragile volcanic chards occur both in Upper Coniacian Glanegg Fm. (this study) and in the Upper Paleocene sectors of the Nierental Fm. (Egger et al., 1995). For the Coniacian, a nearby but volumetrically unimportant alkaline mafic source is known in western sectors of the Northern

Calcareous Alps (Trommsdorff et al., 1990) and cannot fully excluded as similar, contemporaneous rocks are also exposed in Mecsek Mts. in Hungary. Upper Cretaceous, ca. Coniacian to Campanian, volcanics and shallow-level plutons are widespread in the Carpathian-Balkan sectors of the Late Cretaceous orogenic belt and known there as banatite (e.g., Neubauer, 2002; Gallhofer et al., 2015). Interestingly, volcanic rocks are there always associated with Gosau-type basins. We speculate therefore on a banatitic source for these volcanic clasts. This interpretation is supported by the fact that the NCA have been located both in Late Cretaceous much more to south (Kázmer et al., 2003), in the realm of SW trade winds. This would support an eastern origin of volcanic components.

Paleocene bentonites of the Nierental Fm. were related to explosive volcanism in the North Sea area (Egger et al., 2005).

Description of stops

The stops of excursion are described from east to weat, but stops in the central northern part are described at the end because these concerns mostly the Neogene reactivation along strike-slip faults. Not all stops will be visted during the one-day excursion, but their inclusion should allow interested people to see more. Some stops are difficult to reach with a major group, and will be not visited during the Pangeo 2024 excursion. The location of stops can be found on Fig. S-1. The figures related to stops are assigned with "S", and numbering starts with S-1. For the excursion, the use of the following geological maps is recommended: Prey et al. (1969), Plöchinger (1987), Risch (1993), Egger and van Husen (2003) and Pavlik (2009).

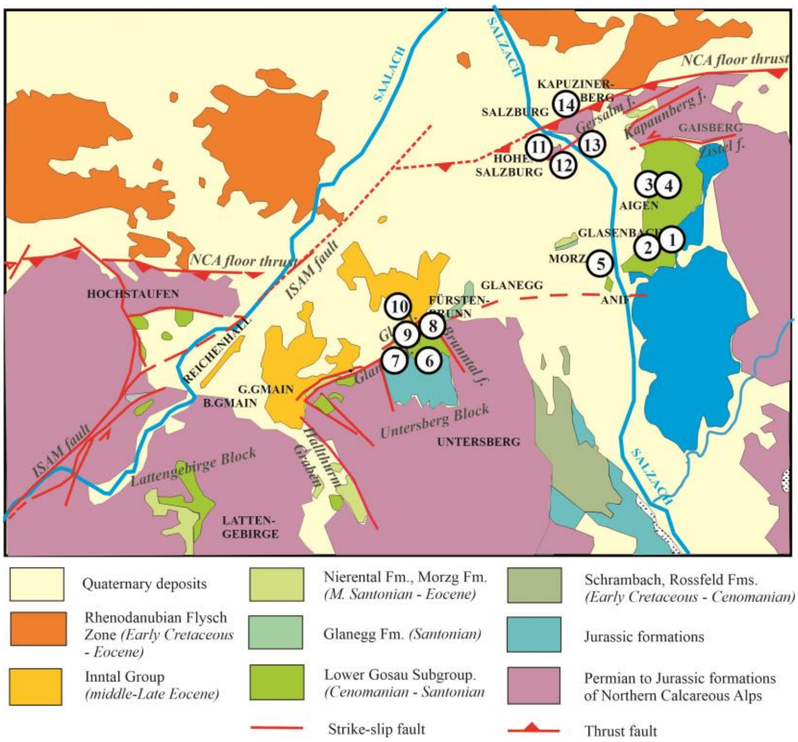

Fig. S-1. Locations of stops described in the field guide.

Stop 1: Glasenbach: Gosau base angular unconformity

N47° 46´ 03.6´´, E 13° 05´ 58.8´´, 545 m

The outcrop exposes reddish conglomerates of the Kreuzgraben Fm. overlying the Middle-Upper Jurassic radiolarites of the Tauglboden Fm. with an angular unconformity (Fig. S-2a, b). The Upper Jurassic to Lower Cretaceous formations are entirely eroded indicating a major break in preserved sediments. On the map-scale, the Jurassic formations are folded underneath the unconformity indicating the pre-Gosau deformation phase. The clasts of the conglomerate have a size between 10 and 20 cm and are coated by lateritic material (Fig. S-2c, d). The components are exclusively limestones, mostly Plassen and Dachstein Limestones, and subordinate cherts. Dolomite clasts (e.g., Hauptdolomite) were not found.

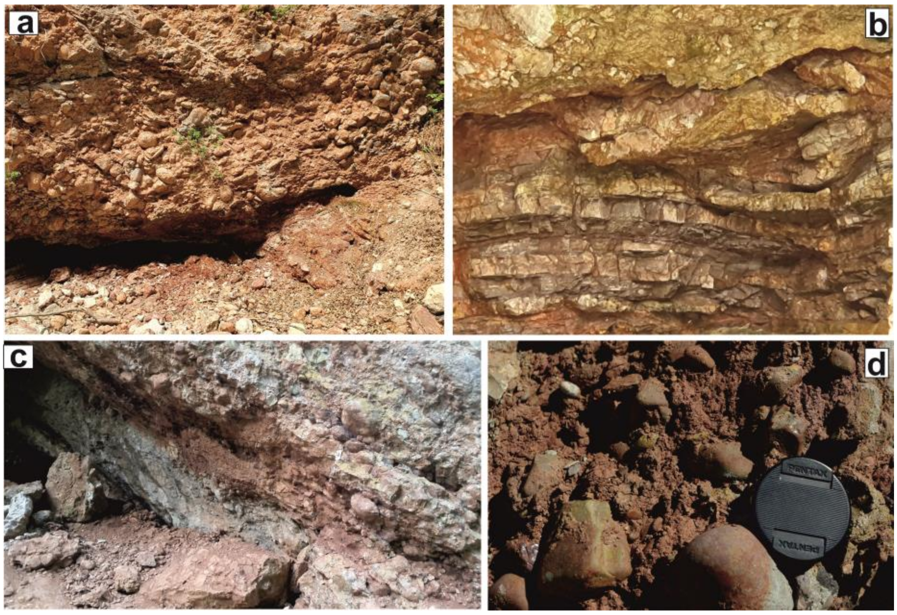

Fig. S-2. (a) Basal angular unconformity between the Tauglboden radiolarite and the basal Kreuzgraben Conglomerate. Note the angular unconformity is apparent as a the normal fault displaces the hanging Kreuzgraben Conglomerate. (b) Angular unconformity. (c) Thick bedded, poorly sorted conglomerate with clasts with red coating. (d) Red coated pebbles in a lateritic, red matrix.

Stop 2: Near Glasenbach entrance

N47° 46´ 03.9´´, E 13° 05´ 49.5´´, 531 m

Red Kreuzgraben Conglomerate. The clast-supported Kreuzgraben Conglomerate contains a ca. 2 m thick lens of reddish mudstone and laterite (Fig. S-2c). The clasts have an intense red coating and reach a size of 40 cm, and show a grain-supported fabric. The layer above the red mudstone lens shows a coarsening upward cycle.

Stop 3: Aigen, Felberbach: Conglomerates of the Lower Gosau Subgroup

N47° 47´11.3´´, E 13° 05´ 36.8´´, 487 m

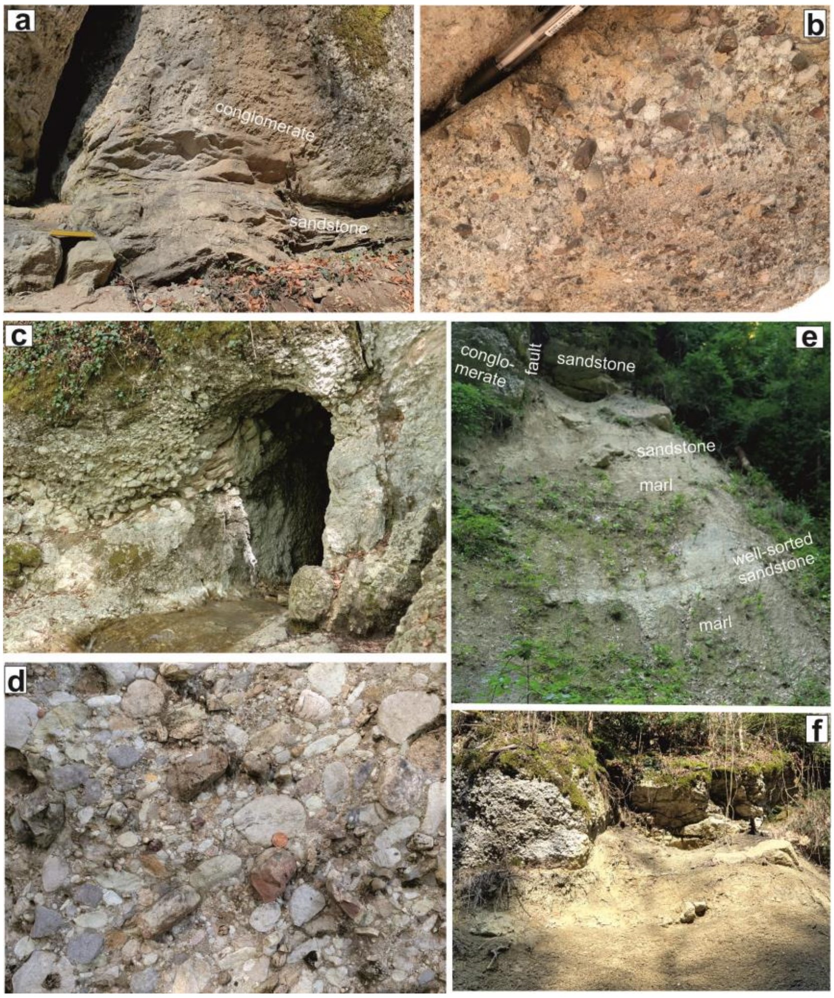

Fig. S-3.Outcrops along the footpath in the Felberbach gorge exposing fluvial conglomerate. (a) Conglomerate channel fill overlying bedded sandstone. (b) Typical carbonate-cemented conglomerate with abundant rounded chert and radiolarite clasts. (c) Fluvial facies with coarse-grained, upward fining conglomerate and sandstone. (d) Coarse conglomerate. (e) Ca. 10 m thick marl exposure and (f) upper part of the same outcrop with a normal fault.

The outcrop exposes thick-bedded clast-supported conglomerates (Fig. S-3a). The clasts are well-rounded and have grain-size varies between 2 to 8 cm. The components are exclusively components from the Northern Calcareous Alps, and limestones dominate. The proportion of various cherts is high and reaches ca. 20 percent, indicating a high compositional maturity (Fig. 6). Furthermore, thin bedded sandstones are exposed and are cut by scour-and-fill structures of conglomerates representing channel fills (Fig. S-3a).

Stop 4: Aigen, Felberbach: Gray marl

N47 47´ 15.50´´, E13 05´ 47.93´´ 536 m

The outcrop on the northern slope of the Felberbach exposes more than 10 m thick grayish-brownish marls, which are interrupted by a layer of carbonatic sandstone with well-rounded clasts (Fig. S-3e, f). The marls are overlain by a meter thick sandstone, which is cut by a normal fault (Fig. S-3e, f). Preliminary biostratigraphic results of Michael Wagreich indicate a Santonian age, although numerous Early Cretaceous resdimented elements were found, too. A further outcrop several tens of meters upstream exposes similar marls, too, which also contain plant relics and a piece of wood. Together with reconstructed ca. 130 m marl section from the abandoned Gänsbrunn coal gallery (Fig. 6) (Fugger and Kastner, 1983), these indicate the presence of thick marls beds within the Gosau strata on Gaisberg (Fig. 5b). This interpretation is also supported by the digital terrane models, which clearly show the distribution of ridges of conglomerate and sandstone and wide areas underlain by weak lithologies like marls (Fig. 5a, b).

Stop 5: Steinernes Theater, Hellbrunnerberg, Mönchsberg Conglomerate with deformation structures

Coordinates: N47° 45´ 24.6´´´, E 13° 04´ 09.2´´, 464 m

The Mönchsberg Conglomerate (Nagelfluh) at the Hellbrunnerberg is overlying the Upper Cretaceous Kreuzgraben Fm. of the Salzburg-Reichenhall Gosau basin. On the eastern side of the Hellbrunnerberg, the base is at an elevation of 465 m indicating a pre-Mönchsberg Conglomerate bedrock terrace. The Quaternary Mönchsberg Conglomerate Fm. is composed fine-grained conglomerate, which is intercalated with coarse grit and pebbly sandstone. In contrast to other Nagelfluh deposits, clasts of the NCA are dominating, mostly in part cherty limestones from the Oberalm Fm. indicating local sources at the base of the Mönchsberg Conglomerate differing from the overlying more coarse-grained conglomerates with a significant proportion of metamorphic rocks (mostly from the Tauern window area). The artificial outcrop build as the “Steinernes Theater” (“rocky theater”) exposes normal faults, sometimes in part as conjugate Mohr faults, some are extensively cemented as deformation bands (Fig. S-a) with the following orientations: The conjugate Mohr normal faults steeply dip WNW and NE (Fig. S-4, 5) and some calcite-filled veins are in their X-Y plane. Together, these indicate NE-SW extension. Normal faults show two sets: SSW-dipping ones are similar to the conjugate deformation bands, a few steeply W-dipping ones are the result of a separate E-W extension event. A few reverse faults dip NNE or WSW and potentially indicate a stage of ENE-WSW shortening (Fig. S-5c, d).

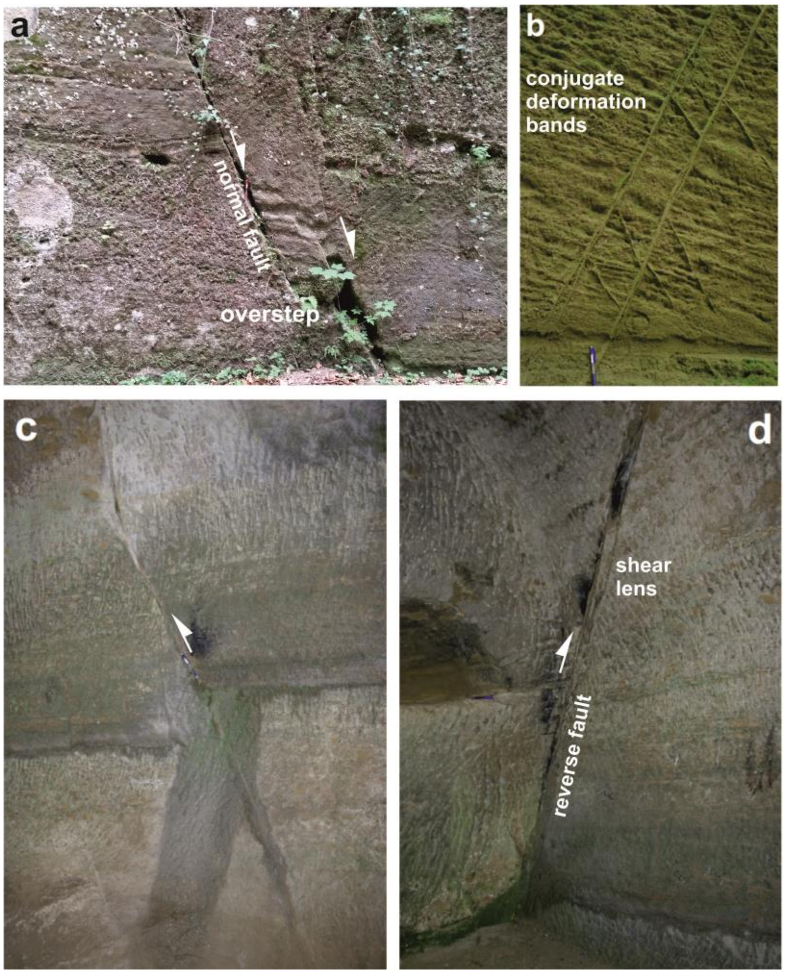

Fig. S-4. Fault structures in the Steintheater at Hellbrunnerberg. (a) Normal fault with an offset of ca. 1.5 m. (b) – Conjugate Mohr deformation bands. (c) Reverse fault with a vertical offset of ca. 25 cm. (d) Reverse fault with shear lenses and a vertical offset of ca. 25 cm.

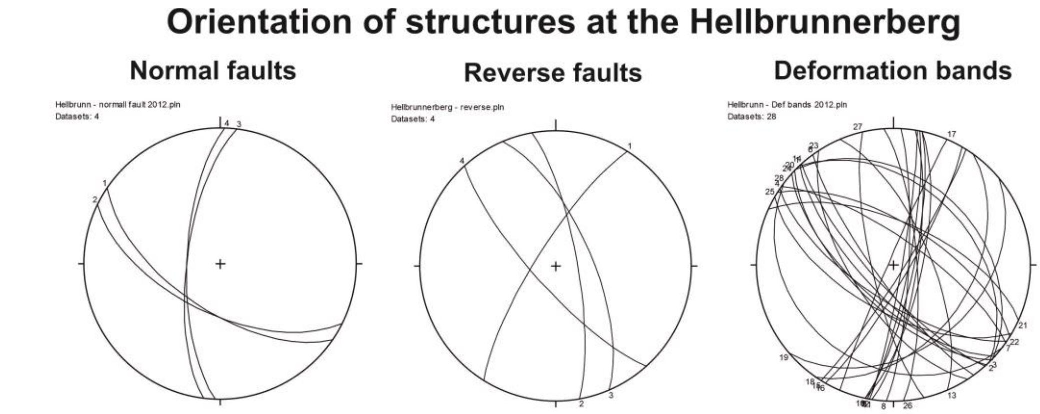

Fig. S-5. Orientation data of structures in the Mönchsberg Nagelfluh at the Steintheater at Hellbrunnerberg. (a) Normal faults. (b) Reverse faults. (c) Deformation bands in conjugate Mohr arrangement.

Stop 6: Kieferbruch: "Untersberg marble"

N47° 44´ 13.9´, E 12° 59´ 20.6´´, 617 m

The Kieferbruch is the largest, recently active quarry within the Untersberg Fm. It exposes a slope breccia, the so-called "Untersberg marble", which is overlying the Upper Jurassic–Lower Cretaceous Plassen Limestone with an angular unconformity at its base, which is not exposed at present. I suggest to rename "Untersberg marble"as Untersberg Fm. to formalize the lithostratigraphic unit and to take the Kiefer quarry to Veitlbruch area as the type locality. The exposure was described in detail by Kieslinger (1964), Höfling (1985) and Leiss (1988a). The Untersberg Fm. rests on Plassen Limestone, and mainly contains bauxite at the base, breccia, several dm thick finer breccia and grainstone layers. The grainstone beds dip uniformly to NNW with a dip angle of 23–33°. The lowermost portion of the section contains bauxite, which is mainly exposed as the matrix infill between partly huge angular blocks of Plassen Limestone (Fig. S-6e, S-7a, b). Even resedimented bauxite blocks occur (Fig. S-7d). Rare steeply S-dipping clastic dykes separating huge blocks of Plassen Limestone indicate ca. N-S syndepositional extension. The basal breccia is interpreted as a terrestrial deposit, with an unconformity at top (Fig S-7a). Leiss (1988a) and Höfling (1985) describe a high number of bioclasts both in the reddish basal bauxite breccia as well as from overlying grayish fine breccia and grainstone layers, which include rudists, bryozoa, anthozoa, miliolids and other foraminifera indicating a marine environment of the fine breccia and grainstone lithofacies. As the terrestrial basal bauxite breccia also contains resedimented bioclasts including hippurites, older reefs must be assumed, and these should be separated by from reefs of a younger generation. In general, debris flows are assumed for the deposition of the fine breccia and grainstone lithofacies, which also contain the fossil debris. Beside the by far predominating Plassen Limestone, other components like Dachstein Limestone, Hauptdolomite, radiolarite, and bauxite are rare. Resedimented grainstone intraclasts reveal the erosion of already lithified Lower Gosau rocks (Fig. S-7d).

Fig. S-6. Untersberg Fm. in Kiefer quarry (state: May 2018). (a) Terrestrial bauxite-cemented breccia is overlain, after an unconformity and relief, by submarine grainstone beds and fine-grained breccia beds. Detail of (a) is shown in (c). (b) Grayish fine breccia affected by S-directed antithetic normal faults. The grayish layer is ca. 12–15 cm thick. (d) Terrestrial breccia with meter-sized elongated Plassen Limestone block with a breccia-filled, bauxite-cemented clastic dyke.

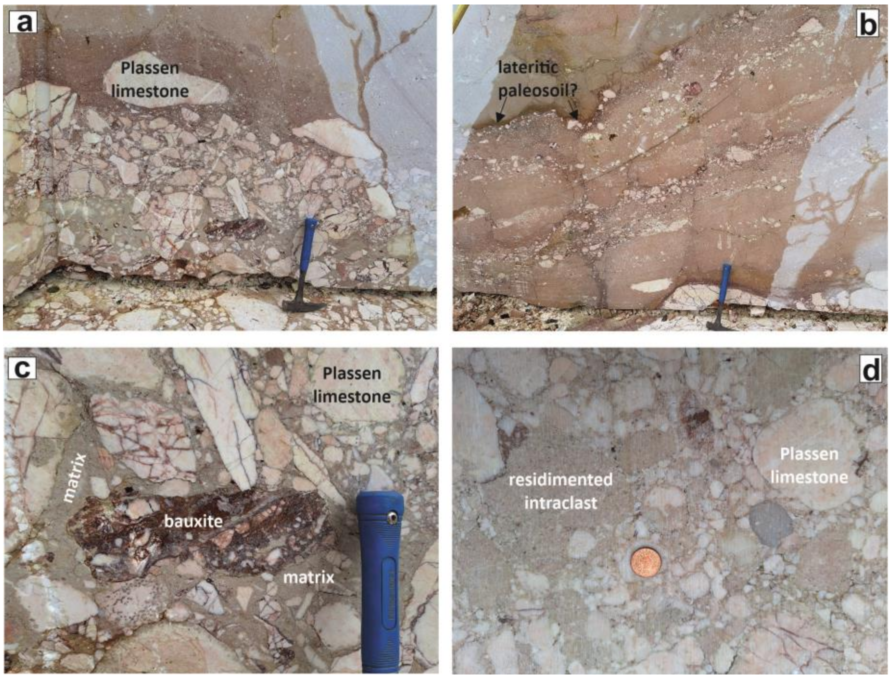

Fig. S-7. Untersberg Fm. in Kiefer quarry (state: August 2024). (a) Debris with angular Plassen Limestone blocks and resedimented large bauxite clasts. Note the in situ brecciation of some Plassen Limstone blocks. (c) Detail of (a). (b) Remnants of potentional paleosoils and relief above the reddish breccia. Note the compositional change to the overlying light greenish-grayish coarse debris flow. (d) Block showing the composition of breccia, with predominant angular Plassen Limestone clasts, resedimented grainstone intraclasts of the Lower Gosau Group and a single clast of grayish limestone. This block shows the erosion of already lithified Lower Gosau rocks during deposition of the grainstone layers. Note also the reddish coating of some clasts and apparent pressure solution seams.

Because of the marine nature, it is assumed that the present dip of strata of the finer breccia and grainstone lithofacies is a later effect and steepened by post-depositional tectonic movement. Two further structural stages can be distinguished: (1) antithetic normal faults (Fig. S-6b) dipping roughly to the south indicating ca. NNW–SSE extension (Fig. S-8b), and (2) steep dextral strike-slip faults indicating ca. NE–SW strike-slip compression (Fig. S-8a).

<u>Stop 7: Bridge Kühlbach along Römerstraße</u> (E Veitlbruch)

N47° 44´ 15.4´´, E 12° 59´ 02.4´´, 576 m

The roadcuts E and W the bridge across the Kühlbach along the Römerstraße expose thick-bedded limestones and breccias, which exhibit subvertical E–W-trending fault planes with dextral subhorizontal striae indicating WNW–ESE strike-slip compression (Fig. 8d). Another set of strike-slip faults trend N-S and indicate NNE-SSW strike-slip compression. Both fault sets are considered as expression of the dextral Glanegg fault. In the Kühlbach E of the bridge, decimeter-thick carbonate breccia beds of Untersberg Fm. are exposed, which dip with an angle of ca. 40 degree to the north. Further north in the Kühlbach, these carbonate breccia beds are overlain by several meter thick dark marls.

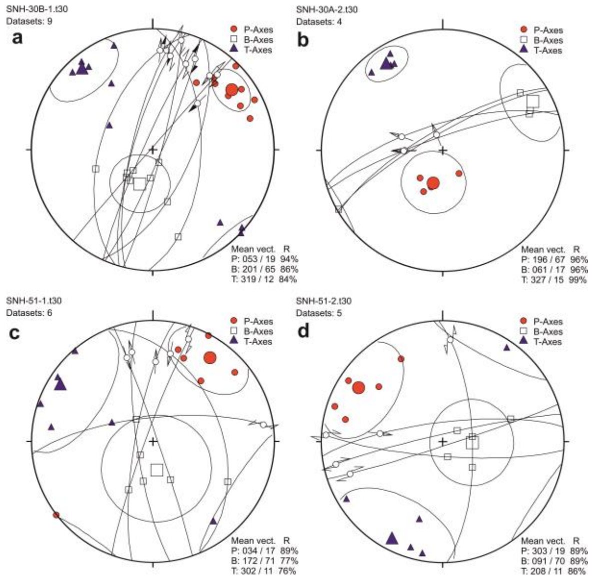

Fig. S-8. Selected orientation data from the Untersberg Fm. of the Kiefer quarry (a, b) and from the bridge across the Kühlbach (c, d). (a) NE–SW dextral strike-slip. (b (c) NNW–SSE extension. (d) WNW–ESE dextral strike-slip.

Stop 8: Kühlbach: Eocene marls of the Nierental Fm.

Coordinates: N47° 44´ 28.6´´, E 12° 59´ 19.0´´, 506 m

In the Kühlbach valley SW of Fürstenbrunn, just below the bridge, subhorizontal to gently S-dipping gray-reddish marls of the Nierental Fm. are exposed (Fig. S-9a). Biostratigraphy constrains a Paleocene (Thanetian) age from a borehole, which was done for the bridge construction (Egger et al., 2017). Therefore. the exposed reddish marls should have a Thanetian age. Note the gentle S-dip of the marls, which is interpreted as the expression of the dip againts the leading transtensional fault (Glanegg fault) indicating formation of a halfgraben.

Stop 9: Kühlbach: Eocene upper Nierental Fm.

Coordinates: N47° 44´ 26.5´´, E 12° 59´ 09.3´´, 523 m

Note that this outcrop on the northern slope of the Kühlbach is difficult to access because of the need to cross the Kühlbach and/or slippery slopes.

In the Kühlbach valley SW of Fürstenbrunn, ca. 200 m W of the bridge (Stop 8), a ca. 6.5 m thick succession of various-colored marls with two paraconglomerate and several carbonate sandstone layers is exposed (Figs. S-9b-e, 10). From several nearby outcrops, potentially including that of the stop, Egger et al. (2017) found an Eocene age (Ypresian and lower Lutetian). The sections contains several thin, in part amalgamated turbiditic carbonate sandstone beds and two layers of paraconglomerate. Because of the presence of sandstones and paraconglomerate layers, the succession belong to the upper Nierental Fm. The emplacement of sandstones is by turbidite mechanism as also testified by gently WSW-plunging slump folds (Fig. S-9e), which indicate a transport from the NNW or ESE. Two beds of paraconglomerates contain well rounded sedimentary rocks also constraining their origin from submarine mass flows. The paraconglomerate 1 bed contains dominantly light-grayish marly limestone, whereas other rock types like greenish glaucony sandstone, and purple and grayish marly limestones are subordinate. In the paraconglomerate 2 layer is also dominated by light grayish limestone, and purple-colored sandstone clasts are rare.

Fig. S-9. Field photos of Eocene rock types of the upper Neirental Fm. in the lower part of the Kühlbach Valley. (a) Red S-dipping Eocene marls of the Nierental Fm. (b) Exposure ca. 200 m W of bridge with a successions of gray, brown and reddish marls, paraconglomerates, and carbonatic sandstones. (c) Paraconglomerate 1 bed. Note well rounded pebbles in a marly matrix. (d) Greenish, potentially tuffaceous layer in the footwall of a carbonate sandstone. (e) Slump fold in carbonatic sandstone.

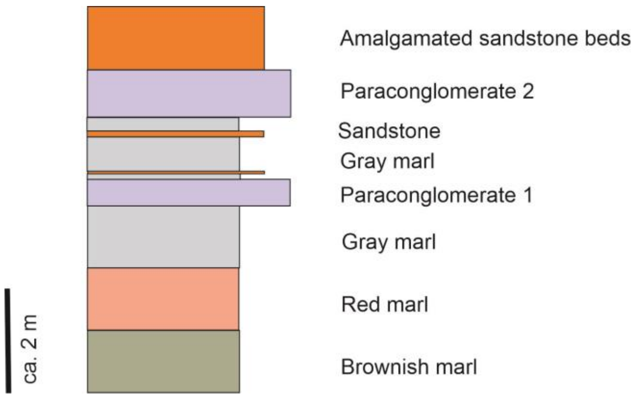

Fig. S-10. Sedimentary succession of Stop 9. For the description, see text.

Stop 10: Holzeck near Fürstenbrunn: Holzeck Conglomerate

At the Holzeck hill, the Holzeck Conglomerate (new lithostratigraphic unit) is exposed, which was mapped by Seefeldner (1957) Prey et al., (1969), and Prey (1980) as “Interglacial conglomerate”, and the richness of metamorphic rocks was already recognized (Fig. S-11). Here, we call it Holzeck Conglomerate, and a detailed study will be presented in a paper by Neubauer and Kessler (in prep.). Some details were already mentioned in Kessler and Neubauer (2018). Preliminarily, we assign the conglomerate as uppermost part of the Inntal Group. Clasts show a good roundness, foliated metamorphic clasts are often strongly elongated. Only a coarse bedding is visible (Fig. S-11a, b).

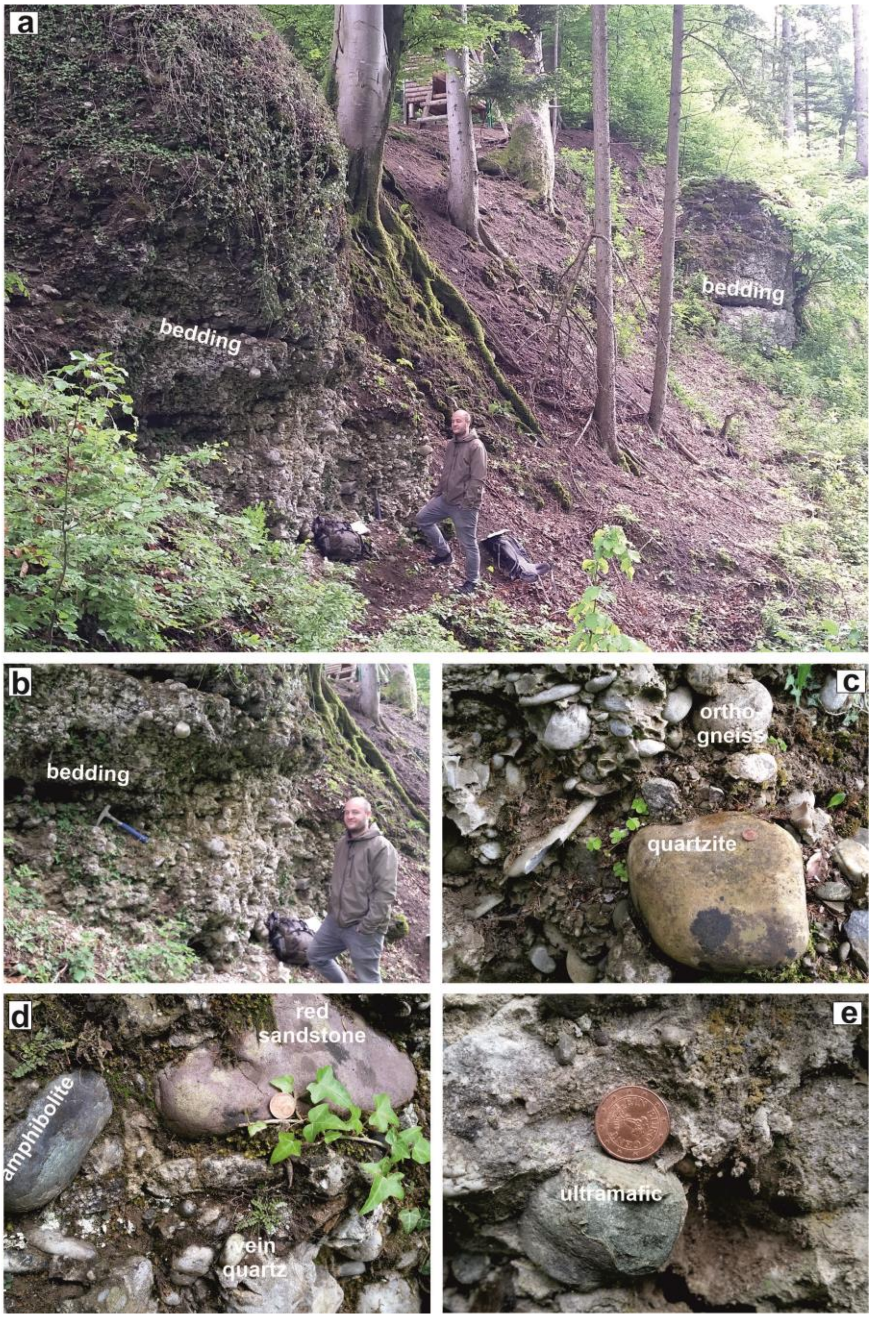

Fig. S-11. Field photos from the Holzeck Conglomerate. a) Overview over two exposures on the eastern slope. b) Outcrop showing the coarse grainsize, N-dipping bedding, roundness of clasts and carbonate cement. c), d) and e) Photographs showing the variety of clasts.

The largest boulder reaches ~30 cm, the average grainsize is between 6 – 8 cm, nearly all clasts are larger than 1 cm. The matrix is sand-grained, although in these outcrops difficult to find. The conglomerate composition is shown in Fig. S-12. Metamorphic clasts dominate by far and include vein quartz, serpentinite, porphyric granite-gneiss, orthogneiss, metagranite, pegmatite, biotite-plagioclase gneiss, amphibolite, biotite-chlorite schist, and foliated quartzite. Clasts from the NCA are subordinate raising the question on the source and depositional conditions. NCA clasts include red sandstone, grayish-greenish quartz-sandstone. Light-gray micritic limestone, dark-gray micritic limestone, and red micritic dolomite are similar to Silurian-Devonian lithologies of the Graywacke zone. Rare yellowish carbonate sandstone clasts are likely from the Lower Gosau Group. We suggest that the amphibolite-grade metamorphic clasts derive from the Silvretta and/or Ötztal basement complexes, and were transported through the Unterinntal/Oberaudorf Basin along the ISAM fault.

The conglomerate is exposed much wider, as many blocks and isolated clasts are widespread in the slope north of the Kühlbach, and landsliding underneath the visited plays an important role as digital terrain models show the disintegrating of the Holzeck Conglomerate.

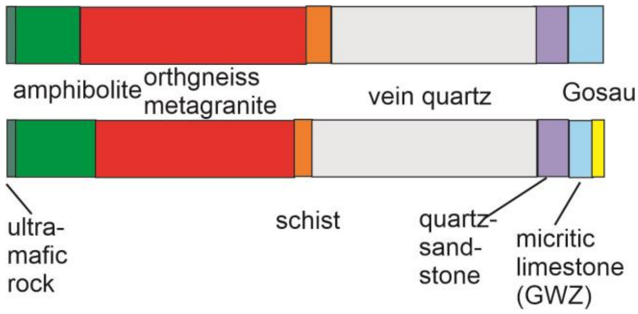

Fig. S-12. Diagram showing the clast compostion of the Holzeck Conglomerate.

Stop 11: Hohensalzburg, near top station of Festungsbahn: syn- and post-Gosau deformation

N47° 48´ 02´´, E 13° 04´ 08.9´´, 454 m

The western wall underneath the Hohensalzburg fortification exposes thick bedded Dachstein limestone, which is affected by a major E-directed normal fault system (Fig. S-13d–f). The bedded limestone contain cm-thick red bauxite veins filled with carbonatic-clastic material (Fig. S-13a, b). Their orientation is ca. NNW–SSE (Fig. S-14a) and argues, therefore, for ENE–WSW extensional deformation during opening of these extensional structures Fig. S-14a). A tension gash filled with epitaxial calcite has a similar orientation (Fig. S-13c).This deformation stage is considered as early Late Cretaceous during initial formation of the Salzburg Gosau basin. Arrays of normal faults indicate later ca. E–W to ESE–WNE extension (Fig. S-14b, c).

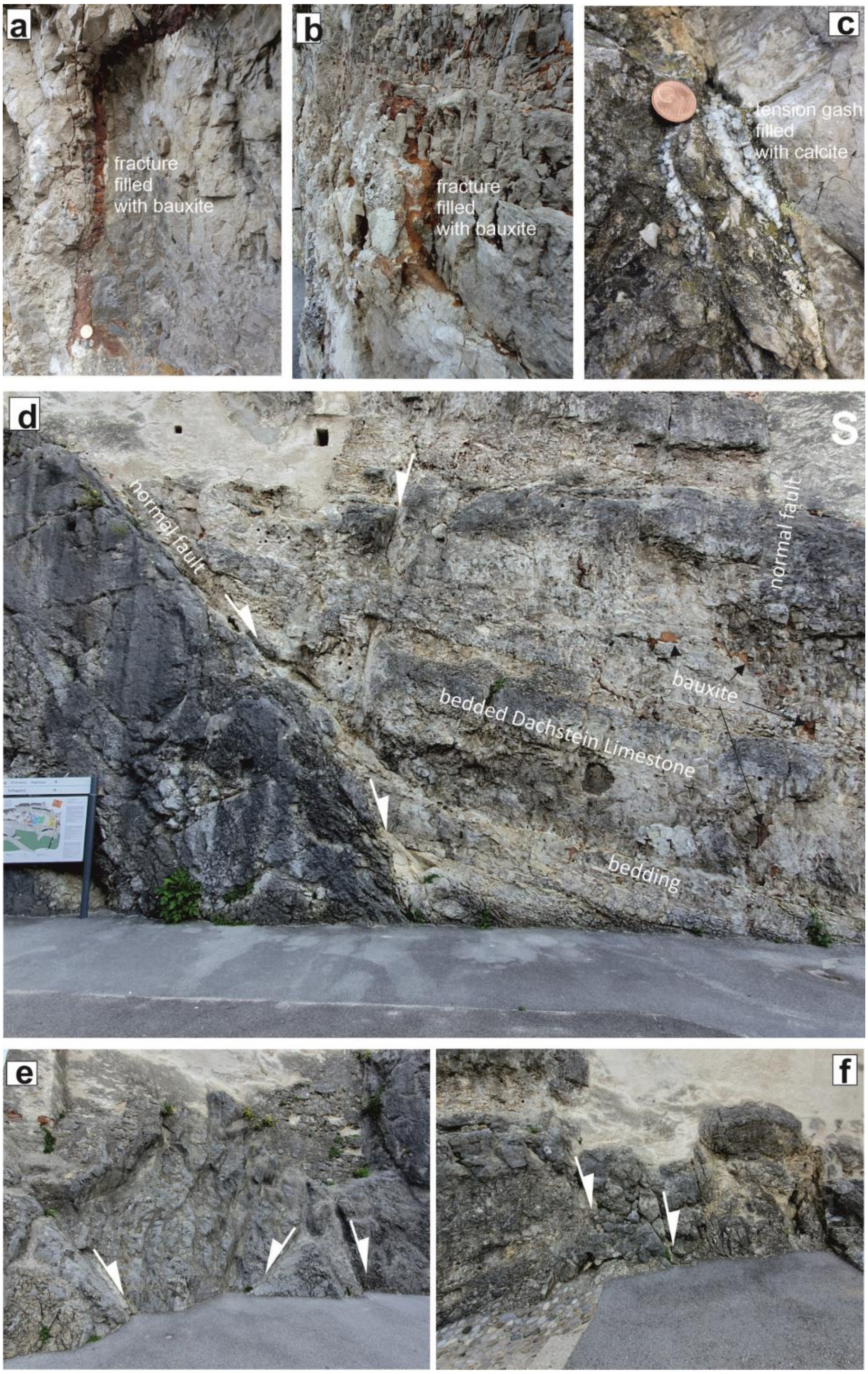

Fig. S-13. Succession of deformation events at western wall of the Hohensalzburg castle. (a) (b) Reddish fractures filled with reddish bauxite-bearing carbonatic-clastic material. (c) Tension gash filled with epitaxial calcite. (d) Major ESE-directed normal fault in the NNW-trending wall, which exposes bedded Dachstein Limestone. (e), (f) Succession of normal faults on the southern side of the fortress (Panoramaterrasse).

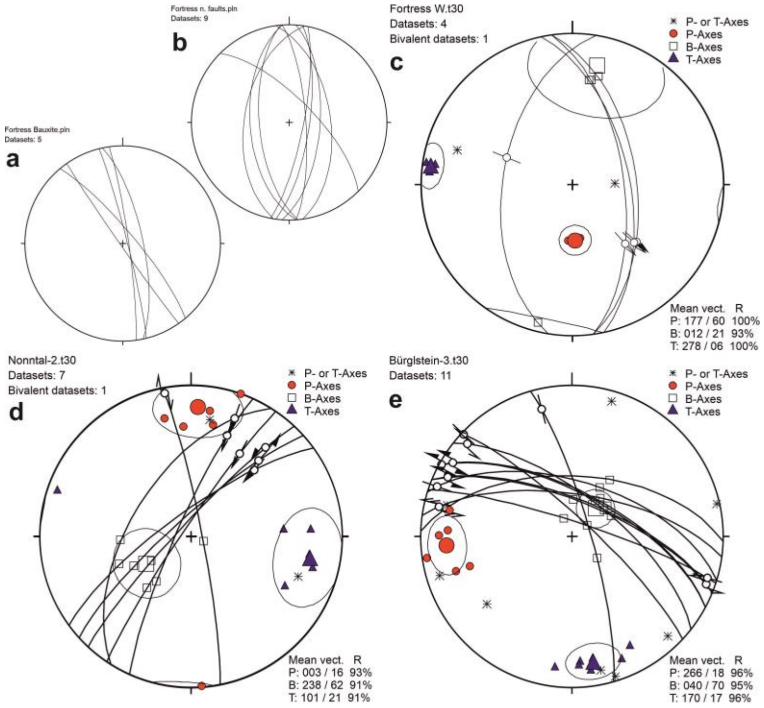

Fig. S-14. Orientation data from western wall of Hohensalzburg castle. (a) Bauxite/laterite filled extensional veins. (b) Normal faults indicate ca. E–W extension. (c) Fault-striae data indicate WNW–ESE extension. (d) NE-trending sinistral strike-slip faults at wall of Nonntal indicate N–S strike-slip compression (interpreted as Oligocene-Miocene activity of the ISAM fault. (e) WNW–ESE trending strike-slip faults at Bürglstein indicate late-stage E–W strike-slip compression.

<u>Stop 12. Nonntaler Hauptstraße, Strike-slip fault</u>

N47° 47´ 45.1´´, E 13° 03´ 09.7´´, 430 m

The rock wall along the Nonntaler Hauptstraße exposes bedded Dachstein Limestone and the wall itself represents largely a subvertical ENE-trending strike-slip fault (Fig. S-15a), which is well visible in a digital terrain model (Fig. S-16). Note also two systems of normal faults (orientation is similar to the normal fault systems at Stop 11, Hohensalzburg) predating the strike-slip fault. The Stadtberge (Hohensalzburg, Kapuzinerberg) and the Kühberg in ENE extension can be considered to be confined by strike-slip faults indicating wrenching along branches of the ISAM fault. The Stadtberge are internally less deformed shear lenses along the ISAM wrench system (Fig. S-16).

On the path from Nonntal to Bürglstein (Stop 13), a view to the southwestern Kapuzinerberg exhibits a fold structure within bedded Dachstein Limestone and a major W-dipping normal fault (Fig. S-17a, b).

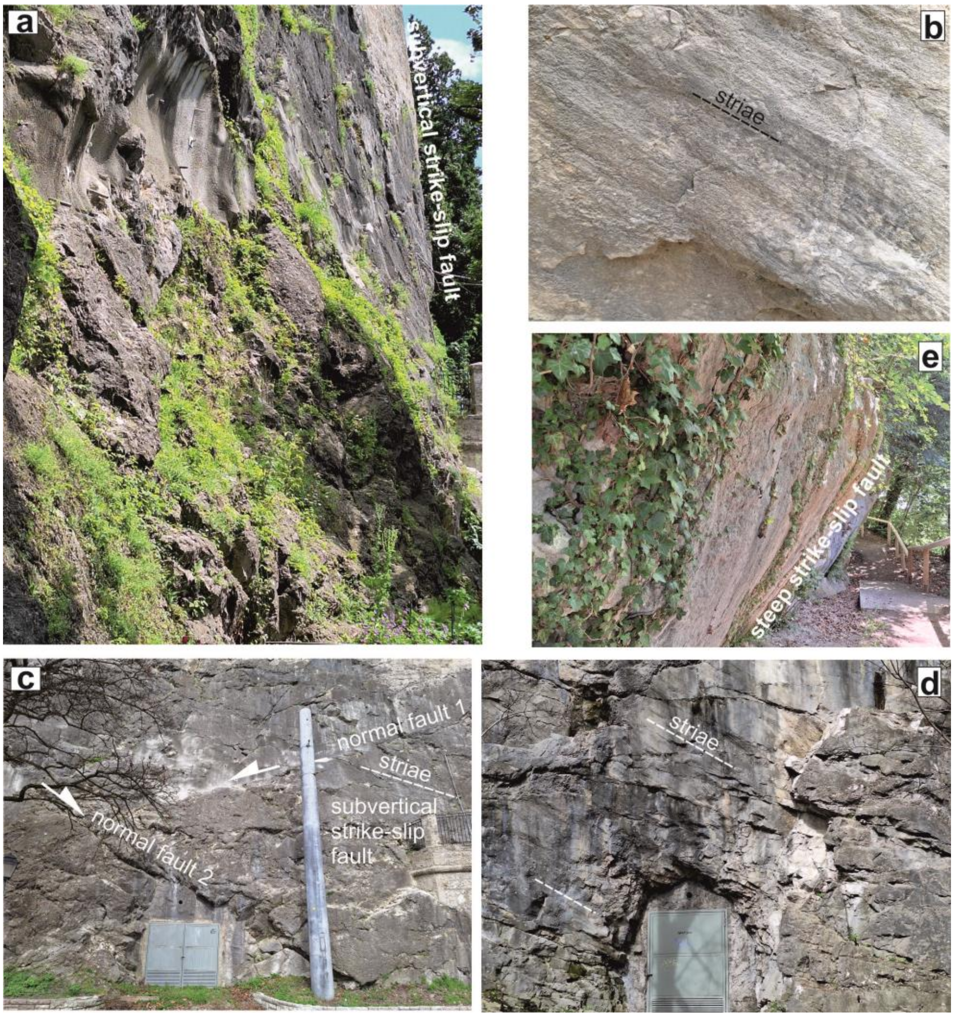

Fig. S-15. Outcrop-scale structures at Nonntaler Hauptstraße. (a) (b) (d) Strike-slip fault and older normal faults in the southern wall of the Nonntal hill. Associated fault-striae data are shown in Fig S-14d) (c) Two sets of older normal fault systems predating strike-slip faults in the wall along the Nonntaler Hauptstraße.(e) Steep N-dipping strike-slip fault at Bürglstein. Associated fault-striae data are shown in Fig S-14e.

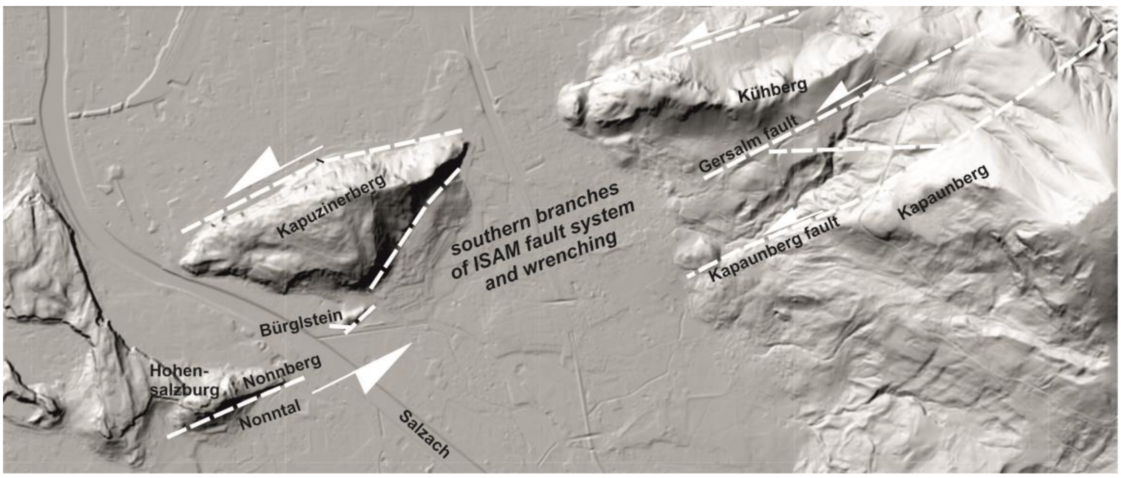

Fig. S-16. Digital terrain model showing the distribution of main faults in the Nonntal, Kapuzinerberg and Kühberg areas interpreted as wrench system along a branch of the ISAM fault system.

Stop 13: Salzburg, Bürglstein hill near UKH: Strike-slip fault

N47° 47´ 55.0´´, E 13° 03´ 27.7´´, 435 m

The outcrop located on the footpath on the southern side of the Bürglstein hill exposes limestones with abundant slickensides and subhorizontal striae. These features are interpreted to be part of a major sinistral strike-slip fault considered to reactivate a fault belonging to the strike-slip fault responsible for the opening of the Late Cretaceous Salzburg-Reichenhall basin.

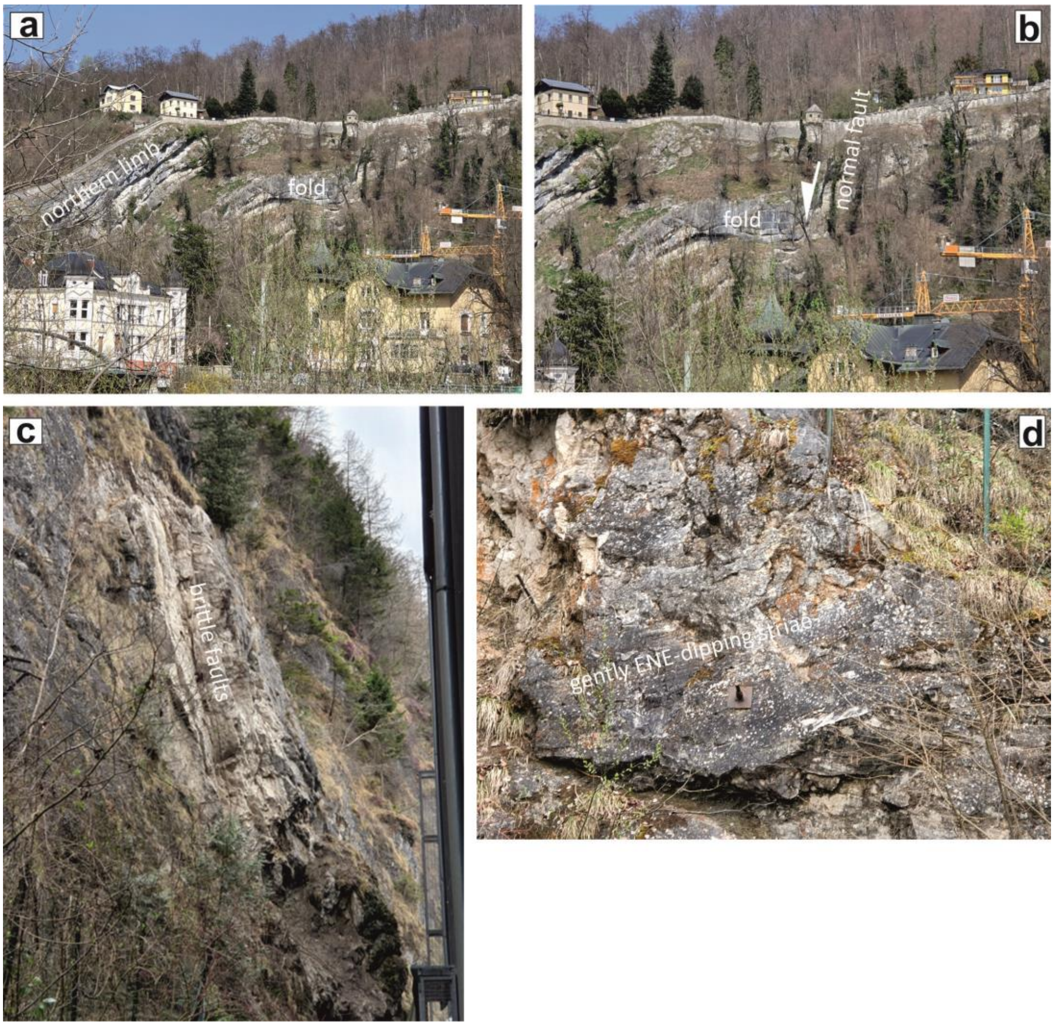

Fig. S-17. (a) View to the southwestern slope of the Kapuzinerberg exhibits a fold structure within bedded Dachstein Limestone and a major W-dipping normal fault. (b) Enlarged detail of (a). (c) Subvertial cataclastic fault zone behind the Stadtarchiv. The fault zone is considered being part of the Innsbruck-Salzburg-Amstetten fault zone. (d) Subhorizontal striae on the steep fault plane showing strike-slip displacement.

Stop 14: Northern toe of Kapuzinerberg: ISAM fault

N47° 47´ 48´ 17.6´´, E 13° 03´ 07.6´´, 469 m

The western part of the northern slope of the Kapuzinerberg is well exposed but increasingly less accessible because of recent protection constructions against rock-fall. The northern slope exposes a cataclastic fault, which is considered being part of the ISAM fault (Egger, 1997). The outcrops, e.g., behind the Stadtarchiv, expose dolomitized meter thick-bedded Dachstein Limestone and Dachstein dolomite, which are affected by a steeply N-dipping cataclastic fault zone (Fig. S-17c). Shear lenses are common, and on slip surfaces, subhorizontal striae can be observed, with a mostly sinistral sense of shear (Fig. S-17d).

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