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Geology of central Northern Switzerland: Overview and some key topics regarding Nagra's seismic exploration of the region

Herfried Madritsch[1]

Key words: tectonics, stratigraphy, eastern Folded Jura, 2D-seismics, central Northern Switzerland

Zusammenfassung
Bei dem vorliegenden Kurzartikel handelt es sich um die Zusammenfassung eines Vortrags, den der Autor an der 82. Jahresversammlung der SASEG 2015 in Baden hielt. Er bietet einen kurzen Überblick über die Geologie der zentralen Nordschweiz, wobei auf drei thematische Aspekte fokussiert wird: eine Einführung zur Tektonik des Nordschweizer Permokarbontrogs, eine Übersicht der mesozoischen Sedimentabfolge, welche auch die von der Nagra vorgeschlagenen Wirtgesteine für die Lagerung von radioaktiven Abfällen umfasst, sowie die neogene tektonische Entwicklung der Region, insbesondere die Entstehung des Jura-Gebirges. Diese Aspekte repräsentieren Schlüsselthemen bei der seismischen Exploration durch die Nagra, welche kontinuierlich zu einem besseren Verständnis der faszinierenden Geologie der Region beiträgt.

Abstract
The article provides a brief overview of the geological evolution of central Northern Switzerland as outlined in an oral presentation given at the 82nd SASEG annual convention 2015 in Baden. It focuses on an introduction to the Permo-Carboniferous Trough of Northern Switzerland, a brief description of the Mesozoic sedimentary sequences to be found in the region, including the potential host rocks for radioactive waste disposal proposed by Nagra, and the Late Cenozoic tectonics of central Northern Switzerland, in particular the formation of the Jura Fold-and-Thrust Belt. These aspects represent some of the key topics regarding Nagra's ongoing seismic exploration of the region that has, and still is, contributing significantly to a better understanding of the region's fascinating geology.

1 Introduction

The area of central Northern Switzerland lies in the northern Alpine foreland of the Central Alps (Fig. 1). Since the early 80s, it has been explored by Nagra in search of a suitable site for a high-level waste repository. As a consequence, the regional geology was studied in great detail and outlined in depth in several Nagra technical reports, most recently in the geological syntheses for Stages 1 and 2 of the Sectoral Plan for Deep Geological Repositories (Nagra 2008 and Nagra 2014a, respectively).

This short article builds on an oral presentation given by the author at the 82nd SASEG annual convention in Baden on 20th June 2015. The original presentation was intended to serve as an introduction to the first of two convention excursions leading into the easternmost Jura Mountains. It also aimed to address some key topics relating to the seismic exploration of the region that were presented afterwards in more detail by the follow-up speaker Dr. B. Meier (see summary by Meier 2015, this volume). The article follows the concept of the original oral presentation. It provides an overview of the geological evolution of the region (Fig. 2), focusing on three main aspects:

- An introduction to the Permo-Carboniferous Trough of Northern Switzerland that formed in the aftermath of the Variscan orogeny and strongly influenced the later geological evolution of the area.
- A brief description of the Mesozoic sedimentary sequences found in the region that were targeted by the convention

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excursion and include the potential host rocks for radioactive waste disposal as well as their upper and lower confining formations.

- The Late Cenozoic tectonics of central Northern Switzerland, in particular the formation of the Jura Fold-and-Thrust Belt that largely defined the tectonic units observable in the area today.

2 Permo-Carboniferous Trough of Northern Switzerland

The Paleozoic basement in the investigation area is characterized by the Variscan orogeny (Thury et al. 1994 and references therein). The associated tectonic processes resulted in intense ductile deformation, metamorphism of the crystalline basement

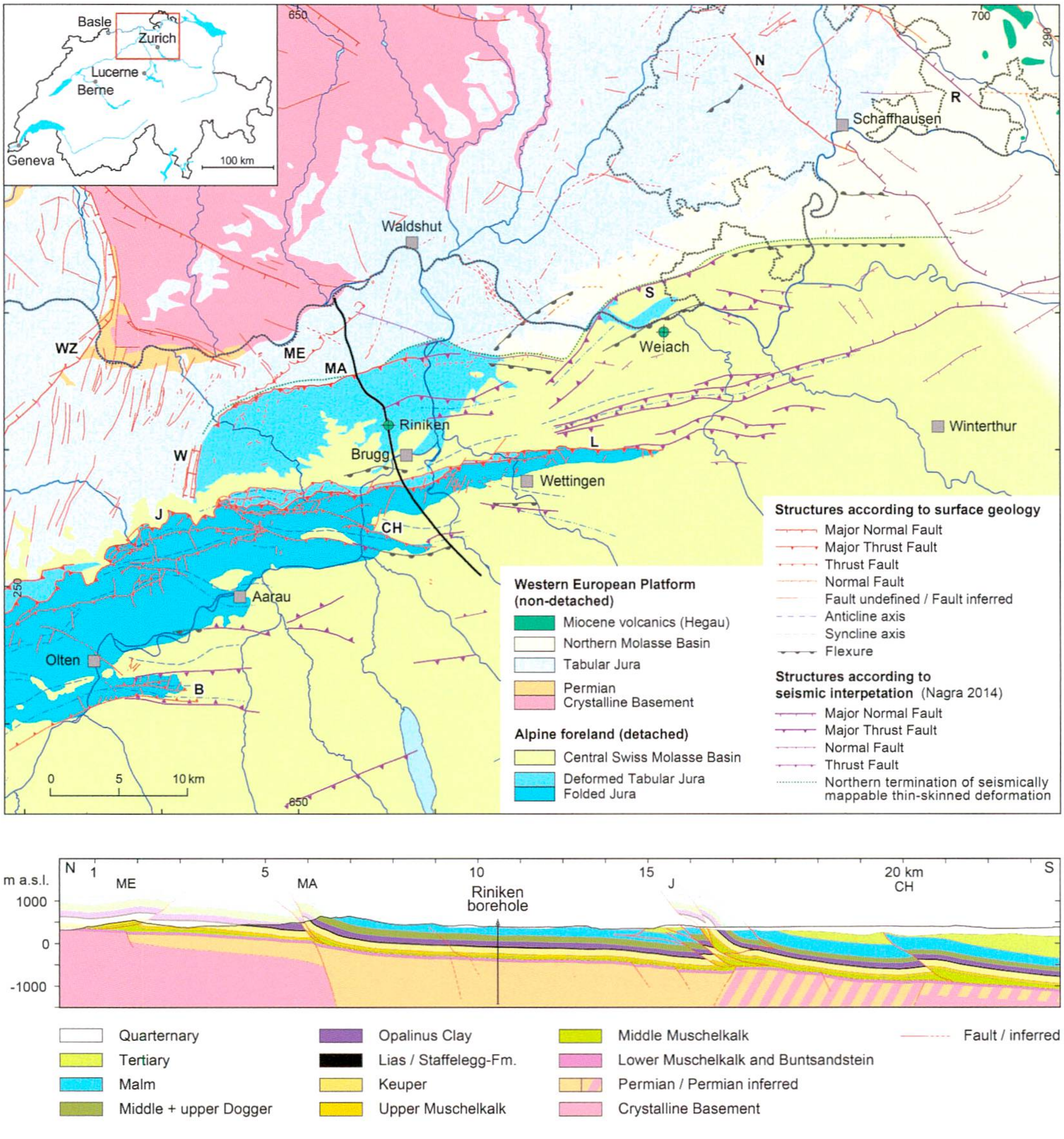

Fig. 1: Tectonic map of central Northern Switzerland (modified after Nagra 2014a). Shades of blue indicate the Folded Jura, Deformed Tabular Jura and Tabular Jura tectonic units (compare Fig. 6). Selected regional fault zones: B: Born-Engelberg Anticline; CH: Chestenberg Thrust; J: Jura Main Thrust; L: Lägern Anticline; MA: Mandach Thrust; ME: Mettau Thrust; N: Neuhausen Fault; R: Randen Fault; S: Siglistorf Anticline; W: Wölflinswil Graben; WZ: Wehra-Zeinigen Fault.

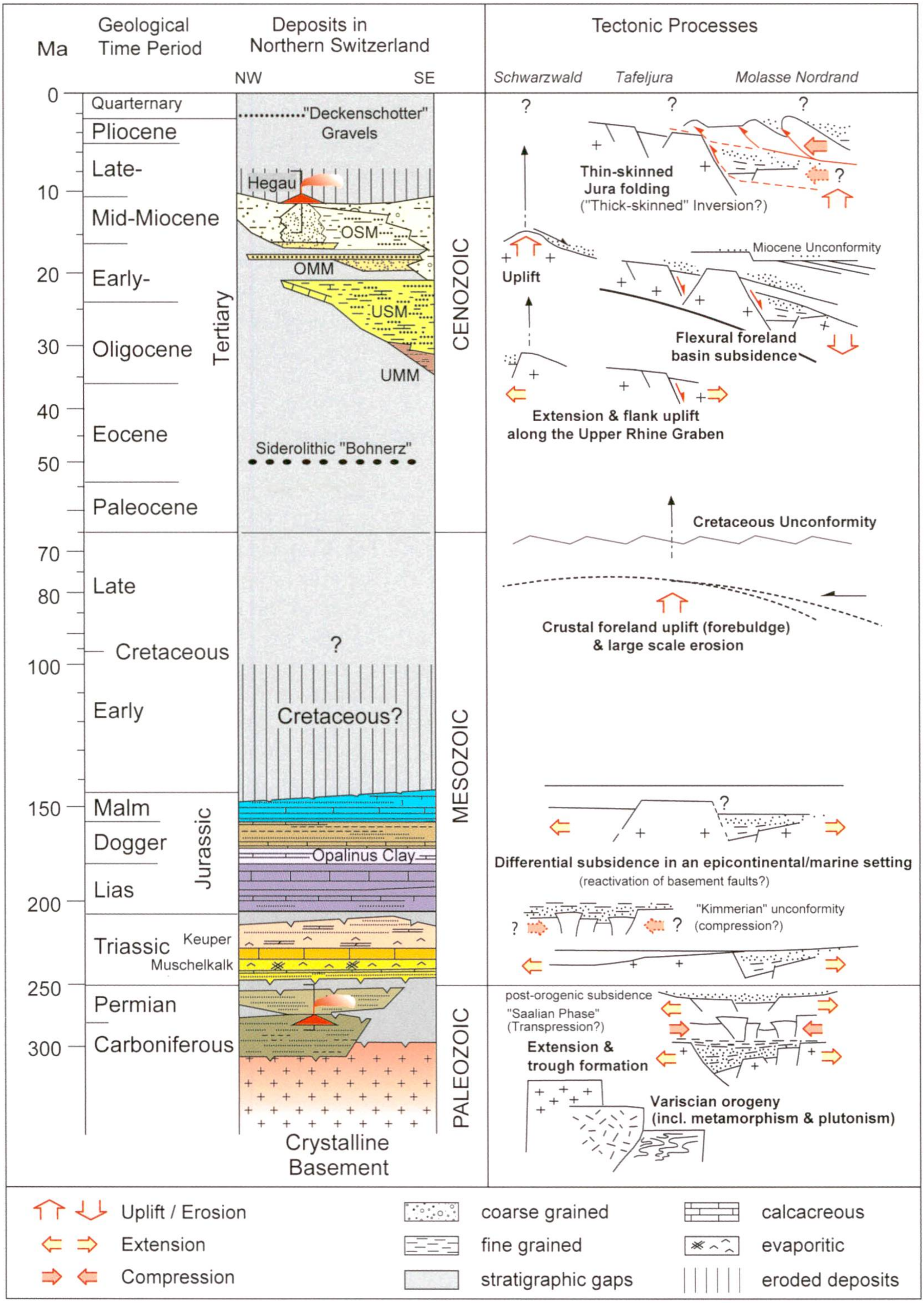

Fig. 2: Overview of the geological evolution of central Northern Switzerland (modified after Nagra 2014a).

rocks and granitic intrusions. In the aftermath of the Variscan orogeny, wrench tectonics during Carboniferous and Permian times led to the formation of intramontane troughs found all over western Europe (Ziegler 1982, McCann et al. 2006). The Permo-Carboniferous Trough of Northern Switzerland is completely buried beneath Mesozoic and Cenozoic strata. Deep exploration wells and 2D seismic campaigns carried out by Nagra during the 1980s allowed the subsurface extent of the Trough to be characterized and its overall ENE-WSW strike to be determined (Diebold et al. 1991). The detailed tectonic interpretation of the Trough remained largely conceptual and a matter of scientific debate, with some authors inferring a complex multistage tectonic evolution including phases of transpression (Diebold et al. 1991), while others suggested a more simple rift-like evolution (Marchant et al. 2005).

The new 2D seismic data acquired on behalf of Nagra in 2011/12 (Madritsch et al. 2013) combined with newly processed gravity maps (Green et al. 2013) yielded additional information on the Trough's geometry and its possible formation kinematics by filling some important data gaps in the area of the lower Aare valley. The tectonic map of the Trough was updated (Fig. 3) and underlines the importance of NW-SE striking transfer faults allowing the formation of deep pull-apart style basins along the Trough's strike (see Naef & Madritsch 2014 and Meier 2015, this volume).

Several authors suggested multiple post-Paleozoic reactivations of the Permo-Carboniferous Trough in Northern Switzerland (Laubscher 1986, Diebold & Noack 1997, Wetzel et al. 2003). As outlined in chapter 4 of this article and also the contribution in this volume by Meier (2015), the Trough indeed had a strong impact on Mesozoic sedimentation processes and the nucleation of deformation zones during the later Cenozoic events, in particular the formation of the Jura Fold-and-Thrust Belt.

3 Mesozoic stratigraphy

This section provides an overview of the Mesozoic stratigraphy of central Northern Switzerland. It focuses on selected stratigraphic units in the area surrounding the lower Aare valley in Canton Aargau which was visited during the convention excursion (Fig. 4).

During the Triassic, a successive marine transgression in the area of Northern Switzerland led to the deposition of an epicontinental sediment sequence including fine grained clastic sediments, evaporites, limestones and dolomites (Geyer et al. 2011). The evaporitic series of the Middle Muschelkalk and the Lower Keuper served as the primary detachment horizons during the Late Miocene formation of the Jura Fold-and-Thrust Belt (Buxtorf 1916, Jordan et al. 1990). The Keuper together with the Liassic Staffelegg Formation (Reisdorf et al. 2011) were defined as the lower confining units of the Opalinus Clay (Nagra 2014a) that may contribute to the effective containment zone of a radioactive waste repository. A large portion of these units was observed and discussed in the course of the convention excursion in the Gruhalde clay pit near the village of Frick (Fig. 4a, b). They consist predominantly of clayey marls but calcareous, dolomitic and sandy units also occur (e. g. «Arietenkalk» / Beggingen Member and Gansingen Dolomite seen in the clay pit). These units are up to several meters thick, form weathering-resistant ‹hard beds› in outcrops and typically show a higher density of fractures and faults. Within the Staffelegg Formation the facies changes laterally with a ‹clay-rich facies› from Frick to Schlattingen and a ‹calcareous-sandy facies› south of the Jura Fold-and-Thrust Belt (Kiefer et al. 2015). The amount of ‹hard beds› below the Opalinus Clay increases in the region with the ‹calcareous-sandy facies›.

The Middle Jurassic Opalinus Clay overlying the Staffelegg Formation is considered to be the most favorable host rock for radioactive waste disposal in Switzerland (Nagra 2014b). The unit consists of partly sandy claystones that were deposited in a shallow marine environment (Wetzel & Allia 2003). Across Northern Switzerland, the Opalinus Clay shows a substantial thickness of 70 to 130 m and homogeneous lithological and mineralogical properties from the outcrop to micro-scale (Nagra 2002 with references). A very high clay content supports the rock's key properties with respect to radioactive waste disposal, namely low permeability, high sorption and self-sealing capability of fractures (Nagra 2002, Traber & Blaser 2013, Nagra 2014a with references).

While the Opalinus Clay was deposited in a similar depositional environment over the entire area of Northern Switzerland, the overlying Middle Jurassic sediments show stronger lateral facies variations, indicating a more heterogeneous depositional environment characterized by differential subsidence (Wetzel & Allia 2003; Bläsi et al. 2013). Two facies domains can be distinguished, with the transition coinciding approximately with the lower Aare valley (Fig. 5). To the east, the Opalinus Clay is overlain by a claystone sequence referred to as the ‹Brauner Dogger› by Nagra (2008) and considered as a potential host rock for disposal of low- and intermediate-level waste. The sequence is mainly argillaceous in composition, but contains micritic, sandy or biodetrital limestones and iron oolites that may occur isolated or in sequences. The lateral correlation of some of these less clay-rich

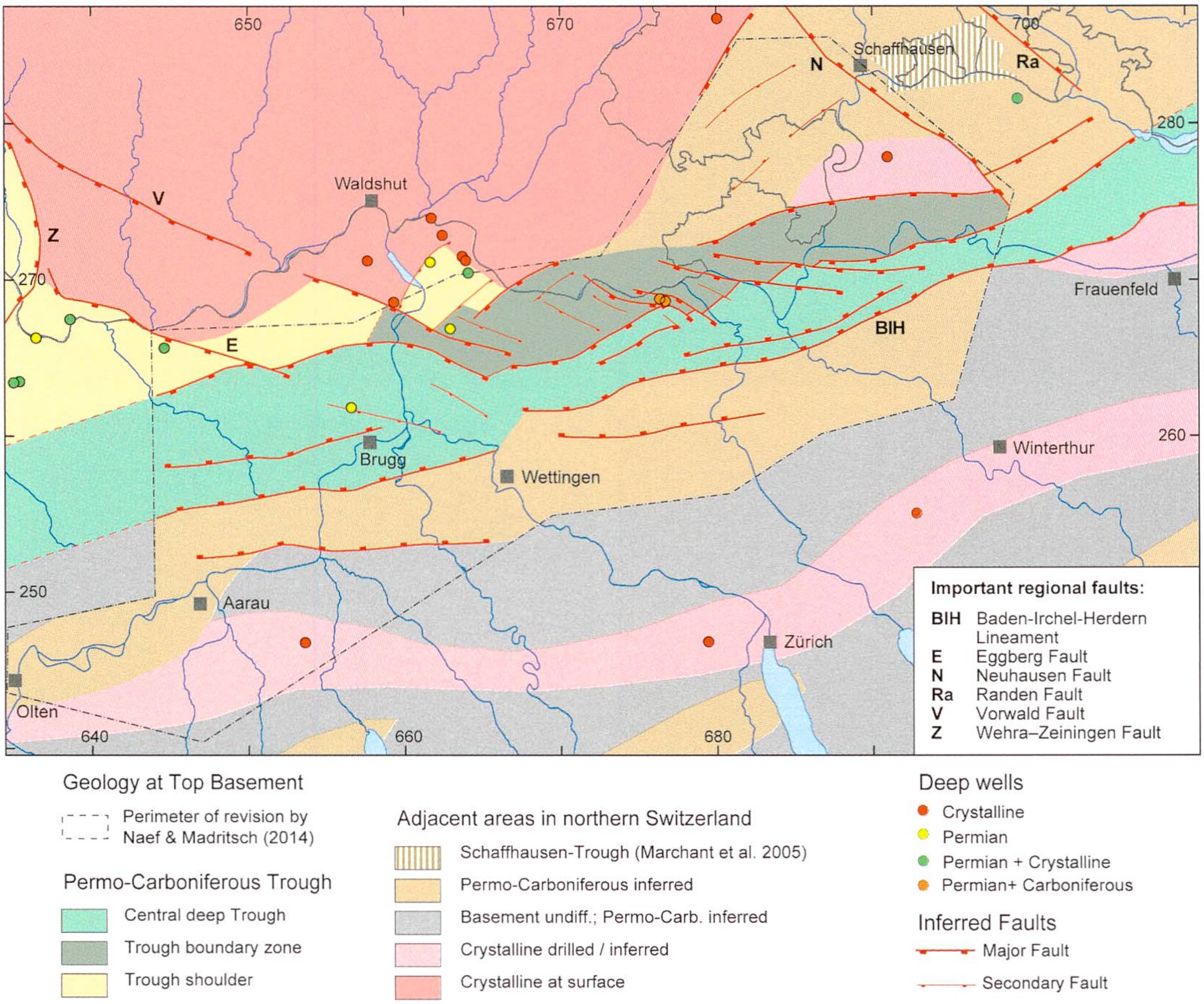

Fig. 3: Revised tectonic map of the Permo-Carboniferous Trough of Northern Switzerland (modified after Naef & Madritsch 2014).

sequences often remains ambiguous (Bläsi et al. 2013). West of the Aare valley, the Opalinus Clay is overlain by the Passwang Formation featuring complex internal lithology changes (Burkhalter 1996), followed by the thick oolithic limestones of the Hauptrogenstein Formation. The Klingnau Formation representing a transition facies between the units of the ‹Brauner Dogger› sequence and the ‹Spatkalk› of the Hauptrogenstein Formation could be seen during the SASEG convention excursion in the Schümmel quarry near Holderbank (Fig. 4c, Bläsi et al. 2013).

The transition between the Middle and Upper Jurassic could also be seen in the course of the convention excursion. The decimeter-thick hardground horizon is interpreted to represent an extremely condensed section of the Ifenthal Formation (Bitterli-Dreher 2012). The Upper Jurassic then sets in with the Wildegg Formation composed of the Birmenstorf and the Effinger Member (Gygi 2000a, 2000b). The Effingen Member reaches more than 210 m thickness west of the Aare valley and was proposed as potential host rock for a low- and intermediate-level waste repository (Nagra 2008). The Effingen Member can be divided into calcareous marl sequences and limestone sequences (Fig. 4d). The latter reach thicknesses of up to more than 10 m. By analyzing the clay content throughout the Effingen Member derived from geophysical borehole logs, the limestone sequences could be correlated

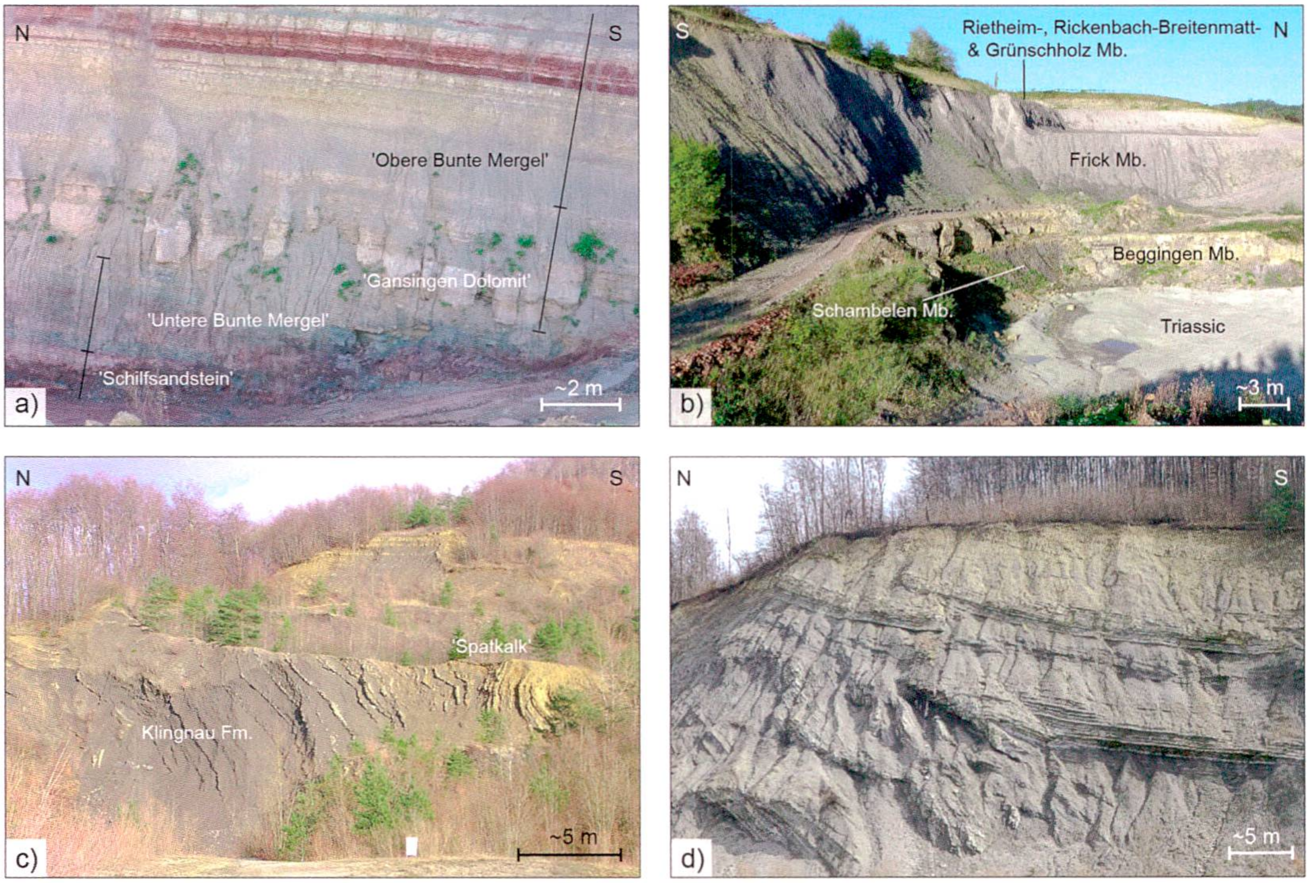

Fig. 4: Field images of selected stratigraphic units as exposed in the outcrops visited during the first excursion of the SASEG annual convention 2015. a] Sediments of the Upper Keuper as exposed in the Gruhalde clay pit near the village of Frick (coordinates: 643'000/261'900). b] The Staffelegg Formation also exposed in the Gruhalde clay pit (see coordinates above). c] The Klingnau Formation as exposed in the Schümmel quarry near Holderbank (coordinates: 655'200/253'200) yielding insights into the Chestenberg Anticline. The clay-rich marls are dipping to the south and are overlain by crossbedded limestones («Spatkalk») belonging to the Hauptrogenstein Formation. d] The Effinger Member of the Wildegg Formation as also exposed in the Schümmel quarry (see coordinates above). Note the intercalated limestone beds that were thrusted when the Chestenberg Anticline was formed in the context of Late Miocene Jura folding.

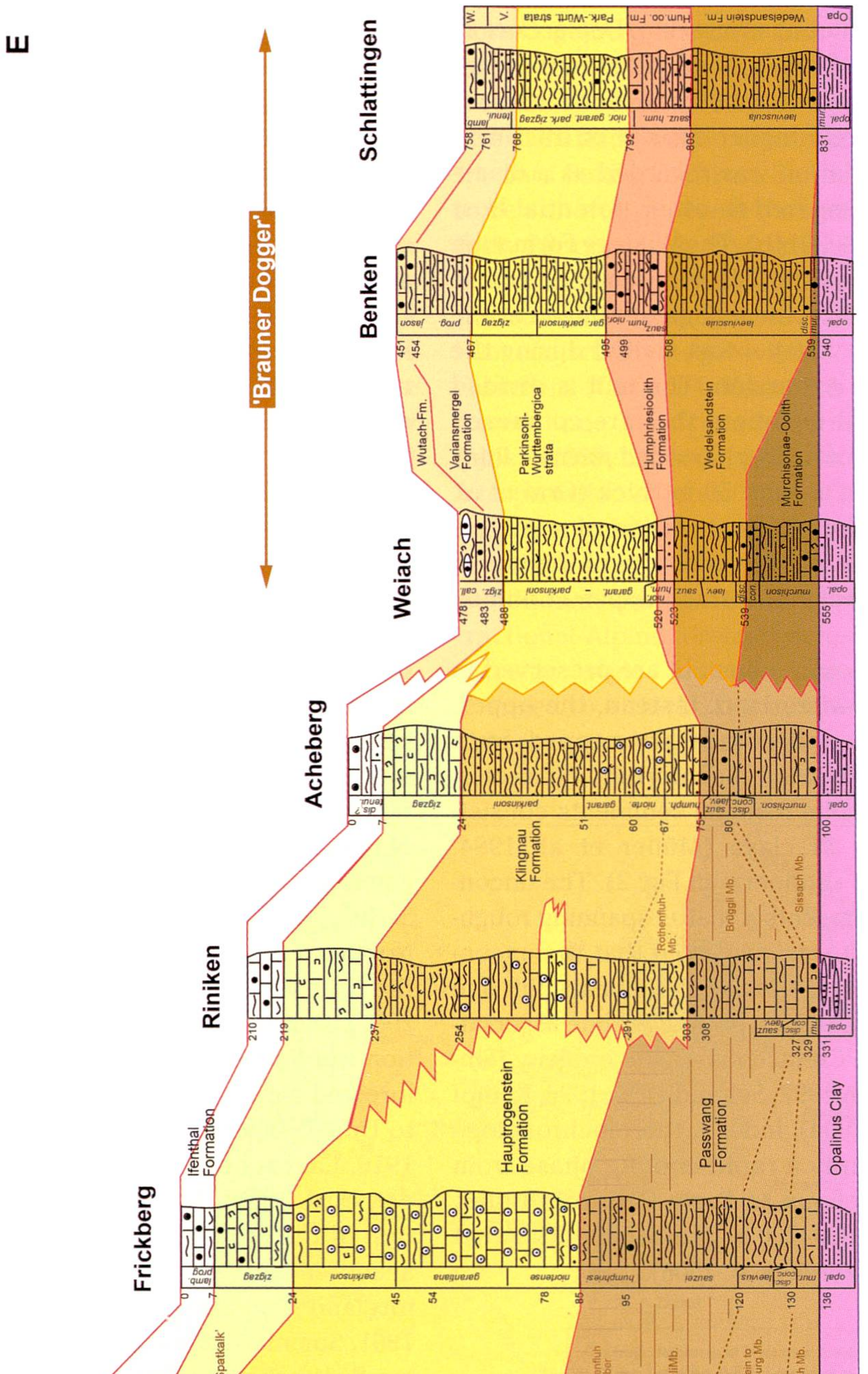

Fig. 5: Facies transitions between different Middle Jurassic units overlying the Opalinus Clay in central Northern Switzerland (taken and translated from Bläsi et al. 2013, Meier & Deplazes 2014).

over a distance of several km (Deplazes et al. 2013, Nagra 2014a). Given that the rheologically competent limestone beds show a comparatively higher density of fractures, their correlation was regarded as a disadvantage compared to other potential host rocks (Nagra 2014b). The Wildegg Formation is followed by the Villigen Formation whose type location – the village of Villigen in the lower Aare valley – was visited during the convention excursion. The unit is divided into several members that are composed primarily of often well bedded micritic limestones. It is around 50 m thick (Graf et al. 2006) and forms a succession of relatively erosion-resistant rocks on top of the potential host rocks and their upper confining units.

No Cretaceous sediments are preserved in Northern Switzerland. Instead, the uppermost Malm limestones are capped by a regional erosional unconformity characterized by Eocene residual sediments consisting mainly of clays (Müller et al. 1984, Siderolithic «Bohnerz» in Fig. 2). The unconformity represents a hiatus spanning roughly 100 Ma. It was suggested that the unconformity reflects a phase of regional uplift due to the initiation of a forebulge zone associated with the Cretaceous Alpine orogeny (Sinclair & Allen 1992, Schmid et al. 1996, Kempf & Pfiffner 2004). Indeed, thermochronological data imply a rapid cooling phase from Late Cretaceous to Early Cenozoic times, suggesting 600–700 m of erosion during that period (Mazurek et al. 2006).

4 Late Cenozoic tectonics

From the latest Oligocene onwards, the area of central Northern Switzerland became submerged again and formed part of the northern Alpine Molasse Basin (Fig. 2). The latter is considered as a type example of a flexural foreland basin that developed in close response to syn- and post-collisional thrusting and erosion processes, its sedimentary fill being marked by two coarsening-, thickening-, and shallowing-upward megasequences (Pfiffner 1986, Schlunegger et al. 1997). In Northern Switzerland, flexural subsidence during the Early Miocene at the outer margin of the Basin occurred simultaneously with crustal uplift in the northward adjacent Black Forest Massif (Ziegler & Dèzes 2007). This tectonic setting resulted in local extension documented by flexures and normal faults. Analysis of seismic reflection data across Northern Switzerland shows that pre-existing basement faults associated with the Permo-Carboniferous Trough of Northern Switzerland were reactivated during that process (Naef et al. 1995, Diebold & Noack 1997). The prominent Neuhausen and Randen Faults in northeasternmost part of the region (Fig. 1) are considered to represent the boundary towards the extensional / transtensional Hegau-Lake Constance fault system (Ibele 2015 with references therein, Madritsch 2015). The main phase of activity of the latter postdates Early Miocene times and is associated with local volcanic activity. Sedimentation in the Molasse Basin of Northern Switzerland lasted at least until the Late Miocene (~ 10 Ma, Rahn & Selbekk 2007). During this time, the Alpine deformation front propagated far into the northern foreland along a décollement in the Middle to Upper Triassic evaporites (e. g. Buxtorf 1916, Laubscher 1961, Burkhard 1990, Jordan et al. 1990). This resulted in the formation of the arcuate Jura Mountains widely accepted as representing a thin-skinned foreland fold-and-thrust belt (Laubscher 1961, Sommaruga 1997). The area of Northern Switzerland is dissected by the easternmost part of the Jura Fold-and-Thrust Belt (Fig. 1). The associated regional thrust faults largely define today's tectonic regime. From north to south, one can distinguish 4 tectonic units (Fig. 6): i) The Tabular Jura located north of the actual Jura Fold-and-Thrust Belt is characterized by horizontally layered to slightly SSE dipping Mesozoic sediments that lie autochthonously upon the Paleozoic basement of the Black Forest Massif and form its southern and south-eastern flank; ii) The Deformed Tabular Jura further to the south is characterized by the isolated occurrence of décollement-related thrusts (for example the prominent Mandach Thrust visited during the convention excursion) but is otherwise only mildly deformed; iii) The main deformation zone of the Jura Fold-and-Thrust Belt further to the south is often referred to as the Folded Jura. It is characterized by closely spaced, mostly ENE-WSW striking thrust sheet stacks and tight thrust-related folds. One of these folds is the Chestenberg Anticline which was seen in the course of the convention excursion; iv) The Subjurassic Zone marks the transition zone between the Jura Fold-and-Thrust Belt and the central Swiss Molasse Basin. This tectonic unit features prominent décollement-related structures such as the Born-Engelberg Anticline and, like the Folded Jura, reveals a strong lateral gradient in tectonic shortening (Jordan et al. 2015).

The main thin-skinned deformation phase of the Jura Fold-and-Thrust Belt is considered to be a short-lived event that lasted until the Early Pliocene (e. g. Becker 2000). However, several geomorphological investigations at the front of the Belt have revealed mid Post-Pliocene activity (e. g. Nivière & Winter 2000, Giamboni et al. 2004, Madritsch et al. 2010). Based on geodynamic considerations (Mosar 1999, Lacombe & Mouthereau 2002), interpretation of recent stress (Becker 2000) and seismic data (Rotstein & Schaming 2004, Giamboni et al. 2004), several authors suggested that, during this latest stage of contractional Alpine foreland deformation, the tectonic style in the Jura Mountains changed to a thick-skinned mode, presumably also involving the contractional reacti-

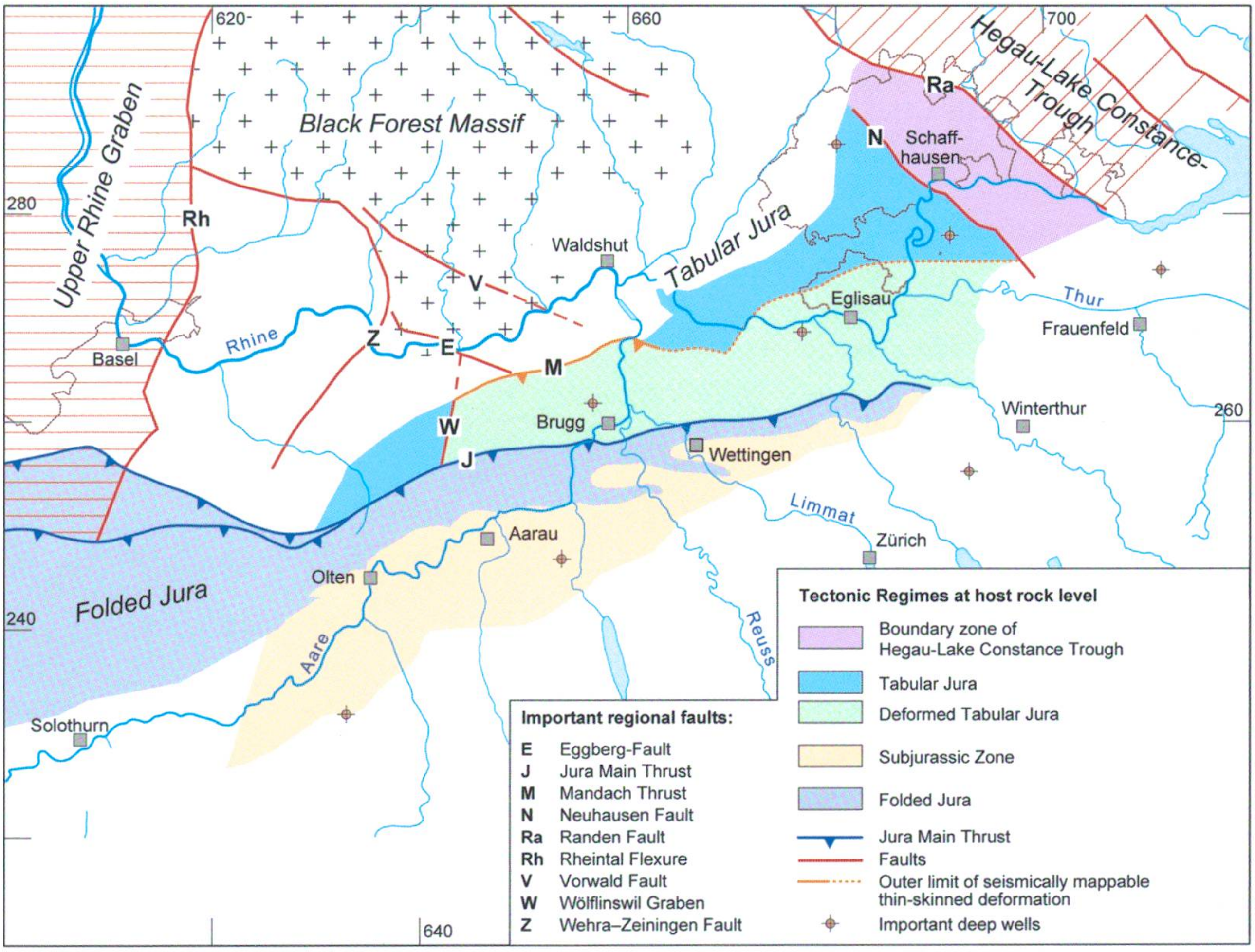

Fig. 6: Tectonic units of Northern Switzerland (taken and translated from Nagra 2014a).

vation of basement structures such as the Permo-Carboniferous Trough of Northern Switzerland (Pfiffner et al. 1997, Ustaszewski & Schmid 2007, Madritsch et al. 2008). The interpretation of the reprocessed and new 2D seismic data yielded no clear evidence for such deep-seated deformation, however a mild thick-skinned component to the deformation of some regional structures – for example the Mandach Thrust – cannot be fully excluded either (Madritsch et al. 2013). In any case, Nagra's most recent seismic interpretation efforts confirm the strong spatial relationship between nucleation points of thrust faults in the sedimentary cover and major bounding faults of the Permo-Carboniferous Trough (compare Meier 2015 this volume). These relationships were already inferred during much earlier seismic studies (e. g. Laubscher 1986) and confirm the strong impact of old basement structures on the region's younger tectonic evolution.

The various geomorphic indications for Quaternary tectonics in the Alpine foreland raise the question to what extent and by what mode might tectonic deformation in Northern Switzerland still be active today. Geodetic measurements suggest very slow rates of active deformation close to the error margin (Nagra 2014a with references). Instrumentally recorded seismicity is mild, suggesting that the present-day tectonic regime is characterized by strike-slip to normal faulting (Kastrup et al. 2004).The limited representativeness of comparatively short-term instrumental measurements of active tectonics for the 1 Ma time period of concern for a radioactive waste repository can, to some extent, be compensated by the geomorphic analysis of Quaternary sediments that have the potential to record subtle neotectonic movements over longer timescales. An example of this approach was discussed during the convention excursion. Along the Mandach Thrust, topographic analysis of Late Pleistocene gravels using highest resolution digital terrain models based on LiDAR data (Light Detection and Ranging) allows a surface rupture of the fault during the Latest Pleistocene and Holocene times to be excluded. In most cases, however, subtle ongoing tectonic activity of faults in Northern Switzerland cannot be entirely excluded, which is one reason why regional fault zones and tectonic zones that witnessed reactivation throughout geological time are widely avoided during the siting process for a radioactive waste repository (Nagra 2014a).

5 Conclusion

Northern Switzerland has a fascinating geology. Geological highlights to be witnessed in the field and in seismic data include complex facies transitions of Mesozoic units, text book examples for thin-skinned deformation structures and evidence for polyphase reactivation of long-lived basement fault zones. Nagra's exploration activities throughout the last 30 years have contributed significantly to a better understanding of the regional geology and provided knowledge that is also of relevance for both the geoscientific and geoeconomic community.

Acknowledgements

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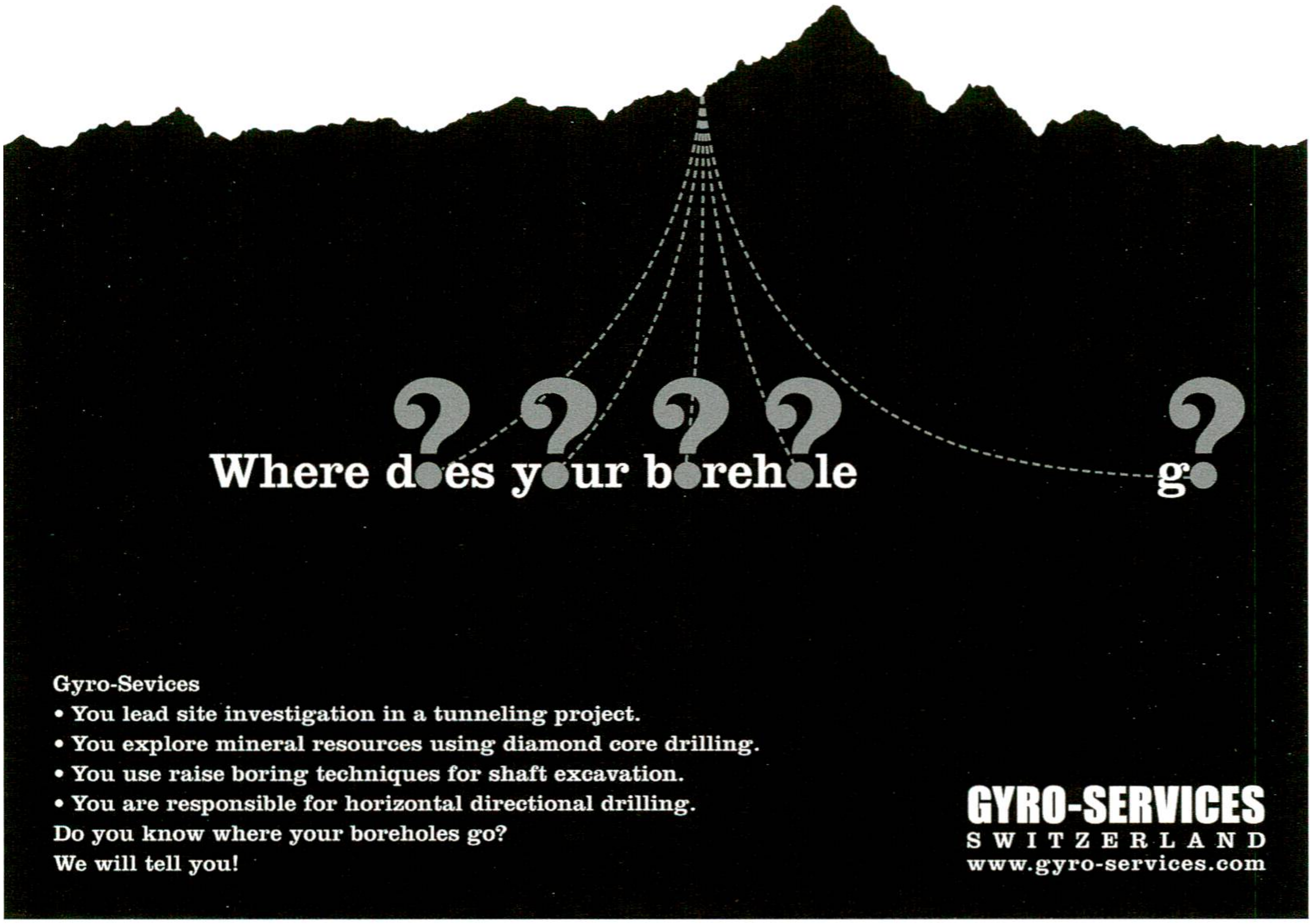
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