

Arbeitsbericht NAB 12-23

**Tectonics of the Hegau and
Lake Constance region:**

**A synthesis based on
existing literature**

August 2015

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University of Fribourg,
geosfer AG, St. Gallen

Nationale Genossenschaft
für die Lagerung
radioaktiver Abfälle

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1 Introduction

This report presents a synthesis on the tectonics of the Hegau and Lake Constance (HELC) region based on a literature review that was carried out in between autumn 2011 and spring 2012. As can be seen in Fig. 1 the HELC region straddles the border of northeastern Switzerland (cantons of Thurgau and Schaffhausen) and southwestern Germany (Baden-Württemberg). Its most eye-catching geographic feature is Lake Constance with its three basins. The large Upper Lake (Obersee) in the east, the long and narrow Lake Überlingen (Überlingen See) in the northwest and the rather shallow basin of the Lower Lake (Untersee) in the southwest. The region between Lake Überlingen and Lower Lake is termed Bodanrück, or badische Halbinsel (Badenian peninsula) by older authors. Lake Constance is sourced and drained by the River Rhine, one of the major rivers of Central Europe. The latter is referred to as Alpine Rhine (Alpenrhein) upstream of Lake Constance. Downstream from the lake, the river is known to as High Rhine (Hochrhein) until reaching Basel where it enters the Upper Rhine graben and is referred to as Upper Rhine (Oberrhein).

Lake Constance lies in the Molasse Basin between Upper Swabia in the north, the Hegau in the northwest and the Thurgau in the south. North of the Hegau a cuesta-like landscape is developed which gradually rises towards the northwest to form the Swabian Alb, the Baar and the Black Forest. Towards the west along the High Rhine, the cuesta landscape narrows to form the Tabular Jura. To the south beyond the High Rhine, the Tabular Jura reaches the easternmost foothills of the Jura Mountains. To the north it flanks the southern Black Forest which is divided into Dinkelsberg in the west and Hotzenwald in the east (Fig. 1)

The geology of the HELC has been the object of investigation for several centuries of field mapping. The results of these investigations have revealed a complex pattern of faults and fault zones. More recent seismological observations indicate that the wider region is characterised by comparatively frequent, low to medium seismic activity. However, to date no comprehensive tectonic synthesis for the HELC region exists that would allow for a sound geodynamic / tectonic interpretation of the observed seismicity.

The goal of this literature based synthesis is to provide an overview of the geodynamic and tectonic history of the HELC region. For this purpose the report not only focuses on the study area itself, but also considers the large-scale tectonic framework. The core of the synthesis is a thorough review of previous investigations addressing the geology of the HELC region and surrounding areas as well as a compilation of existing geologic maps. A historic overview of geologic research in the HELC region and the cartographic material considered for the tectonic compilation are presented in Chapter 2. The results of the review are summarised in the following five chapters, namely the geodynamic frame (Chapter 3), the geologic and tectonic setting (Chapter 4), the characterisation of local structures (Chapter 5), coherence between tectonics and volcanism (Chapter 6) and implications for recent tectonic activity (Chapter 7).

All structural elements found in the literature (mainly brittle structures such as faults and fault zones) were compiled and are provided in an ArcMAP project together with the according references. On the basis of this compilation, the regional fault pattern is described and local anomalies from the observed trends were identified.

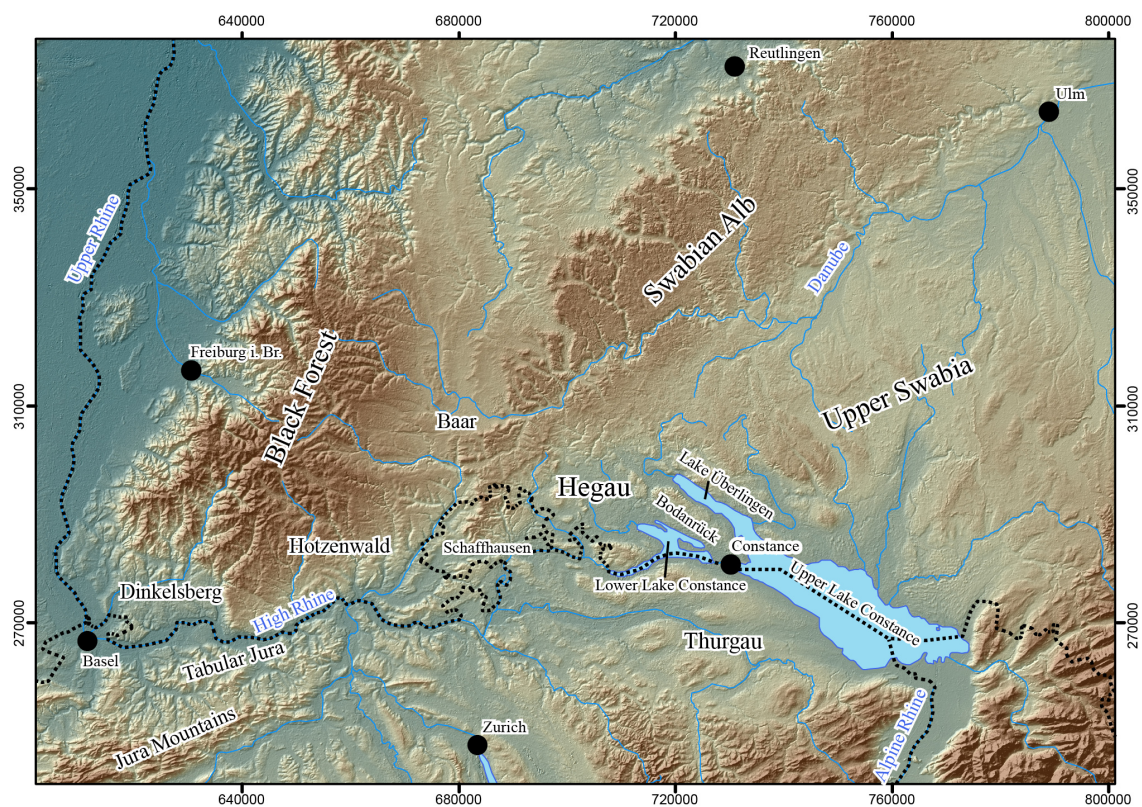


Fig. 1: Geographic overview of the larger study area. Lake Constance is subdivided into Lake Überlingen, Upper Lake Constance and Lower Lake Constance

2 Previous work and cartographic material

2.1 Historic overview of geologic research in the Hegau and Lake Constance region

Throughout the HELC region tectonic structures were discovered and described since the beginning of the 20th century when systematic mapping started. Schalch (1901) investigated the western Lake Constance area and mapped Donaueschingen (1904), Bonndorf (1906), Blumberg (1908), Geisingen (1909), Stühlingen (1912), Wiechs-Schaffhausen (1916), and Jestetten-Schaffhausen (1921) as official geologic map sheets of the Großherzogtum Baden. In the HELC region Schmidle (e.g. 1911, 1916, 1918, 1931, 1946) and Erb (e.g. 1931, 1932, 1934, 1935) largely improved the knowledge of both, the stratigraphy and the tectonics of the region. Additional important knowledge during this first phase of mapping arose from the investigations of Gutmann (1910), Knapfer (1912) and Wittmann (1937). Reck (1923) described the Hegau volcanoes in great detail.

In its late stage this first detailed investigations resulted in a couple of larger scale synthesis, for example by Paul (1948a,b, 1955) for the southern Black Forest or the tectonic "compendium" of Carlé (1955). Also hypothetic tectonic (Carlé 1955) and tectono-volcanic (Cloos 1939) models were proposed.

After the Second World War geologic investigations were driven by the oil industry and focused on the Molasse of Upper Swabia. Large seismic campaigns were carried out and deep exploration wells were drilled. The insights regarding the subsurface structure of the region gained during these exploration activities were published by Elberskirch & Lemcke (1953), Volz (1959), Lemcke & Wagner (1961) and others. A second phase of hydrocarbon exploration with additional seismic surveys started in the early 1980ies and further improved the knowledge of the Molasse Basin's tectonic evolution (e.g. Betz & Wendt 1983, Bachmann & Müller 1992). In the Hegau area hydrocarbon exploration was comparatively less intense. West of it no exploration activities were carried out at all. Since the 1980ies hydrogeologic investigations in the course of thermal water exploration in the Molasse Basin and aquifer characterisation in the Hegau resulted in regional descriptions of the fault network (e.g. Bertleff 1986, Vogelsang & Villinger 1987, Interreg IIIA 2007).

Comprehensive mapping during the 1960ies to 1990ies by Schreiner lead to an in-depth knowledge of the geology of the Hegau region manifested in several 1:25 000 map sheets. The knowledge gained during these mapping campaigns is well summarised in the explanatory note of the 1:50 000 overview map of the region (Schreiner 1992).

The development of advanced geologic methods led to investigations of specific topics in the Hegau. With the possibility of absolute age dating, the volcanic lithologies in the Hegau were dated (e.g. Lippolt et al. 1963, Weiskirchner 1972). Mäussnest & Schreiner (1982) mapped even small volcanic occurrences by geomagnetic survey. Ernst (1969, 1971) looked for faults by measuring gas exhalation into the soil. Most recently, geological investigation in the HELC region concentrate on the seafloor of Lake Constance (Wessels et al. 2010).

Recent tectonic investigations by contrast are generally rare in southwestern Germany and mostly restricted to the area of the Rhine Graben. Tectonic syntheses are given only by Schönenberg (1973) in a very short manner and by Reicherter et al. (2008). Rupf & Nitsch (2008) and Geyer et al (2011) provide general geologic syntheses.

Only for the Albstadt shear zone some seismotectonic concepts and tectonic hypothesis are published (Illies, 1978, 1982, Schneider 1993, Reinecker und Schneider 2002). These studies intend to understand crustal scale kinematics and the regional relevance of this fault zone.

2.2 Cartographic materials for the Hegau and Lake Constance region

The German part of the study area is fully covered with published 1:25 000 map sheets of the official geologic map of Baden –Württemberg (Fig. 2). The age of these maps ranges from recently published and revised to sheets that are over 100 years old. Some map sheets are published in "preliminary edition", which basically means that they were published without explanatory notes. The Swiss part of the study area is covered by the 1:25 000 map sheets of the Swiss geologic Atlas. The explanatory notes of these 1:25'000 map sheets provide the most detailed information on the geology and the tectonic structure of the respective area, as well as important literature references.

Larger scale maps exist from both, the German as well as the Swiss part of the study area. The 1:50 000 map of Schreiner (1992) gives an overview of most of the HELC region. For overview purposes the 1:200'000 and 1:500' 000 scale maps from Baden-Württemberg, the 1:500'000 geologic map of Bavaria and the 1:500'000 geologic and 1:500'000 tectonic map of Switzerland were considered as well as the 1:100 000 geologic map of central northern Switzerland (Müller et al. 1984).

The vector-based digital map "GK50" on the scale 1:50'000 is currently available for the western half of the larger study area. It will successively be extended further east and cover the whole study area in the near future. On the online map server of the Landesamt für Geologie, Rohstoffe und Bergbau Baden-Württemberg (LGRB 2011), the geologic map 1:300'000 and the geologic model of Baden-Württemberg in 1:500'000 (Geologisches Landesmodell, Rupf & Nitsch 2008) can be viewed. Further data such as the location of wells are also provided (LGRB 2011). Vector-based digital maps from the Swiss part are available in 1:25 000 for the published map sheets of the Swiss geologic Atlas and in 1:500 000 for Switzerland as a whole (Swisstopo 2011).

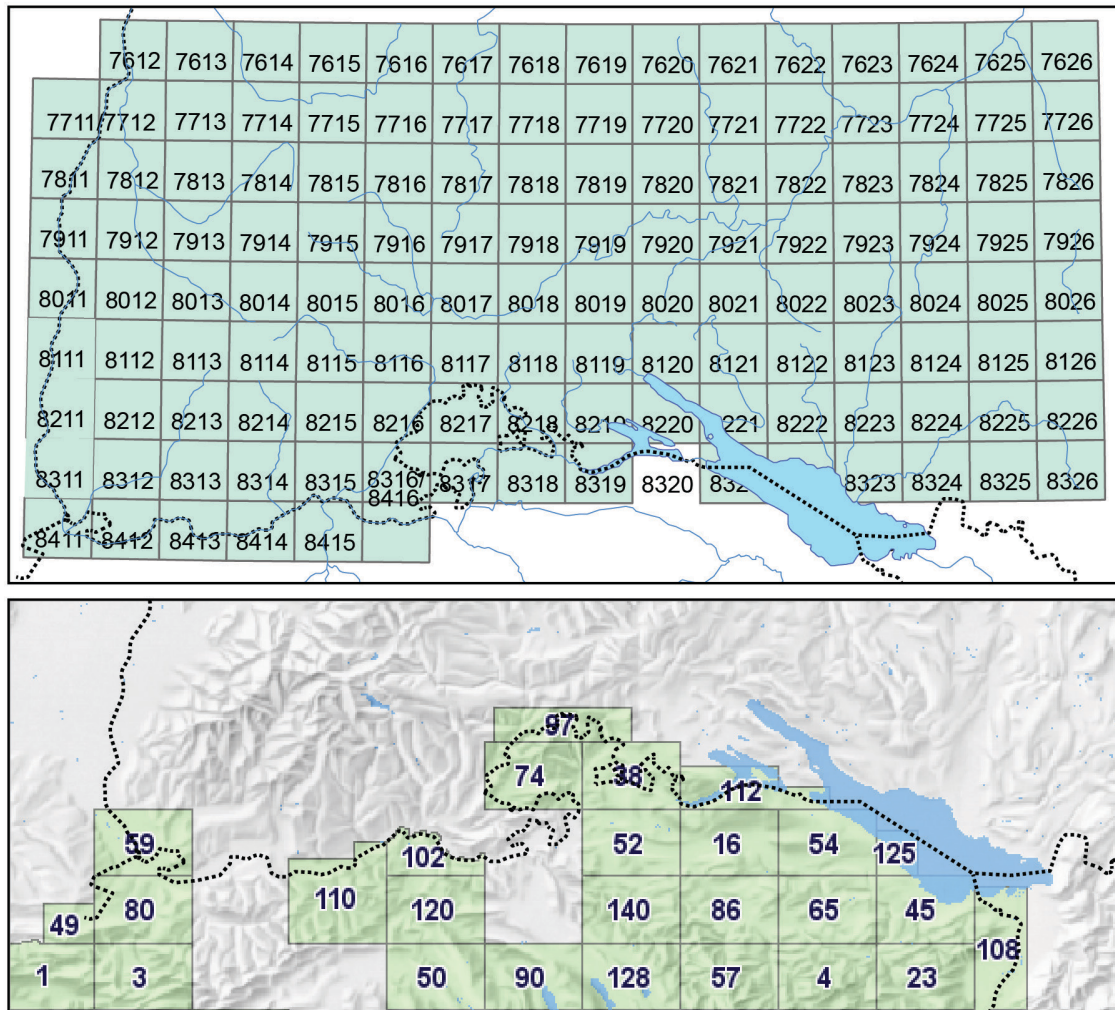


Fig. 2: 1:25'000 map sheets with official numbers of the geological map of Baden-Württemberg (upper map) and of the Geological Atlas of Switzerland (lower map) that are of relevance to the study area
(after LGRB 2012 and Swisstopo 2012)

3 Geodynamic overview

3.1 Present-day geodynamic setting

The HELC region lies in a geodynamic key location at the transition between the orogen of the European Alps and its northern foreland (Fig. 3). The northern part is constituted by the southwestern edge of the South German Triangle and is strongly characterised by the development of the European Cenozoic Rift system. The southern part encompasses the northernmost extent of the peripheral Alpine foreland basin (Molasse Basin).

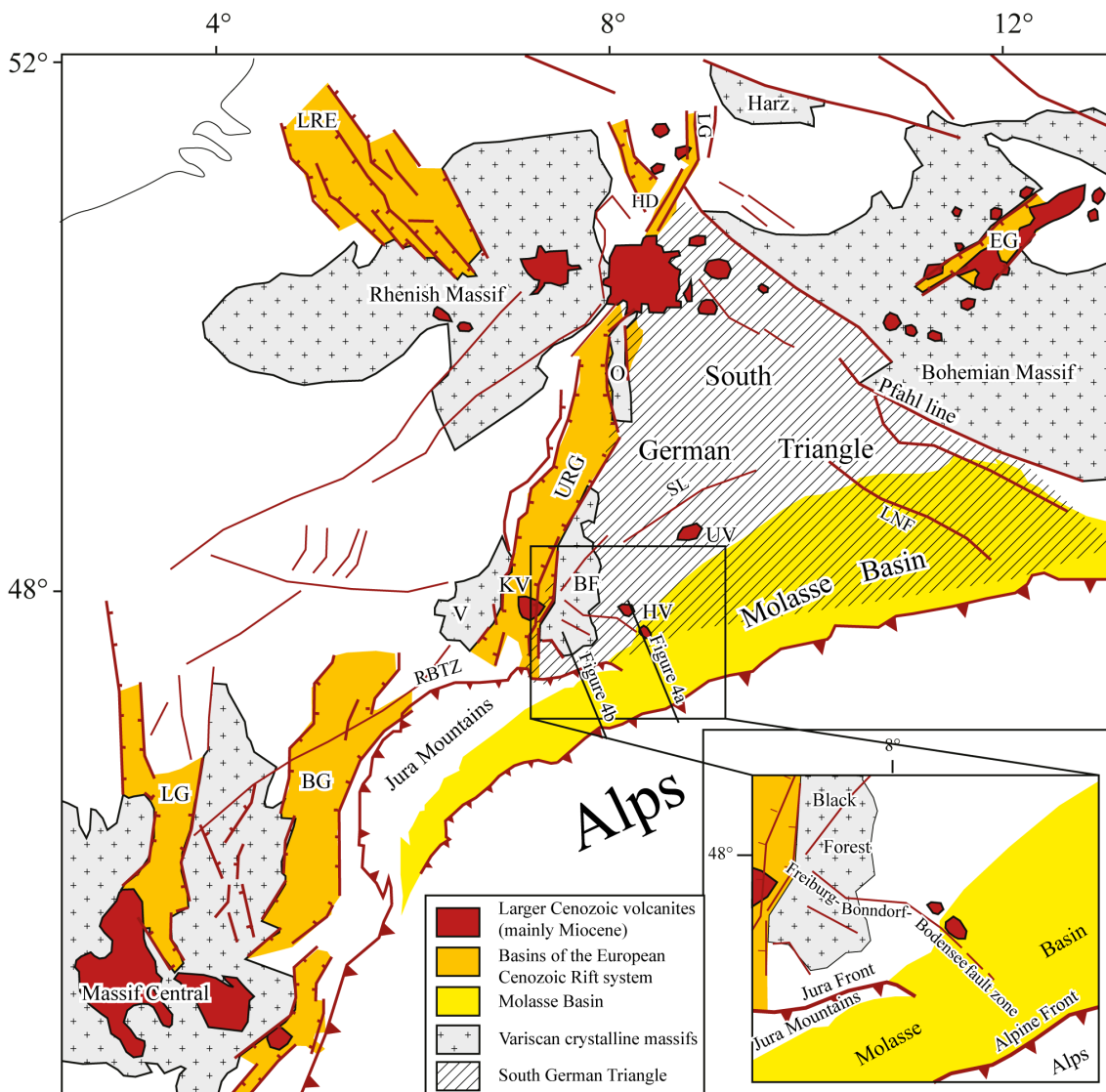


Fig. 3: Large tectonic units of central Europe north of the Alps

Inset shows the larger study area. Traces of cross sections given in Fig. 4 are indicated. BF = Black Forest, BG = Bresse Graben, EG = Eger Graben, HD = Hessian depression, HV = Hegau volcanic field, KV = Kaiserstuhl volcanic field, LEG = Leine Graben, LG = Lorraine Graben, LNF = Landshut-Neuötting fault, LRE = Lower Rhine Embayment, O = Odenwald, RBTZ = Rhine-Bresse transfer zone, SL = Swabian Lineament, URG = Upper Rhine Graben, UV = Urach volcanic field, V = Vosges Mountains. Modified after Dèzes et al. (2004), Ziegler & Dèzes (2007) and Burkhard & Sommaruga (1998).

3.1.1 South German Triangle and European Cenozoic rift system

The South-German-Triangle (Reicherter et al. 2008, "Südwestdeutsche Grossscholle", Carlé 1955) is part of the Central European platform and is constituted by Mesozoic units. In the area of interest the stack of sedimentary rocks is slightly inclined towards the southeast resulting in a cuesta landscape. The northeastern border of the triangle towards the Bohemian massif is formed by NW-SE striking reverse fault zones (e.g. the Pfahl line, Carlé 1955, BGLA 1996). It's southern border is formed by the Oligocene-Miocene Molasse basin of the Alpine foredeep. In the west, the South German Triangle is bordered by the European Cenozoic rift system (ECRIS), a crustal structure that crosses the European platform from the western Mediterranean to the North Sea (Illies 1977, Ziegler 1992, Dèzes et al. 2004). Its central and most prominent part is formed by the 300 km long, NNE-SSW striking graben structure of the Upper Rhine graben (URG). In its southern parts, the URG spatially interact with the northern front of the Jura Mountains. Within the ECRIS, the URG is connected with the Bresse graben via the NE-SW striking Rhine-Bresse Transfer Zone (RBTZ) (Illies 1977, Ziegler 1992; Madritsch et al. 2009). North of the URG the ECRIS is divided into two branches. The northeastern branch reaches through the Hessian depression in the Leine graben while a northwestern branch reappears north of the Rhinish Massif in the lower Rhine embayment. Ziegler (1992) related the spatial distribution of the structures of the ECRIS to the distribution of Permo-Carboniferous troughs. Such a relationship was shown for the Rhine-Bresse transfer zone (e.g. Madritsch et al. 2009).

The central South-German-Triangle is characterised by widespread steep fault zones that strike NNW-SSE (eggisch), N-S to NNE-SSW (rheinisch), NE-SW (erzgebirgisch), ENE-WSW (variszisch or schwäbisch) and WNW-ESE, to NW-SE (herzynisch) (Carlé 1955). The fault zones that clearly reveal a Cenozoic activity are largely thought to be older lineaments that were reactivated under varying Cenozoic stress fields. The mapped offsets at the individual fault zones are mostly normal and reverse. Strike-slip faulting is difficult to determine, though often likely when considering the paleostress and recent stress configurations (Schönenberg 1973, Reicherter et al. 2008, chapter 3.3).

3.1.2 Molasse Basin and northern Alpine front

The southern part of the study area belongs to the Alpine Molasse Basin (Fig. 3). This basin represents a classical peripheral foreland basin (Karner & Watts 1983, Pfiffner 1986, Allen et al. 1991). It extends from Vienna in the east to Savoy south of Geneva in the West, following the northern rim of the Alpine chain for about 700 km. The Basin is filled with Oligocene and Miocene clastic sediments that were deposited in two shallowing-up megacycles (Trümpy 1980, Homewood et al. 1986). The main formations are the Lower Marine (UMM), Lower Freshwater (USM), Upper Marine (OMM) and Upper Freshwater Molasse (OSM). In the eastern Alps and in the eastern part of the central Alps the northern Alpine deformation front is located in the southern parts of the Molasse Basin. The internal Molasse units are already incorporated in the Alpine nappes, forming the fold- and thrust belt of the Subalpine Molasse (Trümpy 1980). At the Molasse Basin – Subalpine Molasse transition, the thrust front often shows a conspicuous triangle zone that is characterised by a back-thrust on top of a blind thrust (Vollmayr & Wendt 1987, Müller et al. 1988, Pfiffner et al 1997, Berge & Vial 2005, Fig. 4).

Further west the actual deformation front of the Alpine orogen jumps north to form the front of the Jura Mountains (Figs. 3 and 4). This arcuate range represents a foreland fold-and-thrust belt with remnants of Molasse preserved in its synclines. The Jura Mountain deformation and the passive transport of the western Swiss Molasse Basin in its back is thought to have occurred on top of a décollement in Triassic evaporites in the Late Miocene (Buxtorf 1916, Laubscher 1961;

Burkhard 1990). The westward increase of shortening in the Jura Mountains is accompanied with decrease in shortening accommodated in the Subalpine Molasse (Burkhard 1990). However, the northward jump of the orogenic deformation front is apparently not accompanied by any kind of large scale transfer structure and the autochthonous eastern Molasse apparently transforms into the transported detached western part without any distinct structural expression. In the westernmost Molasse Basin close relationships between folding and thrusting (Beck 1946, Rutsch 1947) and strike-slip faulting (Ibele 2011) are reported along the front of the Subalpine Molasse. Even further to the southwest, the Jura Mountains front again joins the front of the western Alps merging with the Subalpine Chains of France (Fig. 3).

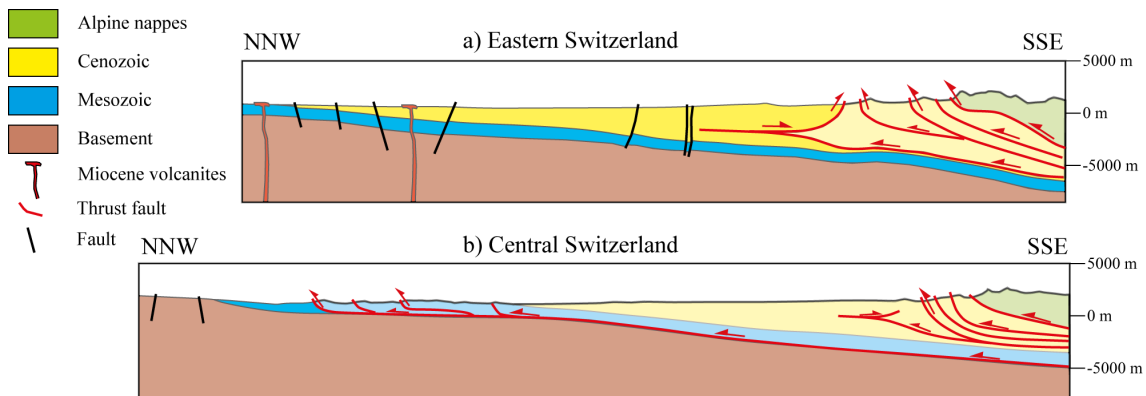


Fig. 4: Two simplified cross sections illustrating the change of the Alpine front along strike

In the east the Alpine thrust front is located in the southern part of the Molasse Basin whereas in the west the thrust front is located at the front of the Jura Mountains and the whole Molasse basin is passively transported on top of a décollement. The parts of the sections attributed to the Alpine orogenic wedge are given in pale colours. See Fig. 3 for location.

3.2 Paleogeographic and tectonic evolution

The paleogeographic evolution of southwestern Germany (Fig. 5) is discussed in Geyer et al (2011) and Rupf & Nitsch (2008). The following section provides a brief summary largely focussing on tectonic aspects.

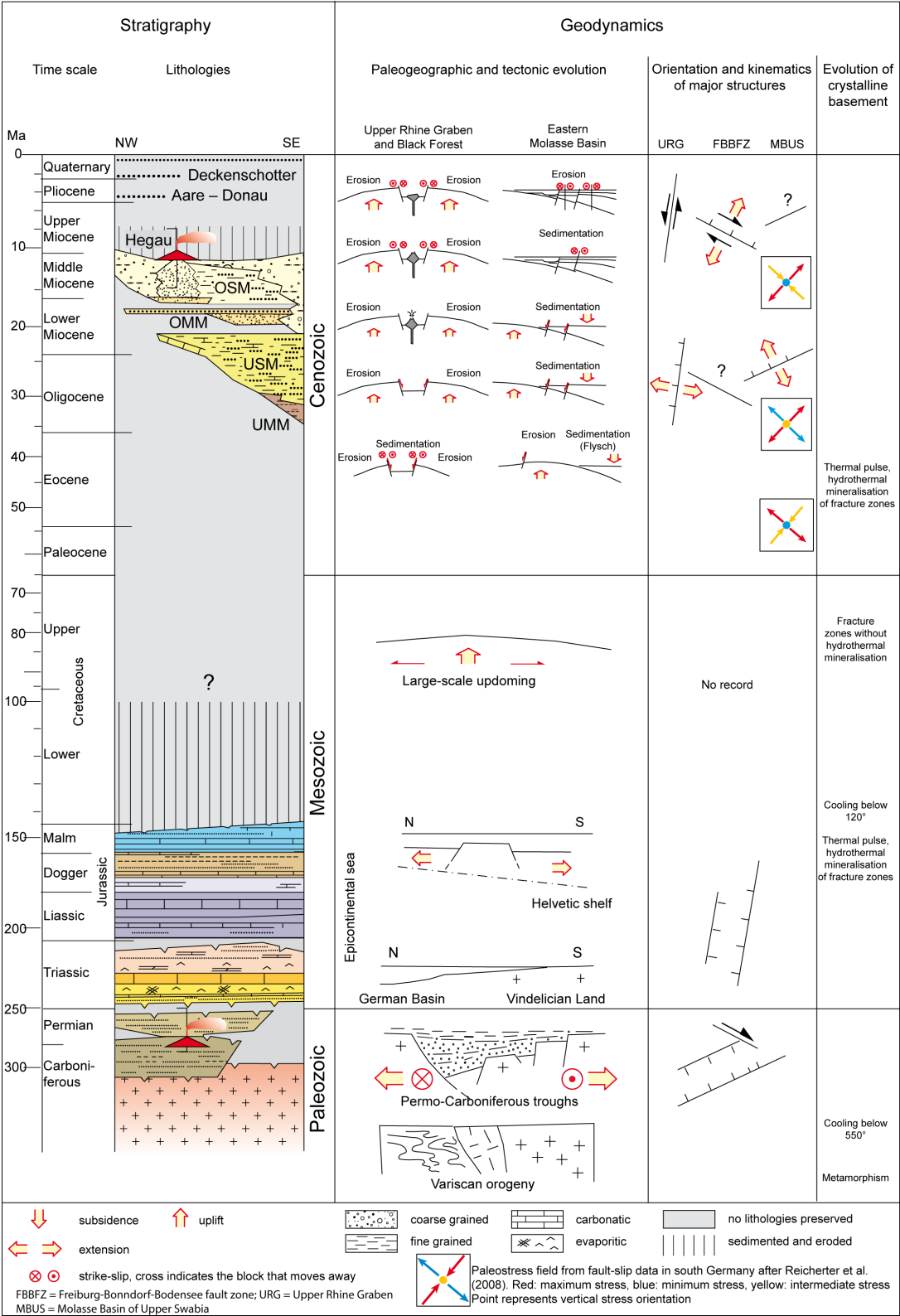


Fig. 5: Evolutionary scheme for southwestern Germany (Modified from Müller et al. 2002). Evolution of crystalline basement after Franzke & Werner (1994), Werner & Franzke (2001), Timar-Geng et al. (2006a, 2006b) and Danišik et al. (2010).

3.2.1 Late Paleozoic

In Central Europe brittle tectonic deformation set on with the collapse of the Variscan orogeny and is characterised by the widespread formation of WSW-ENE striking tectonic basins. In the frame of large-scale right-lateral shear, synthetic second-order faults of WNW-ESE strike and antithetic faults of NNW-SSE strike were formed. The lower Permian paleogeography is accordingly characterised by ENE-WSW and NNW-SSE striking lineaments with sediments accumulated in ENE-WSW striking basins (Fig. 6a). The most important of these basins in the study area is the Permo-Carboniferous trough of northern Switzerland (Figs. 6a and 7), which is separated by the southern Black Forest high from the Breisgau basin and the Schrammberg basin further north. These basins are interrupted along strike by NNW-SSE striking structural highs (Fig. 6a). Some of these structural highs seem to be fault related (western edge of the Schrammberg trough, Rupf & Nitsch 2008, Nitsch 2011, personal communication).

Late Paleozoic sediments are also reported from several wells in the HELC region (compare chapter (Fig. 7). It is general assumed that these occurrences are related to the Permo-Carboniferous trough of northern Switzerland (see chapter 4.1).

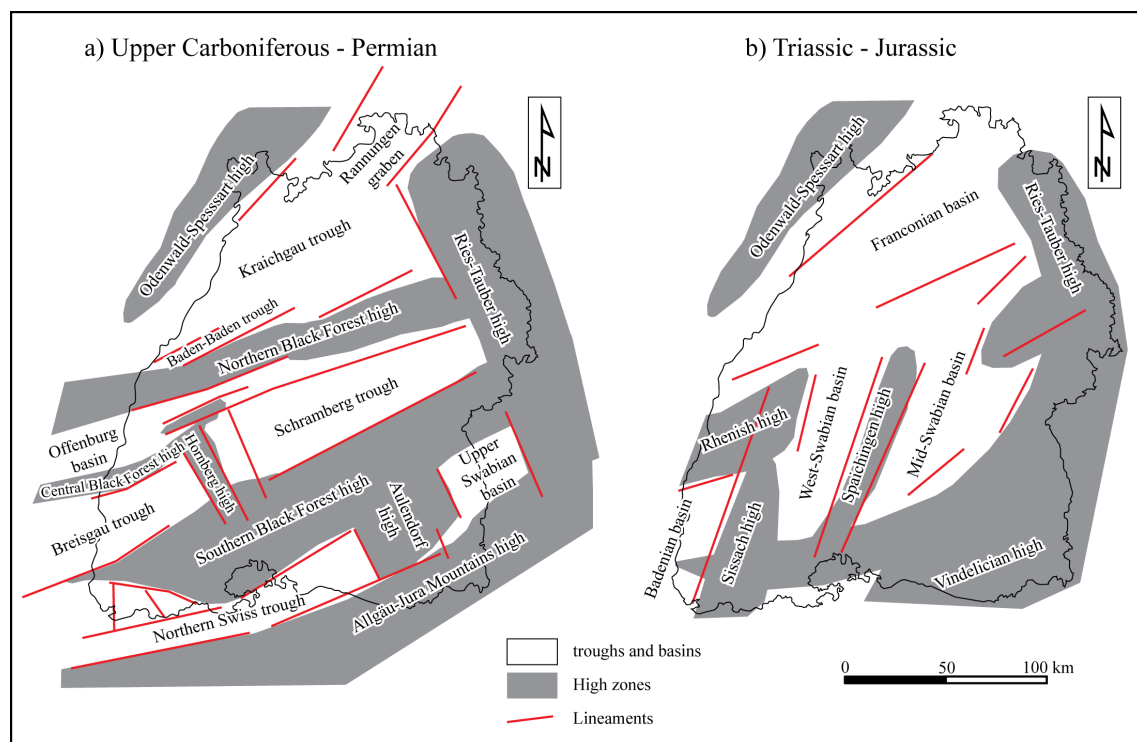


Fig. 6: Distribution of high zones, basins and lineaments in a) the late Paleozoic and in b) the Mesozoic in Baden-Württemberg (SW Germany)

In the map for the late Paleozoic, basins are termed "trough" where sediments are more than 100 m thick, and "basin" where there is less than 100 m sediment. Modified from Rupf & Nitsch (2008).

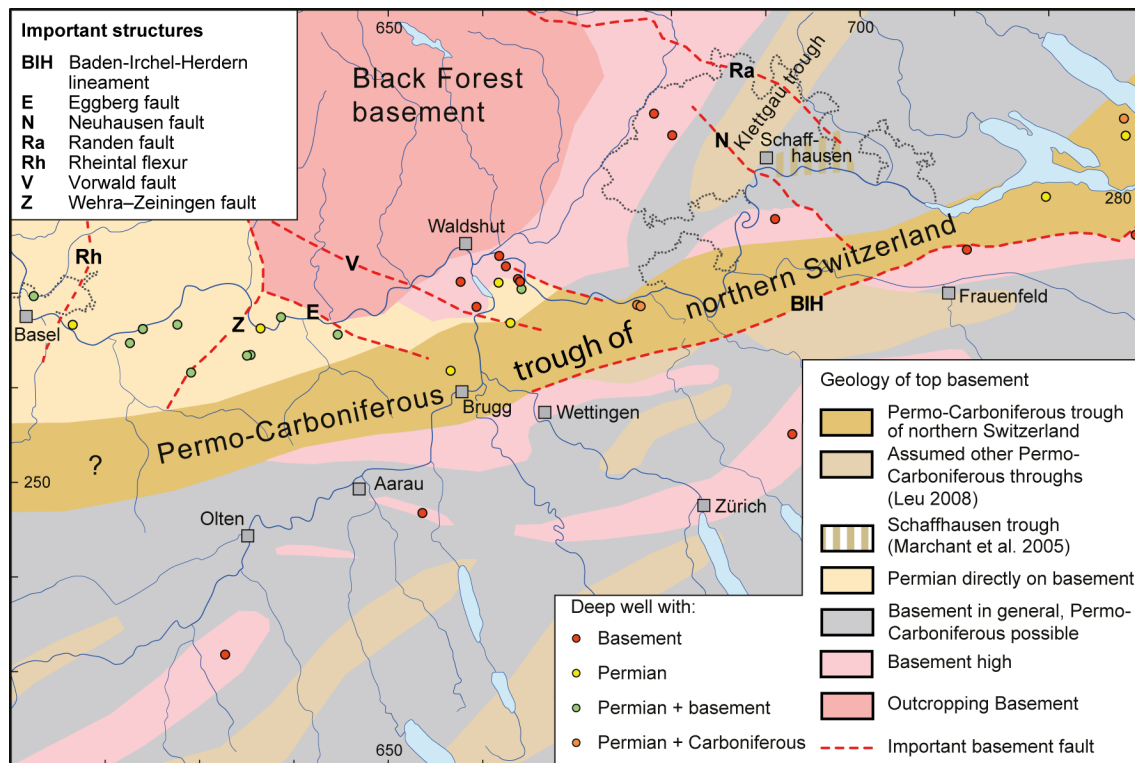


Fig. 7: Overview of the Permo-Carboniferous trough of northern Switzerland between south of Basel and the Lake Constance

The trough axis strikes WSW-ENE. In the central part, detailed studies revealed the northern border of the trough to be offset by the WNW-ESE striking Eggberg fault, Vorwald fault and Hotzenwald fault. Figure modified from Nagra (2008).

3.2.2 Mesozoic

During the Mesozoic, the larger study area was subject to subsidence and sedimentation. The HELC region was part of the Vindelician High (Fig. 6b) indicated by the comparatively lower stratigraphic thicknesses of sediments from that time period in the area (Rupf & Nitsch 2008).

The largest depositional thicknesses are reached in the Mid-Triassic in the NNE-SSW oriented West-Swabian basin (Fig. 6). They include a mid-Muschelkalk salt horizon representing a NNE-SSW striking deposit contiguous with the salt horizon found beneath Jura Mountains (Wild 1968, Simon 2003, Geyer et al. 2011). The salt deposit does not continue further east, where only anhydrites can be found (Wild 1968, Simon 2003). From the Upper Triassic onwards the Mid-Swabian Basin (Fig. 6b) developed. In the Dogger the basin reached its largest extent with the deposition of thick clay sequences between the town of Reutlingen (Fig. 1) in the NNE and the Hegau in the SSW. The basin's western border towards the Spaichingen high (Fig. 6b) is proposed to coincide with the Cenozoic Albstadt shear zone (Rupf & Nitsch 2008). During the Malm a major paleogeographic change occurred to the southeast of the study area with the drowning of the Vindelician high in the Helvetic basin. From that time onwards subsidence in the study area came to a halt and the region was uplifted. Only in the southeastern part of the region sedimentation reinitiated during the Oligocene and Miocene formation of the Molasse Basin.

From a tectonic point of view it is important to note that in the paleogeographic record, ENE-WSW striking (Variscan) and NNE-SSW striking (Rhenish) elements form important lineaments in the early and late Permian as well as in the Mesozoic, respectively. NW-SE striking (Hercynian) elements are, however, rather insignificant in the pre-Cenozoic evolution (Fig. 6).

3.2.3 Cenozoic

In the northern Alpine foreland, Cenozoic deformation led to the reactivation of older brittle fault structures. In Germany, it started during the Late Cretaceous and is known as the Saxonian tectonic phase (Reicherter et al. 2008). In central and northern Germany this deformation phase is characterized by the formation of anticlines caused by salt flow that was initiated by a combination of overburden and tectonic stresses. In contrast, no substantial compression is recorded in southern Germany, where normal- and strike-slip faulting predominates (Carlé 1955, Schönenberg 1973, Reicherter et al. 2008). Determination of the exact deformation timing is hampered by a wide-spread hiatus between the Late Jurassic and the Oligocene.

The most important and much better constrained Cenozoic tectonic events in southwestern Germany are the formation of European Cenozoic rift system (ECRIS) including the opening of the Upper Rhine Graben (URG), the related uplift of the Black Forest massif and volcanic activity documented in the Kaiserstuhl, Urach and Hegau region, as well as the Alpine collision leading to the down flexing of European crust and formation of the Molasse basin.

The URG initiated in the Eocene and developed mainly during the Oligocene (Schumacher 2002), showing vertical offset of several kilometres in the southern part. The Miocene to recent tectonic history of the URG is generally dominated by the reactivation of border faults according to NW-SE compression, resulting in oblique left-lateral movement with a normal component (Schumacher 2002, Plenefisch & Bonjer 1997, Cloetingh et al. 2006).

Uplift of the Black Forest and Vosges Massifs to both sides of the southern half of the URG is documented by thermochronology and the hydrothermal evolution of the crystalline basement as well as by the denudation products of the cover units. Zircon and apatite fission track cooling ages show a late Variscan cooling and significant thermal pulses in Jurassic and Eocene times (Timar-Geng et al. 2006a, 2006b, Danišik et al. 2010). Cooling under 120° C occurred during the early Cretaceous (Timar-Geng et al. 2006). The late Jurassic hydrothermal pulse can be related to the large-scale regional uplift that resulted in the wide-spread hiatus between Upper Jurassic and Oligocene sediments in the area (Geyer et al. 2011). Cooling and a prevalence of brittle deformation likely followed this first phase of uplift. The dating of mineralisations in fracture zones and of ore veins reveals Upper Jurassic and uppermost Cretaceous ages, indicating enhanced hydrothermal activity. In contrast, early and mid-Cretaceous times were dominated by brittle faulting without the involvement of hydrothermal fluids (Franzke & Werner 1994, Werner & Franzke 2001).

The well constrained thermal pulse during the Eocene is inferred to be related to the onset of rifting of the URG and is accompanied by the first volcanic activity in the area (Keller et al. 2002, Timar-Geng et al. 2006a, 2006b, Danišik et al. 2010). Erosion products of Mesozoic rocks from the rift shoulders already appear in the sedimentary record of the Upper Eocene (Priabon, Geyer et al. 2011). In contrast, the Juranagelfluh of the Hegau region is Miocene in age, indicating the erosion related to the southeastward retreat of the cuesta landscape on top of the eastern slope of the Black forest (Schreiner 1965) to have occurred significantly later. This second phase of larger-scale uplift lead to emergence of the Vosges and Black Forest massifs since the Miocene (Dèzes & Ziegler 2004). During this time, activity of the URG was left-

lateral strike-slip motion rather than normal faulting (e.g. Schumacher 2002, Cardozo & Behrmann 2006). The young uplift is inferred to be related to lithospheric folding under NW-SE directed stresses (Cloetingh et al. 2006) with the local culmination in the area of the URG caused by the increased erosion along the rift valley (Ziegler & Dèzes 2007), triggering the uplift by erosional unroofing (Simpson 2004).

Late Cretaceous to Pleistocene alkaline volcanics, with peak activity during the Miocene, occurs widespread in Central Europe (Wimmenauer 1974). In southwestern Germany, Late Cretaceous and early Tertiary activity can be related to the evolution of the URG rift (Keller et al. 2002), although the eruption of larger volumes is restricted to the Miocene. These are located punctually in the URG (Kaiserstuhl) but also in the Hegau and the Urach region (Fig. 3), thus correlating with different, rather local tectonic structures.

During the Neogene the direction of compression in Central Europe changed from NNE-SSW to NW-SE (Reicherter et al. 2008). This change resulted in a change from rifting to left-lateral strike-slip in the Upper Rhine graben (e.g. Schumacher 2002, Cloetingh et al. 2006), the formation of the Jura Mountains as an external fold-and-thrust belt in front of the Alps (Laubscher 1961, 1987, Naef et al. 1985, Burkhard 1990), and in the continuous decline of sedimentation and onset of erosion in the Molasse Basin (e.g. Cederbom et al. 2004). This Alpine phase was referred to as the neotectonic period in the larger study area (Becker 1993).

3.3 Paleostress evolution

A paleostress history has been deduced for the Cenozoic of the European platform based on fault slip data (Bergerat 1987, Letouzey 1986) and was summarised in Reicherter et al. (2008) for southwestern Germany.

Bergerat (1987) infers a quite complex evolution of the stress field of Central Europe: Starting with late Eocene N-S compression (1st stage), it contains Oligocene E-W extension (2nd stage), early Miocene NE-SW extension (3rd stage) and finally late to post-Miocene NW-SE compression (4th stage). Reicherter et al. (2008) present a slightly simpler evolution proposing NE-SW compression to have lasted until the Early Eocene, followed by a general phase of extension from Late Eocene to Oligocene times, and a final phase of NW-SE compression in the Neogene (Fig. 5).

Changes in compression strengths can lead to permutation of the principal stress axes and to changes from compression to strike-slip and extension with time (Letouzey 1986). The four stages of Bergerat (1987) can accordingly be interpreted as two stages each comprising one stress permutation, with the horizontal stress axes first oriented N-S and E-W, then NW-SE and NE-SW. The first stress orientation can be attributed to the Pyrenean phase and the second one to the Alpine phase of Africa-European collision (Reicherter et al. 2008). The more general extensional signature recorded in southwestern Germany (Reicherter et al. 2008) includes structures attributed to the 2nd and 3rd stage of Bergerat (1987) and may be a local expression of the transitional phase. No detailed paleostress studies exist for the HELC region itself.

3.4 Pleistocene landscape evolution

Glacial and interglacial periods with alternating sedimentation and erosion episodes have shaped the landscape of the HELC region during the Pleistocene. Apart from multiple glaciation pulses from the southward adjacent Alps into the foreland, the area was also heavily influenced by modification of the regional drainage system. While the region was mostly drained by the Danube river towards the east in Late Pliocene times it is recently drained by the Rhine River towards the west (Villinger 1998, Preusser 2008).

The Pleistocene sediments in the HELC region can be divided into the early Pleistocene fluvial gravel nappes (Deckenschotter) representing a low-relief, N to NW-dipping alluvial plane and Late Pleistocene glacial deposits (Ellwanger et al. 2011).

Incision of the rivers and repeated overprinting by glaciers transferred the low-relief landscape of the Deckenschotter into an amphitheatre-like morphology that is characterised by dips towards the centre of a half-circle in which Lake Constance is situated (Ellwanger et al. 2011). This Late Pleistocene evolution of the Lake Constance amphitheatre (term used by Ellwanger et al. 2011) was not only triggered by the westward deviation of the river system but also by the evolution of the Alpine Rhine valley. Detritus of the early Pleistocene Deckenschotter in the area contain Austroalpine and Rhenodanubian gravels only, indicating a small catchment area above the future Lake Constance (Verderber 2003, Ellwanger et al. 2011). The inner Alpine Rhine drained the Walensee valley and the Linth system (Graf 1993). The connection of the Lake Constance region with the large inner-Alpine Rhine system via the lower Alpine Rhine valley was opened in late Early Pleistocene times (Ellwanger et al. 2011). The resulting catchment area was sufficiently large to supply ice masses for forming extended foreland lobes during the Late Pleistocene glaciations in the Lake Constance region (Ellwanger et al. 2011).

4 Geologic and Tectonic setting

Major fault systems and important tectonic elements of the study area are given in Fig. 8. The geologic units of the study area are summarised in stratigraphic columns in Encl. 1 and 2. In the following, a description of the geologic units precedes an outline of the major fault systems and important tectonic elements.

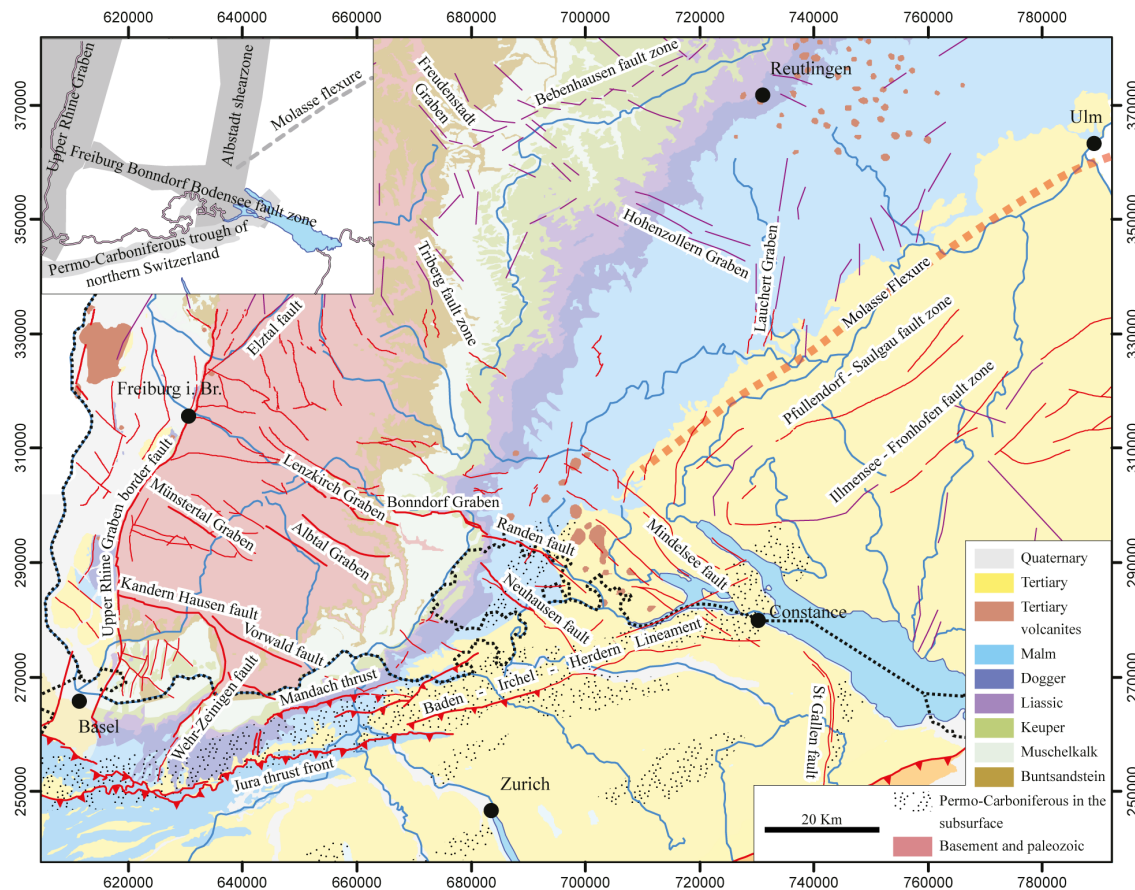


Fig. 8: The larger study area with important tectonic elements of southwestern Germany and northern Switzerland

Inset shows larger-scale tectonic zones. Fault pattern is compiled after Nagra (2008; given in red) and supplemented by faults after Geyer et al. (2011) and Bertleff (1986) (given in violet).

4.1 Geologic setting

In the western and central part of the larger study area, Palaeozoic basement rocks and Triassic sediments are exposed along the southeastern flank of the Black Forest. Surface outcrops in this area expose only the Permian high zones where Triassic Buntsandstein directly overlies the basement. Oxfordian to Tithonian limestones crop out in the Hegau s. str. From the Cretaceous onwards these Mesozoic sediments were uplifted and karstified. Eocene residual clay formations (Bohnerzlehm) were locally deposited on top. Otherwise, the Mesozoic rocks are discordantly overlain by the clastic Oligocene and Miocene Molasse group preserved in the southeastern part of the HELC region s.l. The fourth rock type found in the region are Miocene volcanics.

In the Hegau s.str. (compare Fig. 1), neither Lower Jurassic and Triassic rocks nor Paleozoic sediments or crystalline basement rocks are exposed. In this area these geologic units are only known from the well Dingelsdorf 1 (Fig. 7) and a few other deep wells (see compiled stratigraphic columns in Encl. 1 and 2).

4.1.1 Basement and Palaeozoic rocks as exposed in the southern Black Forest

Basement rocks crop out in the Black Forest (Figs. 1 and 8). They mainly consist of amphibolite-facies Ortho- and Paragneisses (Geyer et al. 2011). In the southern parts of the Black Forest Carboniferous granite plutons as well as granitic dykes are widespread (e.g. Geyer et al. 2011, Schaltegger 2000).

Due to granitic and gneissic basement ejections associated with Deckentuff volcanics in the Hegau, Schreiner (1992) assumed a gneissic basement strongly penetrated by granite intrusions for the HELC region. Apart from late Devonian to early Carboniferous sediments of the Badenweiler-Lenzkirch zone in the Black Forest (Geyer et al. 2011, Güldenpfennig & Lösche 1991, Sittig 1969), no Palaeozoic sediments are known from the larger study area. The well Dingelsdorf 1 drills penetrated 156 m of Carboniferous and 567 m of lower Permian shales and sandstones (Lemcke & Wagner 1961, Encl. 1). This occurrence is interpreted to be related with the Permo-Carboniferous trough of northern Switzerland.

4.1.2 Triassic, Lower and Mid-Jurassic sediments as exposed on the eastern slope of the southern Black Forest

Triassic successions crop out between the Hegau and the Black Forest. Buntsandstein crops out along the eastern slope of the Black forest. The dolomites of the Lower Muschelkalk and the limestones of the Upper Muschelkalk are separated by the dolomites and anhydrites of the Middle Muschelkalk. The Dingelsdorf 1 well implies that these formations are less thick in the Hegau (well Dingelsdorf 1, no Buntsandstein, Muschelkalk 128m, Lemcke & Wagner 1961) as compared with the outcrops further west (Buntsandstein 50m, Muschelkalk 180m, Wurm et al. 1989, Rupf & Nitsch 2008). Moreover, Middle Muschelkalk contains salt deposits in the central part of the larger study area, but only anhydrite in the Hegau region (Bock et al. 2009, Rupf & Nitsch 2008, Simon 2003, Wild 1968). Approximately 120 m of Keuper crop out in both the Southern Baar and the Hegau. While being composed mainly of sandstones and marls in its upper parts the formation can contain gypsum in its lower parts (Rupf & Nitsch 2008). The Lower and Middle Jurassic is characterised by clays with interbedded thin sandstones, limestone and oolites; most units are less than 20 m thick. The highest thicknesses are reached by the Opalinusclay (100 m in the western part, Geyer et al. 2011; 110m in the well Dingelsdorf 1, Lemcke & Wagner 1961).

4.1.3 Upper Jurassic sediments as exposed in the northern and western Hegau and Lake Constance region

In the northwestern Hegau, the Malm successions are well distinguished due to widespread surface outcrops (Fig. 8). According to Schreiner (1992), Oxfordian marls are followed by the well-bedded limestones of the "Wohlgeschichtete Kalke". The Kimmeridgian starts with a thin marl member, continues with the thick-bedded limestones of the "lower Bankkalke" and ends with the marls of the "Zementmergel". The Tithonian thick-bedded limestones of the "Hangende Bankkalke" are preserved only incompletely. The Kimmeridgian bedded limestone and marls represent a basin facies and are laterally replaced by widespread massive limestones ("Massenkalke") with a sponge-reef origin (Geyer et al. 2011). Compared to the northwest Hegau, the Malm sequences in the well Dingelsdorf 1 in the southeastern Hegau show reduced Oxfordian limestone and an increased thickness of the Kimmeridgian to Tithonian massive limestone (Encl. 1). These changes from NW to SE can be regarded as a general trend (Schreiner 1992).

4.1.4 Molasse sediments as exposed in the southern Hegau and Lake Constance region

In the HELC region three Molasse formations are present with thicknesses generally increasing towards the southeast: the Chattian to Aquitanian Lower Freshwater Molasse (USM), the Burdigalian Upper Marine Molasse (OMM) and the Langhian to Tortonian Upper Freshwater Molasse (OSM) (Encl. 1 and 2).

In the HELC region fluvial and marine sediments of the Molasse formations can additionally be subdivided into a basin and a rim facies (Schreiner 1992, Fig. 9). The basin facies of the USM is represented by sandstones and shales; thicknesses increase from 250 m in the central Hegau to 450 m in the well Dingelsdorf 1 (Schreiner 1992). The rim facies of the USM is represented by the lower "Juranagelfluh" and is characterised by pebbles of Mesozoic rocks coming from the northwest (Schreiner 1965). The basin facies of the OMM is dominated by the thick sandstone beds of the "Heidenlöcher Schichten" and the "Sandschiefer" (Geyer et al. 2011, Schreiner 1992). At the transition to the OSM, the distinctive, about 1 m thick horizon of the "Albstein" pedogenic carbonate is developed (Nägele 1962, Schreiner 1992). The poorly preserved rim facies of the OMM consists of thin carbonates rich in shell detritus and sand ("Randengrobkalk"), covered by a thin sandstone layer as well as scattered "Albstein" occurrences (Geyer et al. 2011, Schreiner 1992). The basin facies of the OSM consists of up to 200 m thick mica-rich sandstones near Überlingen (Geyer et al. 2011, Schreiner 1992). Its rim facies is represented by the up to 150 m thick conglomeratic upper "Juranagelfluh" that contains pebbles like the lower "Juranagelfluh", indicating a sedimentation source to the north (Schreiner 1965).

During the uppermost OMM to lower OSM sedimentation, Molasse deposition is interrupted in the central HELC region by a phase of erosion leading to the development of a broad basin-parallel channel ("Graupensandrinne"). The "Graupensandrinne" s.str. has removed the OMM and is partly incised down to the Mesozoic (Kiderlen 1931, Schreiner 1992). The so-called extended "Graupensandrinne" is broader to the south and has left remnants of OMM (Haus, 1951). The erosion of the "Graupensandrinne" left a 20 km wide gap in the Albstein pedogenic horizon (Fig. 9). It is filled with the "Graupensand" ("Graupensandrinne" s. str.) and the up to 10 m thick Kirchberg beds that were deposited by the eroding fluvial system (Kiderlen 1931). The Kirchberg beds are themselves covered by the sediments of the OSM (Schreiner 1992).

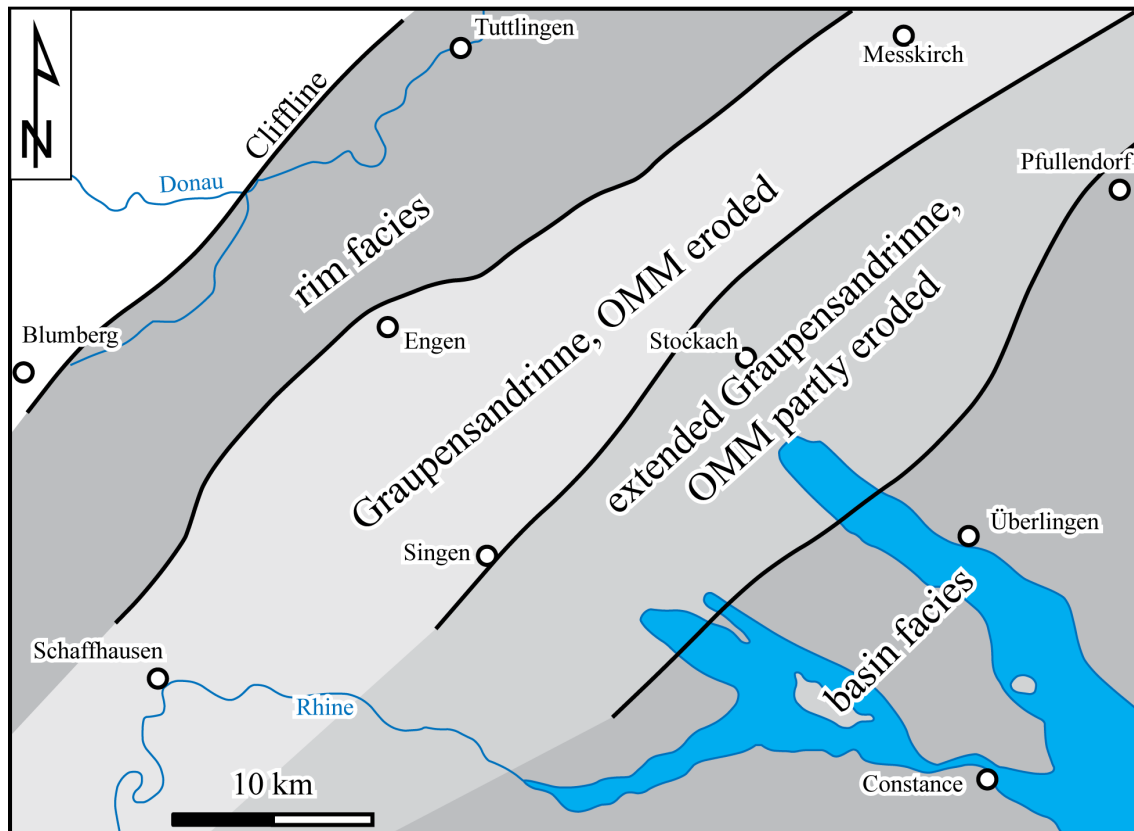


Fig. 9: Facies distribution of the OMM in the Hegau
After Schreiner (1992)

4.1.5 Miocene volcanics in the Hegau and Lake Constance region

The volcanic products in the HELC region can be divided into the older "Deckentuff", the intermediate basalts and the younger phonolites (Fig. 10). Inter-bedding of volcanic rocks with OSM deposits indicates that the volcanic activity is upper Miocene in age, which is also constrained by absolute age dating (mainly K-Ar) (Schreiner 1992, Table 1).

In the southern parts of the Hegau the effusive volcanic "Deckentuff" deposits cover a relatively large (about 36 km²) area. Ar-Ar dating ranges between 16.1 Ma (Lippolt et al. 1963) and 12.4 Ma (Weiskirchner 1972). The basalts form seven isolated occurrences and several dykes reaching from the central to the northern Hegau. They are dated at 11.8 Ma (Weiskirchner 1972). At the same locality a Hornblende-rich tuff is preserved which is dated at 9.4 Ma (Weiskirchner 1972). The phonolites are found at four closely spaced points within the "Deckentuff" area, with ages ranging between 8.0 and 6.9 Ma (Weiskirchner 1972).

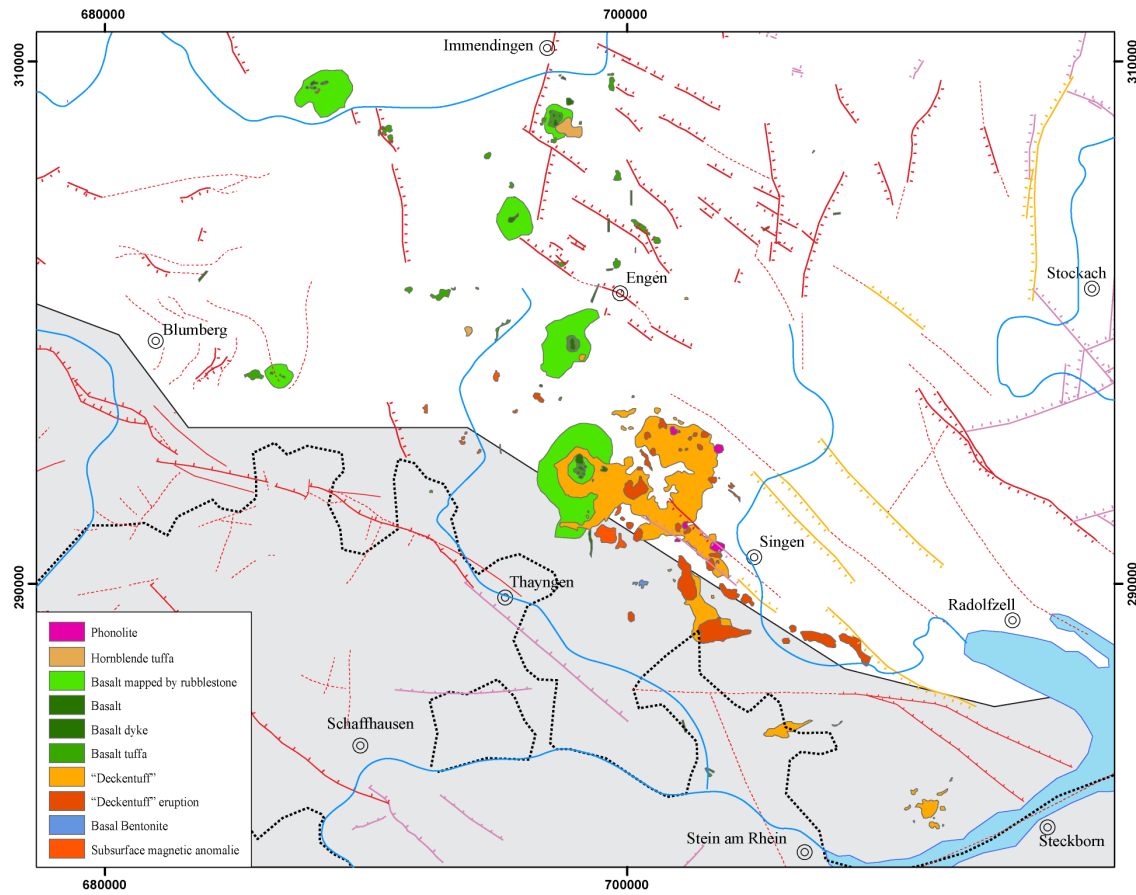


Fig. 10: Detailed map of the Hegau volcanics with fault pattern

Volcanics after Mäussnest & Schreiner (1982). For details on the shown fault pattern see Encl. 3.

Tab. 1: Age of volcanics from the Hegau area

Location	Lithology	Age (Ma)	Stage	Reference
Hohenkrähen	Phonolith	6,9	Messinium	Weiskirchner (1972)
Gönnersbohl	Phonolith	8,0	Tortonium	Weiskirchner (1972)
Hohentwiel	Phonolith	9,5	Tortonium	Lippolt et al. (1963)
Höwenegg	Basalt	11,8	Serravalium	Weiskirchner (1972)
Höwenegg	Hornblendetuff	9,4	Tortonium	Weiskirchner (1972)
Hohenstoffeln	Deckentuff	12,4	Serravalium	Weiskirchner (1972)
Junkersbühl	Deckentuff	16,1	Burdigalium	Lippolt et al. (1963)

4.2 Tectonic setting and major fault systems

4.2.1 Permo-Carboniferous trough of northern Switzerland

The Permo-Carboniferous trough of northern Switzerland is well documented by seismic and well data (e.g. Diepold 1985, Matter 1987, Bachmann et al. 1987, Pfiffner et al. 1997, Marchant et al. 2005, NAGRA 2008, Fig. 7). It strikes roughly ENE-WSW between south of Basel and Lake Constance. Sub-troughs and border faults are comparatively well known in this area (Müller et al. 2002, Marchant et al. 2005, NAGRA 2008). The ENE-WSW striking southern and northern borders are partially offset by WNW-ESE striking conjugate faults, indicating a transtensive right-lateral tectonic regime to be responsible for trough formation (Müller et al. 2002, Marchant et al. 2005). In the Lake Constance region the nearly 500 m of Permo-Carboniferous sediments in well Dingelsdorf 1 at Lake Constance are in sharp contrast to 0 m recorded in the wells Salem 1 and Harresheim 1, only 15 to 20 km further east along strike of the presumed structure (Fig. 11). This points towards a complex trough geometry.

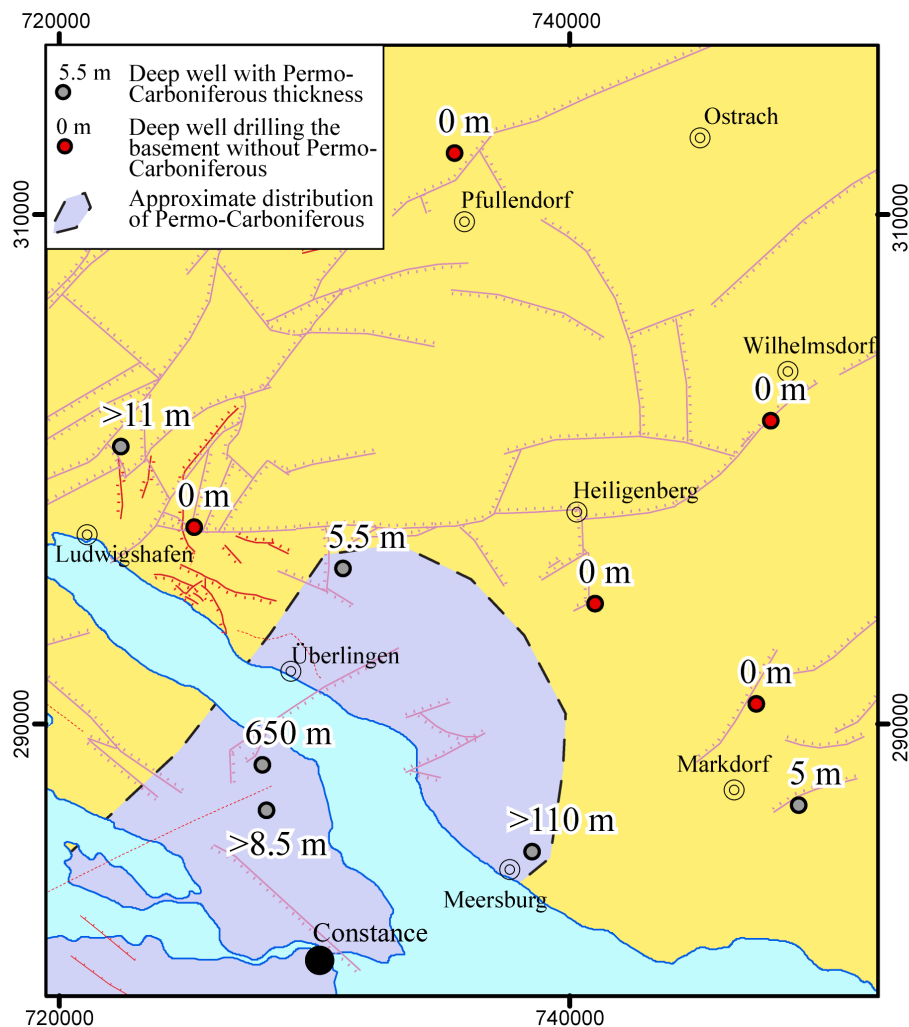


Fig. 11: Eastern end of the Permo-Carboniferous trough of northern Switzerland

From the well Dingelsdorf 1 with 650 m of Permo-Carboniferous sediments, thicknesses decrease rapidly towards northeast along strike of the trough. Approximate border of Permo-Carboniferous is taken from the Nagra dataset. Fault pattern is a detail of Encl. 3 (see there for further legend).

4.2.2 Freiburg-Bonndorf-Bodensee fault zone

The Freiburg-Bonndorf-Bodensee fault zone (FBBFZ; Paul 1948b, Carlé 1955) consists of several individual structures forming a zone that reaches from Lake Constance to the Upper Rhine Graben (Figures 8 and 12). It was recognised in the early 20th century (e.g. Schmidle 1918, Regelmann & Regelmann 1921, Paul 1948b) as an important tectonic element connecting the volcanic fields of the Hegau and the Kaiserstuhl. The fault zone strikes WNW-ESE, but individual fault strike vary between NW-SE and E-W. Mapped fault offsets are normal, but outcrop-scale structures such as slickensides often suggest horizontal movements (e.g. Wirth 1984). The most important elements of the fault zone are the NW-SE striking normal faults in the Hegau region, the WNW-ESE striking Randen fault, the E-W striking Bonndorf graben and the WNW-ESE striking Lenzkirch Graben (Fig. 12). From Lake Constance in the east to the URG in the west, the system crosses all stratigraphic levels from the basement up to the Tertiary Molasse deposits.

The NW-SE striking normal faults of the Hegau region and the Randen fault are described in more detail in chapter 5. They pass westwards into the E-W striking Bonndorf Graben. The western end of the Bonndorf graben connects to the Lenzkirch graben which again strikes WNW-ESE. The Bonndorf graben shows vertical offsets between Muschelkalk and Keuper rocks, while in the Lenzkirch graben Buntsandstein and basement rocks are juxtaposed. The Paleozoic sediments of the Badenweiler-Lenzkirch zone (Güldenpfennig & Loeschke 1991, Sittig 1969) are dissected by the Lenzkirch graben (Bangert 1991). Further west fault traces are less well mapped since they dissect rather uniform granite and gneiss complexes in the high Black Forest. However, outcrop-scale field evidence including WNW-ESE to NW-SE striking brecciated zones show clear evidence of enhanced post metamorphic faulting (Freudenberg 1940). Fission track studies imply Miocene normal faulting between the Feldberg area and the trace of the Freiburg-Bonndorf graben (Link 2010). Precise levelling data reveals that WNW-ESE to NW-SE striking faults may locate a considerable amount of recent movement in the southern Black Forest (Demoulin et al. 1998). Near the intersection with one of the eastern border faults of the Upper Rhine Graben, Stellrecht (1958) mapped fractures parallel to the FBBFZ actually dominating over those associated with the Upper Rhine Graben fault system. In summary, the reported observations imply that there is a more or less continuous fault zone reaching from the Bodensee area into the area of the Freiburg-Bonndorf graben.

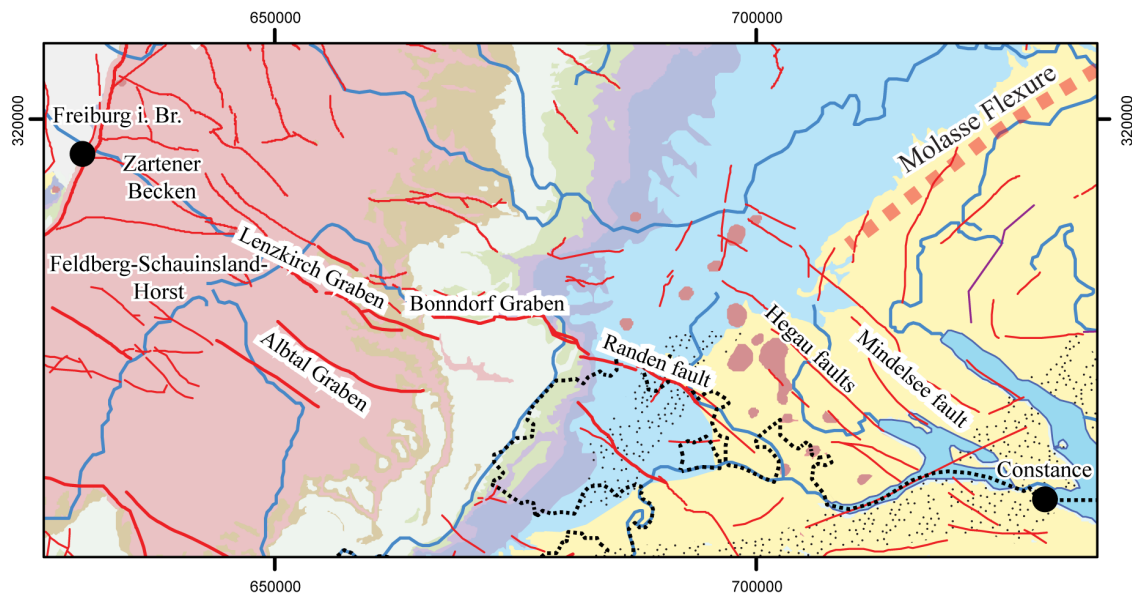


Fig. 12: Detail of Fig. 8 illustrating the major elements of the Freiburg-Bonndorf-Bodensee fault zone

Legend for faults and lithological units as well as source literature see Fig. 8.

4.2.3 Albstadt shear zone

The Albstadt shear zone was defined by seismic activity recorded mainly during the last century in the region of the Zollernalb near Albstadt (Schneider 1993, Reinecker & Schneider 2002, Reicherter et al. 2008). The events of 1911 with ML 6.1, 1943 with ML 5.5 and 1978 with ML 5.7 (Schneider 1979, Haessler et al. 1980) belong to the strongest earthquakes in Central Europe. Focal mechanisms in the Albstadt region are very similar in characteristics, all being related to left-lateral strike-slip on NNE-SSW striking steep fault planes located in the crystalline basement no deeper than 10 km (Stange & Brüstle 2005).

The dominant surface structure close to the recent seismicity is the NW-SE striking Hohenzollern Graben. Mapped bulk offset of the strata along this structure is normal, but slickenside populations imply right-lateral movement along WNW-ESE striking fault planes and conjugate left-lateral movement along NNE-SSW striking fault planes (Hoffers 1974). Illies (1978) speculated that the seismicity underneath the Hohenzollern graben is due to its location at the centre of an area currently undergoing counter-clockwise rotation in a strike-slip regime, with the graben reflecting a thin-skinned pull-apart basin (Fig. 13a).

From the seismological point of view no clear evidence exists that the active shear zone extends beyond the region of the Zollernalb (Stange & Brüstle 2005). Nevertheless, Schneider (1979, 1993) proposed the earthquakes to be the current expression of a larger seismogenic zone, extending from the region of Heilbronn in the north to the Glarus Alps in the south (Fig. 13e). This idea was taken up by authors formulating a tectonic model for a large scale shear zone. In the models of Illies (1982) and Schneider (1993), local seismicity is caused by the intersection of N-S striking and NW-SE striking larger structures (Figs. 13c and 13d). This intersection presumably leads to stress accumulation and to seismic faulting in an otherwise rather aseismic shear zone. Illies et al. (1981) proposed a termination of seismic activity in the URG in the near geologic future by relocation to a newly forming seismic belt about 100 km further to east that

is currently expressed in the N-S striking shear zone in the Albstadt region (Fig. 13b). Based on Carlé (1955), Reinecker & Schneider (2002) interpreted the en-echelon arrangement of several NW-SE striking graben systems along the proposed Albstadt shear zone of Schneider (1993) as the surface expression of N-S striking left-lateral strike-slip in the basement (Fig. 13f-h). The required decoupling horizon is presumed to be located the evaporitic sections of the Muschelkalk Formation. The NW-SE striking normal faults of the HELC region are included in this en-echelon array of tension structures.

Although indicated by lineament mapping (Wetzel & Franzke 2003), the existence of a left-lateral Albstadt shear zone lacks surficial geologic field evidence (Reinecker & Schneider 2002, Rupf & Nitsch 2008). From a paleogeographic point of view it correlates spatially with a facies boundary in the lower Jurassic between the Mid-Swabian basin in the east and the Spaichingen high in the west (Rupf & Nitsch 2008).

4.2.4 Molasse flexure

The Mesozoic strata of the Swabian Alb dips 1° towards the southeast, whereas the strata further south shows dips of about 5°. The change in dip occurs along a kink zone in the area of the Danube (Figure 8) that was termed the "Molasseflexur" (Rupf & Nitsch 2008, Geyer et al. 2011). The "Molasseflexur" vanishes along strike across the FBBFZ, southeast of which a continuous general dip of 3-4° is observed.

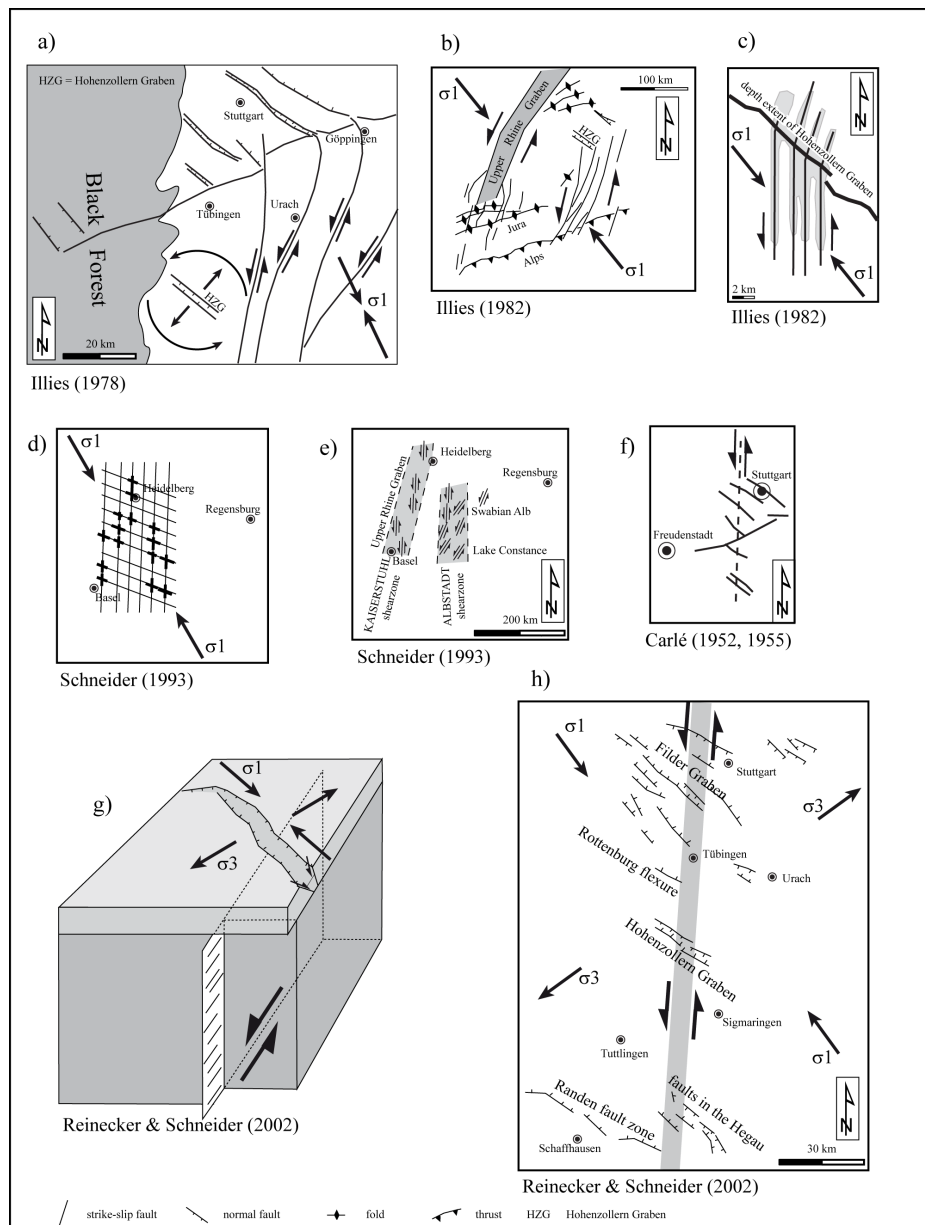


Fig. 13: Different models for the seismicity in the region of the Hohenzollern Graben and the Albstadt shear zone

a) Opening of the Hohenzollern Graben in a pull-apart manner in the frame of counter-clockwise rotation between the Black Forest massif and left-lateral shear, located further east (Illies 1978). b) Left-lateral shear in the northern Alpine foreland along the Upper Rhine Graben and a lamellar shear zone further east (Illies 1982). c) Stress accumulation (grey shaded area) at the crossing points of left-lateral shear zones with the deep prolongation of the Hohenzollern Graben as cause for seismic activity (Illies 1982). d) Location of such stress accumulations in southwestern Germany (Schneider 1993), and e) interpretation of larger seismic belts based on d) (Schneider 1993). f) En-echelon arrangement of graben structures as a result of super-ordinate left-lateral shear (Carlé 1955). g) Decoupling between left-lateral strike-slip along N-S striking fault planes in the basement and normal faulting along NW-SE striking fault planes in the cover (Reinecker & Schneider 2002). h) Interpretation of a larger strike-slip fault zone in the basement (Albstadt shear zone) on the basis of en-echelon arranged normal faults at the surface (Reinecker & Schneider 2002).

5 Local structural characterization of the Hegau and Lake Constance region

5.1 Fault inventory

In the course of this study all fault structures of the HELC region given in the reviewed literature were compiled in an ArcMap project. The resulting structural map is given in Encl. 3 and Fig. 14. The faults were attributed with their most important literature references, the grade of interpretation (mapped, interpreted) and the type of interpretation (seismic interpretation, stratigraphic correlation, etc.). Whenever provided, the sense of shear/offset and the affected lithologies were included as well.

In general, most of the compiled faults were derived from geologic mapping and seismic interpretation. Some examples of the most recent interpretation of seismic lines (Interegg IIIA 2007) are given in Fig. 15. The dominating tectonic features are very steep fault zones with normal offset. Some of these faults caused flexural bending. The Kirchen-Hausen fold, (Hahn & Schreiner 1976, Sander 1978, Fig.16) is the only clearly compressive structure in the region. Concerning the seismic interpretations it has to be noted, that the quality of the seismic lines is often poor. For example, the Mindelsee fault, well mapped at the surface, could not be detected on the crossing 2D-seismic profile "VAR 89" in the course of Interegg IIIA interpretation (Fig. 15).

When analysing the compiled faults given in Encl. 3, it is important to note on the regional differences in fault length. This apparent variation is mainly caused by differences in the source literature, especially due to the degree of interpretation. In the western part of the investigated area, Mesozoic rocks crop out to the surface and most represented faults were mapped in the field. In the eastern and southern part, most of the shown faults were not mapped in the field but interpreted from seismic reflection data (eastern part) or correlation of stratigraphic horizons (southern and central part). These faults are shown as long, often straight lines. They should be considered to represent trends of faulted zones rather than accurate fault traces.

To simplify the following descriptions, faults are grouped according to their strike orientation based on Carlé (1955):

- Hercynian: strike domain: E-W, WNW-ESE and NW-SE,
- Variscan: strike domain NE-SW and ENE-WSW,
- Rhenish: strike domain N-S and NNE-SSW.

Hercynian faults dominate regarding the number of faults. Variscan and Rhenish faults are less common in number, Variscan faults do however often show very long traces. It is interesting to note that the latter faults dominate in the eastern part of the study area (the Molasse), which is where faults are generally interpreted from seismic surveys. In contrast, Rhenish faults are mostly yielded by the results of geological field mapping.

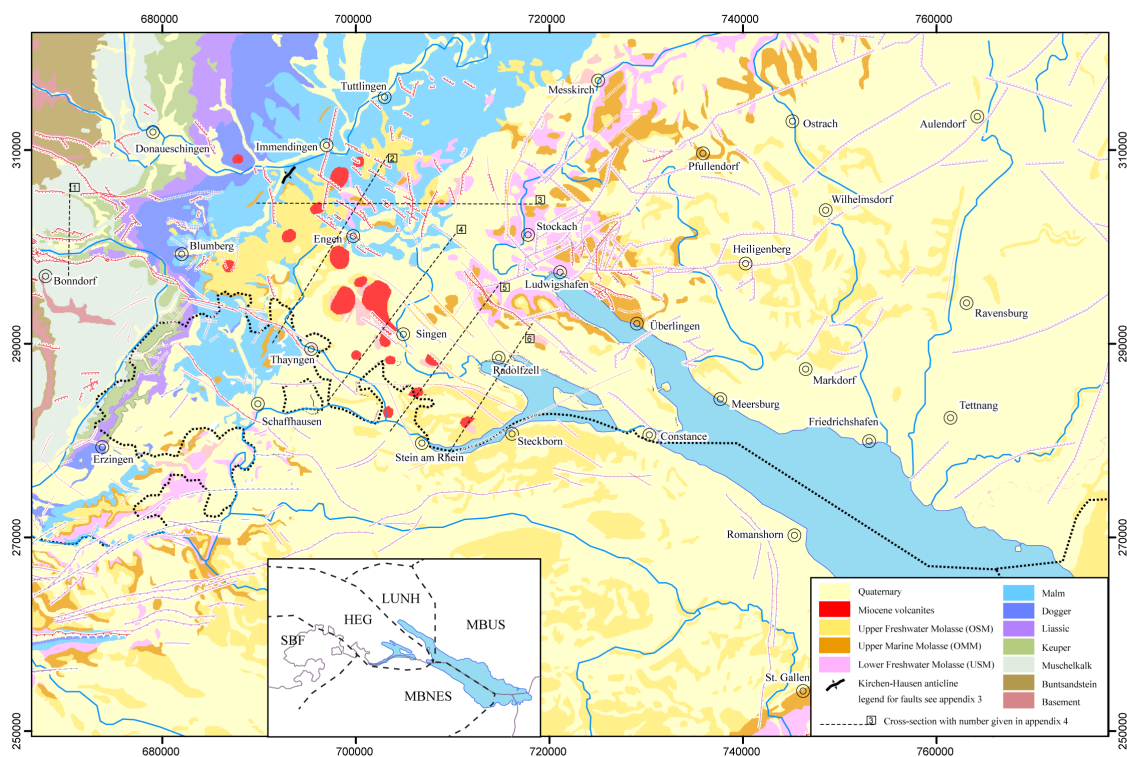


Fig. 14: Geological overview of the Hegau and Lake Constance region

Inset shows the structural compartments as described in chapter 5.2. Legend for faults see Encl. 3. SBF = Southern Black Forest and its eastern slope, HEG = Hegau region s. str., MBUS = Molasse Basin of Upper Swabia, LUNH = Lake Überlingen and its northern hinterland, MBNES = Molasse Basin of northeastern Switzerland.

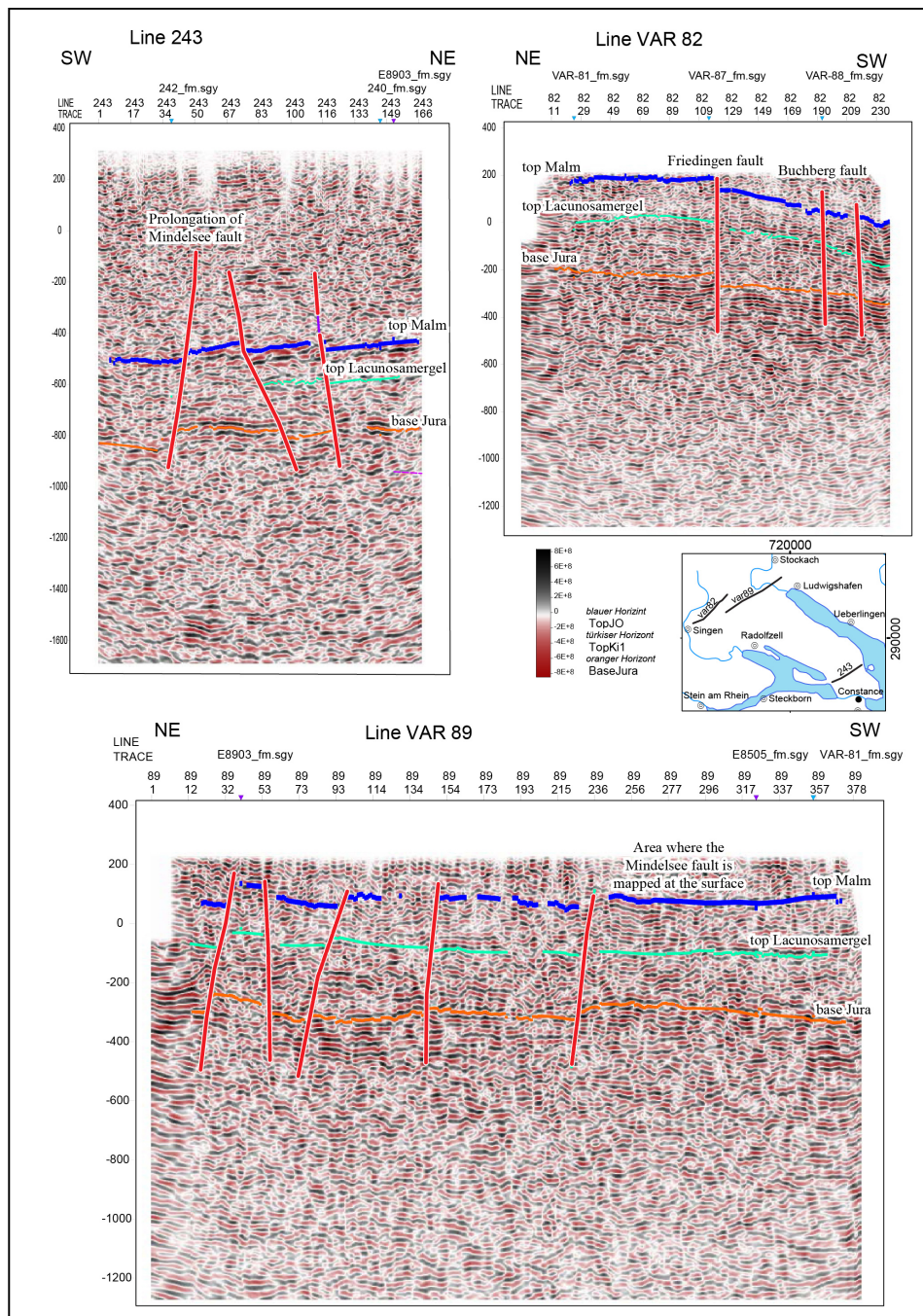


Fig. 15: Selected seismic lines with line interpretations taken from Interegg IIIA (2007)

Line 243 (upper left) shows three faults in the area of Constance. The southwestern most fault could be a NW-SE striking normal fault in prolongation of the Mindelsee fault. Line VAR 82 (upper right) crosses the northern part of the Singen basin and shows three faults with relative down-throw of the southwestern block. The line runs roughly parallel to the central part of cross section 4 in Encl. 4. Line VAR 89 (bottom) crosses the Mindelsee fault, mapped at the surface with a down-throw of the southwestern block, in the area between shot points 89 236 and 89 256. No fault is however visible in the seismic profile. Given the reliability of the geological surface mapping in this area the fault was nevertheless included in the maps of the Interegg IIIA (2007) publication. The faults in the northeastern part of the section belong to the dense fault network in the subsurface of the area of Stockach and show varying strike directions in map view.

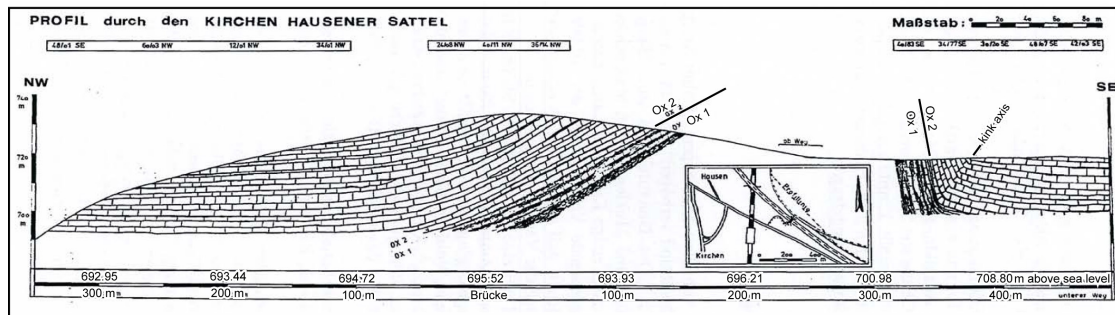


Fig. 16: Cross section of the Kirchen-Hausen fold after Sander (1978)

5.2 Structural compartments

On the basis of the fault inventory shown in Encl. 3, the HELC region is divided into five domains. From north to south these domains are (see inset in Fig.14):

- The southern Black Forest and its eastern slope (SBF), located south of the FBBFZ, east of the URG and north of the Jura Mountains
- The Hegau s.str. (HEG), located north of the Randen fault zone, including the eastern part of the FBBFZ
- The Molasse Basin of Upper Swabia (MBUS), located NE of Lake Constance
- Lake Überlingen and its northern hinterland (LUNH), located in the "Border region" between HEG and MBUS
- The Molasse Basin of northeastern Switzerland (MBNES), located south of Lake Constance.

5.2.1 Southern Black Forest and its eastern slope (SBF)

The region of the SBF is characterised by a regional SE dip of 3-4° and steep faults with vertical offsets of up to 200 m (Rupf & Nitsch 2008, Geyer et al. 2011). The two major fault orientations are WNW-ESE and NNE-SSW striking faults. NE-SW striking faults are present in minor numbers. In general faults of both major strike populations interact in the cover units, while in the basement of the Black Forest, NNE-SSW striking faults are conspicuously less pronounced. The eastern tip of this region forms the southwestern part of the HELC region south of the Randen fault zone and north of the river Rhine.

The Randen fault zone (Carlé 1955, Hofmann et al. 2000, Fig. 17) is mapped in the Jurassic successions between Thayngen and the Wutach valley south of Blumberg (Hofmann et al. 2000, 2002, Franz & Rohn 2004). The fault zone consists of several faults of Hercynian, Variscan and Rhenish strike, but as a whole has a WNW-ESE extent. South and west of the Randen fault zone Hercynian-type faults are mapped in the Upper- and Lower Jurassic successions, occasionally traceable over larger distances (such as the Neuhausen (Schlossranden) fault), the Erzingen fault and the Horheim-Geisslingen fault (Hofmann 1981, Hofmann et al. 2002, Bausch & Schober 1997). In the same area, Variscan type faults also occur widely scattered (Hofmann 1981, Hofmann et al. 2002, Bausch & Schober 1997).

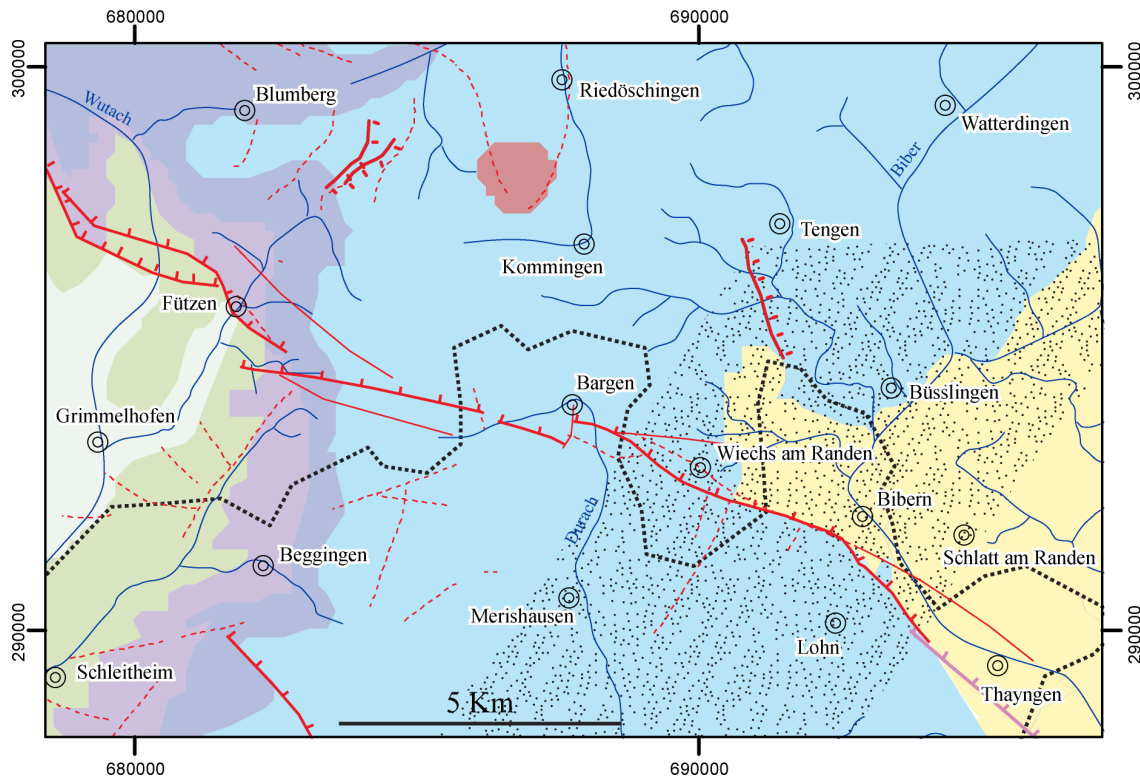


Fig. 17: Detail of Fig. 8 (Lithologies) and Encl. 3 (faults) showing the area of the Randen fault zone between Thayngen and the Wutach river

Legend see Fig. 8 (for lithological units) and Encl. 3 (for faults).

5.2.2 Hegau s.str. (HEG)

This sub-region is characterised by the predominance of faults with Hercynian strike and can be considered as the eastern part of the FBBFZ. While the southern border of the FBBFZ appears to be represented by the Randen fault zone, its northern border is less well defined. Slight differences in fault patterns can be recognised between areas depending on the outcropping lithology.

In the Molasse units of the western Lake Constance region, faults were often mapped at single outcrops and interpreted over larger distances with the help of borehole data (e.g. the Schienerberg fault, (Zaugg et al. 2008, Schreiner 1989, 1995). The Hercynian-type faults resulting from these interpretations are often referred to as the Hegau-Bodensee faults. Between Constance and Singen the mapped faults form a graben structure (see cross section 4-6 in Encl. 4). Subsidence between the southeastern (e.g. Mistbühl and Letzbühl fault; Zaugg et al. 2008) and northwestern border faults (e.g. Mindelsee fault; Gutmann 1910, Schmidle 1911, Kieser 1951, Schreiner 1992) is up to 250 m (Zaugg et al. 2008). Further to the north towards Engen the graben structure is less well pronounced (see cross section 2 in Encl. 4). Even

The area further to the north characterized by Jurassic units, the region is structurally dominated by the WNW-ESE striking Randen fault zone. Relative down-throw of the northern block is 250 m. The NW-SE striking faults further north in the area between Engen and Tuttlingen consistently show relative down-throw of the northern block as well. In consequence, a cross

section perpendicular to fault strike shows a step-fault morphology towards north instead of a graben structure (Cross section 2 in Encl. 4).

Even further to the northwest where Upper Muschelkalk and Lower Keuper successions crop out at surface, faults typically strike is E-W. In cross section view a graben structure is observable (Bonndorf graben, cross section 1 in Encl. 4). It is formed by a major fault zone in the south (Wutachtal fault, Schalch 1904, 1906) and up to four parallel faults in the north. Vertical offset is 200-270 m along the southern fault and sums up to only 150 m across the northern faults (Carlé 1955). Rhenish type structures are also quite common in the area of the Malm outcrops between Engen, Blumberg and Tuttlingen (Schreiner 1992, Franz & Rohn 2004). The most important structure is the Immendingen flexure (Spitz 1930), which is most likely underlain by a fault (cross section 3 in Encl. 4). The Hegau fault was proposed on the bases of the N-S alignment of the major basalt volcanoes in the Hegau region as well as forming the edge of an N-S depression (Reck 1923, Erb 1932). It is regarded as a major element in some older regional-scale tectonic models (Cloos 1939, Carlé 1952, 1955). Detailed mapping has, however, shown that a discrete fault does not exist (Sawatzki & Schreiner 1991, Schreiner 1992, 1995). The Hegau fault was therefore not represented on the map.

5.2.3 Molasse Basin of Upper Swabia (MBUS)

The MBUS is characterised by flat-lying Molasse units for the most part covered by Quaternary deposits. The shown fault pattern is nearly exclusively based on seismic interpretation in the frame of hydrocarbon exploration. It is dominated by normal faults of Variscan strike. The most prominent ones reach from Pfullendorf to Bad Saulgau and from Überlingen to Memmingen (Elberskirch & Lemcke 1953, Volz 1959, Bertleff 1986, Bachmann & Müller 1992). They can be traced along strike towards the southwest into the LUNB region, where they apparently change their strike to NNE-SSW (Pfullendorf-Bad Saulgau zone) or E-W directions (Überlingen-Memmingen zone). With respect to the SE dipping base of the Molasse Basin, these normal faults show both synthetic and antithetic senses. It is, however, important to note that the antithetic senses dominate and also characterise the larger fault zones between Pfullendorf and Bad Saulgau and between Überlingen and Memmingen.

Compared to Variscan type faults, Hercynian type faults are conspicuously rare in the MBUS region. However, a zone of E-W striking faults exists between Bad Saulgau and Memmingen (north of Aulendorf in the map in Encl. 3). Some of these faults were found to offset faults of Variscan strike in a right-lateral sense (Betz & Wendt 1983). In the southeastern part of the MBUS, the fault pattern is less well constrained. Increasing thicknesses of both the Quaternary cover and the Molasse units lead to larger uncertainties in seismic interpretation. Nevertheless, some

Rhenish striking faults do also occur in this region (Elberskirch & Lemcke 1953, Volz 1959). The one west of Ravensburg (Elberskirch & Lemcke 1953) was assumed by Carlé (1955) and interpreted by Volz (1959) along a very straight valley footslope along which OSM deposits of different age were mapped next to each other.

5.2.4 Lake Überlingen and its northern hinterland (LUNH)

The region between Überlingen, Pfullendorf, Tuttlingen and Stockach including Lake Überlingen is characterised by a dense network of faults with a wide scatter of orientation. Fault offsets are mapped between the older Molasse units (e.g. Gutmann 1910, Knupfer 1912, Erb et al 1961) as well as interpreted from seismic surveys (Bertleff 1986, Interreg IIIa, 2007).

Mapped surface faults show traces differing from interpreted faults referring to deeper levels, e.g. to the top Mesozoic in case of the Interreg IIIa interpretation. This may in places lead to artificial densification of the fault network shown in Encl. 3. Situated at the transition between the HEG and the MBUS, the region may be a key for understanding the link between both tectonic domains. While in the area of Constance, simple interference of Hercynian type faults and Variscan type faults occurs, the fault pattern is more complex in the region of LUNH. Rhenish oriented faults are also commonly present and the south-western prolongations of Variscan type faults of the MBUS bend towards N-S and E-W directions.

Hercynian faults in this area are found e.g. in the Sippligen field (Schalch 1901, Schmidle 1911). The E-W striking Hochbühl fault (Knupfer 1912, Rutte 1952) was interpreted to continue towards east in the Überlingen-Memmingen fault zone (Bertleff 1986). Rhenish faults occur scattered over the whole region but dominate locally in the area north and west of Stockach. The Krumbach fault (Werner 1994), the Heudorf fault, the Dornsberg fault and the Schenkenberg fault also have to be mentioned in this respect (Schreiner 1993, 2002). They were mapped (and partially interpreted in case of the Krumbach fault) in the older Molasse units and in the Upper Malm units. They can be interpreted as a wide graben structure (cross section 3 in Encl. 4).

5.2.5 Molasse Basin of northeastern Switzerland (MBNES)

This area was only marginally considered during this study. For the western part the fault pattern shown in Encl. 3 was compiled after Nagra (2008) mostly based on 2D and locally 3D-seismic interpretations.

The fault pattern to the south of Lake Constance (compare Fig. 14) is difficult to assess. As in the MBUS, surface geology of the MBNES is characterised by Quaternary deposits and rare OSM outcrops. Faults shown in the map-sheets of the Swiss geological Atlas and described in the literature were deduced from height correlations of distinct conglomerate and bentonite horizons in the OSM (Hofmann 1952, 1973, 1993, Kälin 2003). Mapped fault traces are largely guided by geomorphic lineaments such as wide valleys filled with Quaternary deposits. Considering the pattern of these faults from the literature despite the mapping uncertainties the region may be regarded as being influenced by both the Hercynian type faults as occurring in the HEG as well as as Variscan type faults typically occurring in the MBUS. This structural pattern may however be incomplete. A recent 3D seismic survey around St. Gallen has revealed a large N-S striking fault zone roughly correlating with some locally mapped normal faults in OSM deposits along the Sitter River (Saxer 1965, Heuberger 2011, pers. comm.).

5.3 Cross sections

Based on the fault inventory from the literature six cross sections were constructed (Encl. 4). Construction is based on LGRB (2011), Interegg IIIA (2007), Schreiner (1989, 1993, 1992, 1997), Nagra (2008). The section crossing the Bonndorf Graben shows a single larger fault at its southern border and three wide-spaced, south-facing faults in the north defining the graben structure. Flexure-type bending of upper Muschelkalk and Keuper successions observed by Schalch (1906) are supposed to be compensated in the evaporitic Muschelkalk. The Randen - Emmingen section is oriented perpendicular to the Randen fault and shows north-facing normal faults only. In the northwestern part of the section the down-throw of the northern block decreases to zero within a short distance and is compensated by flexural bending of the Malm layer (Schreiner 1997).

The section between Länge and Stockach crosses the northern HELC region. Its E-W orientation allows for better illustration of N-S striking faults and flexure zones. Flexures such as the Aulfinger and Immendinger flexure are thought to be located on top of faults rooted in the crystalline basement.

Sections 4 to 6 cross the central Hegau including the so called Singen Basin (referring to the thick Quaternary deposits found here) and Lower Lake Constance. Tectonic structures in this region were often described as NW-SE striking grabens. In contrast to the Randen-Emmingen section the fault pattern can indeed be interpreted as a graben structure in these sections.

5.4 Implications on faulting chronology

The faults presented in Encl. 3 are compiled from geologic maps and seismic interpretation. In some cases age constraints are reported based on the offset strata. Relative chronology may also arise from cross-cut criteria between different faults. In general, faulting can be assumed to be of Cenozoic age since most of the faults zones offset or include segments offsetting the Tertiary units.

5.4.1 Age constraints

In the Molasse Basin of southern Germany, synthetic and antithetic normal faults are reported to be active during the Molasse sedimentation. Southern faults are covered by the younger Molasse, whereas fault activity is successively younger towards north, also offsetting the OSM deposits (Bachmann & Müller 1992). The authors therefore relate these faults to the flexing of the crust during foreland basin migration. The faults in the northeastern part of the study area belong to this system of basin-parallel normal faults. The Pfullendorf-Bad Saulgau fault zone offsets the OMM/OSM boundary at the surface (Szenkler & Ellwanger 2001a). The same is the case for the Hochbühl fault (Knupfer 1912, Rutte 1952, Szenkler & Ellwanger 2001b), which is inferred to continue into the Illmensee-Fronhofen (Überlingen-Memmingen) fault zone (Bertleff 1986). For these faults, fault activity in post-Lower OSM time fits well with their central to external positions within the basin. More internally located faults with age constraints are not reported from the study area. However, a normal fault in the subsurface near Bregenz offsets the Mesozoic units only and ends underneath the triangle wedge of the Subalpine Molasse (Zerlauth et al. 2011). South of Messkirch NE-SW striking faults are sealed by the OMM units (Werner 1994), indicating that basin-parallel faults partly became inactive even in the external part of the Molasse Basin.

Younger faulting in the Molasse Basin of Upper Swabia is revealed by E-W to WNW-ESE striking faults that offset the NE-SW striking fault zones in a right-lateral manner (Bachmann & Müller 1992, Betz & Wendt 1983). Volz (1959) describes a Rhenish striking fault zone near Ravensburg that offsets Sarmatian OSM. He further proposes a certain Pleistocene activity of that zone.

Along the Randen fault, Schreiner (1992) gives 70 m offset for the Lower Miocene and 170 m offset after the Middle Miocene. The "Immendingen flexur" (Spitz 1930) and the "Aulfingen flexur" (Schreiner 1992) are both mapped as bending the base of the OSM (Schreiner 1992). Syn-tectonic sedimentation of the upper "Juranagelfluh" places the main tectonic subsidence of the "Immendingen flexur" into the lower Upper Miocene (Schreiner 1965). The Kirchen-Hausen fold (Hahn & Schreiner 1976, Sander 1978) affects OMM units and is at least Middle Miocene in age (Hahn & Schreiner 1976). This indicates that the fold-type structures in the Malm units are roughly of the same age as the faults in the area.

Absolute dating of volcanics give some quite robust time markers for crossing faults. The Hercynian type Hohentwiel fault and the similarly oriented fault near Bohlingen offset Deckentuff layers (Schreiner 1989, 1995) dated to $16,1-14,0 \pm 0.6$ Ma (Weiskirchner 1972). Wittmann (1937) mapped faults of both Hercynian and Rhenish orientations in the basalt as well as in the Hornblendetuff (11.8 ± 0.6 Ma and 9.4 ± 0.5 Ma, Weiskirchner 1972) of the Höwenegg volcanic field.

5.4.2 Cross-cutting relationships

Cross-cutting relationships between the well mapped Rhenish and Hercynian faults in the area north of Engen show a non-systematic pattern. For example, the Hercynian type Maueneheimer fault cuts and offsets the Rhenish striking Immendingen flexure, while the Rhenish striking Schenkenberg fault offsets some Hercynian type faults. Therefore, the relative chronology between Rhenish striking and Hercynian type faults in the area cannot be reliably assessed.

5.4.3 Phases of activity

In summary, the reported details suggest that tectonic activity along faults of Variscan type orientation is slightly older than along Rhenish and Hercynian type faults.

Tectonic activity is indicated to have increased during and after sedimentation of the OMM (Fig. 18). Distal regions of the Molasse Basin were uplifted and the basin-parallel "Graupensandrinne" developed an erosional channel (Kiderlen 1931, Geyer et al. 2011). Locally some of the related channels appear to be guided by presumed tectonic lineaments (Werner 1994, Schreiner 1992).

The most important phase of tectonic activity in the Hegau region takes place during the Upper Miocene to Pliocene (e.g. Erb 1932, Schreiner 1992, Fig. 18). In its early stage it was accompanied by volcanic activity and deposition of the OSM, but it clearly outlasted both (e.g. Wittmann 1937, Schreiner 1992). Older authors have additionally inferred a strong Pleistocene pulse of normal faulting, especially in the Lake Constance region (Schmidle 1911, Erb 1932, Carlé 1955). However, detailed geologic mapping in the second half of the 20th century could not validate substantial Pleistocene tectonic activity.

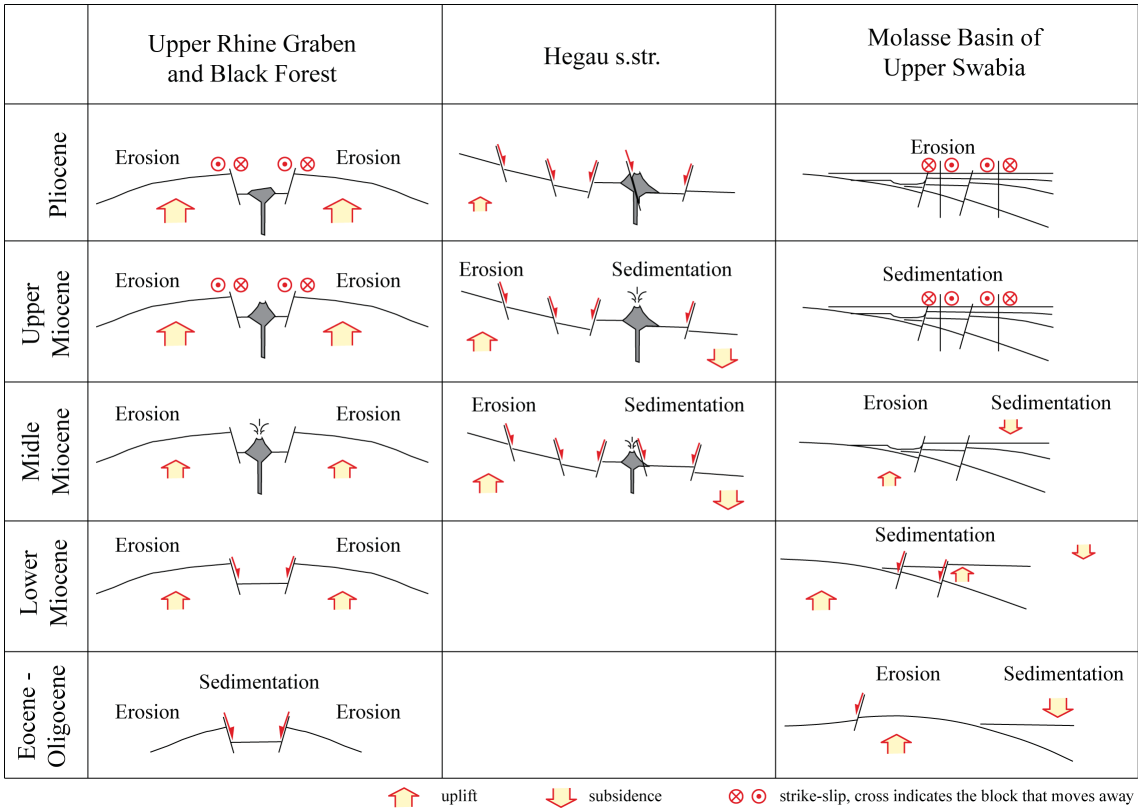


Fig. 18: Tertiary tectonic evolution of the wider Hegau and Lake Constance region and the Hegau s.str.

6 Tectonics and volcanism

The upper Miocene Hegau volcanic field (Fig. 10) belongs to a group of Tertiary volcanic occurrences in the northern foreland of the Alps (Wimmenauer 1974, Keller 1984, Keller et al. 2002). In southwestern Germany, this group also includes the slightly older (Lower Miocene) Kaiserstuhl volcanic field and the Urach volcanic field, which is Lower to Upper Miocene in age (Wimmenauer 1974, Geyer et al. 2011). The location of these volcanic fields was inferred to be linked to triple points of larger tectonic structures (Geyer in Schreiner 2008, p27, Geyer et al. 2011). According to this view the Kaiserstuhl field is situated at the junction of the URG with the FBBFZ, the Hegau field is situated at the junction of the FBBFZ with the Albstadt shear zone (the Hegau-Heldburg lineament of Carlé 1952), and the Urach field is situated at the junction of the Albstadt shear zone with the Swabian lineament (eastern prolongation of the Bebenhausen fault zone (Fig. 8), Seibold 1951). The postulate assumes that all involved tectonic lineaments are large tectonic structures. On the basis of field geologic evidence, this can, however, be testified for the URG only.

In the Hegau region it was recognised early on that the major basaltic eruptions are aligned N-S (Reck 1923). Later geomagnetic surveys confirmed a dominant N-S orientation of the basalt dykes (Mäussnest & Schreiner 1982). Among other indicators, this alignment has led Erb (1932) to propose the N-S striking Hegau fault and Cloos (1939) to postulate that magma ascent in the Hegau has taken place along deeper seated N-S striking fractures decoupled from the NW-SE striking tectonic elements at the surface. The Hegau fault could not be verified by detailed mapping and was therefore rejected by Schreiner (1992). A NW-SE alignment of the older Deckentuff eruptions is less well defined (Mäussnest & Schreiner 1982, Fig. 10).

The Hegau may be further influenced by the ENE-WSW striking border faults of the Permo-Carboniferous trough of northern Switzerland which represents another larger tectonic element. Schreiner (1992) points out that up until now, no Permo-Carboniferous lithologies were found as ejecta in the Hegau volcanics; instead crystalline basement was often reported. According to the compilation maps in Leu (2008), the northern trough border passes just south of the southernmost volcanic chimney at Schienerberg.

7 Implications on active tectonics in the Hegau and Lake Constance region and surrounding areas

7.1 Seismicity and recent stress

Recent tectonic activity in southwestern Germany is obvious from earthquake activity in the Albstadt shear zone and along the URG (e.g. Schneider 1979, 1993, Stange & Brüstle 2005, Plenefisch & Bonjer 1997). Fault plane solutions indicate left-lateral strike-slip on NNE-SSW striking fault planes in the Albstadt region and left-lateral strike-slip as well as normal faulting in the URG (Fig. 19).

In the HELC region itself and along the FBBFZ, earthquakes are rather rare compared with the Albstadt shear zone and the URG (Fig. 19). However, some right-lateral strike-slip earthquakes were recorded along the WNW-ESE striking fault system in the HELC region (Deichmann et al. 2000, Pavoni 1977). Strike-slip and normal faulting earthquakes were recorded in the Molasse Basin of Upper Swabia. Seismicity of that region is characterised by very deep seated (i.e. lower crust) earthquakes, with the exception of the Bad Saulgau region where focal depths are located in the upper crust (Stange & Brüstle 2003).

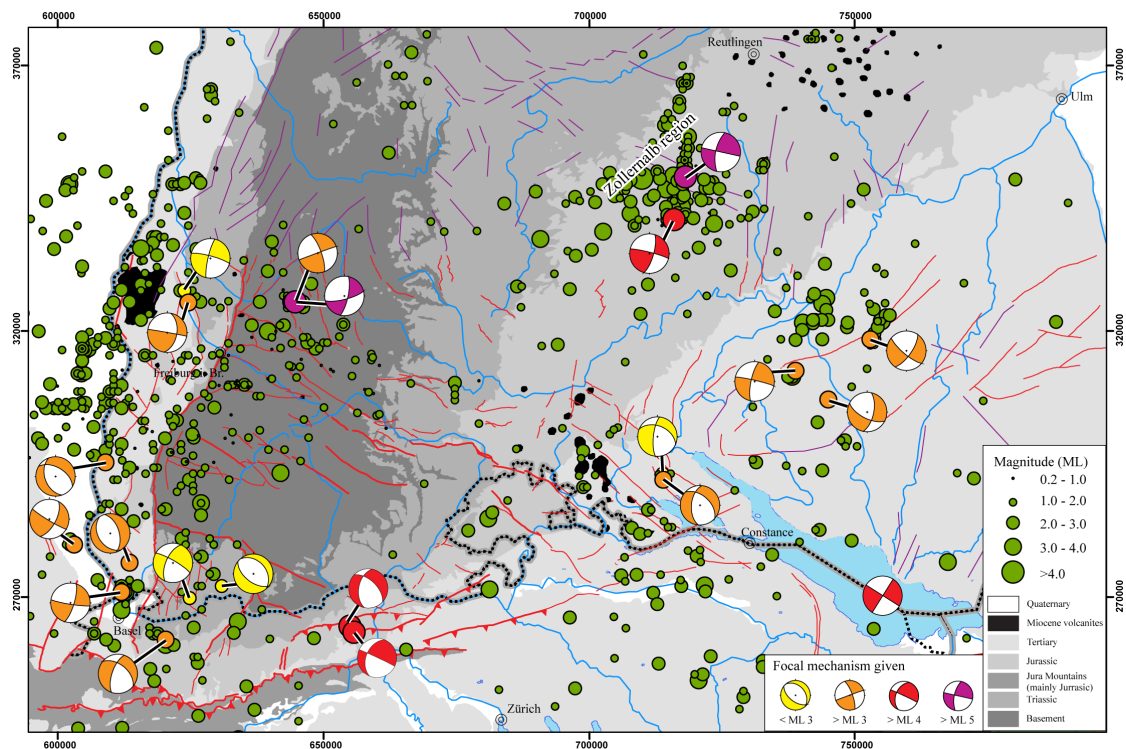


Fig. 19: Instrumentally recorded earthquakes in the study area between 1996 and 2008 (green)

Published focal mechanisms between 1977 and 2008 are given. Data from LGRB (2012), SED (2012), Baer et al. (2005), Deichmann et al. (2006), Haessler et al. (1980). Note that a ML 4.1 event in Lake Constance in 1976 was added with an approximated focal mechanism according to Pavoni (1977). Legend for faults as well as reference literature see Fig. 8.

Stresses derived from earthquake analyses in the northern Alpine foreland are generally NW-SE compression and NE-SW extension. The maximum principal stress axes are perpendicular to the strike of the Alpine chain, rotating from NW-SE in western Switzerland towards N-S in the eastern part and in the study area (Kastrup et al. 2004). Some focal mechanisms indicate normal faulting related to vertical compression. Reverse focal mechanisms with vertical minimum principal stress axes are widely absent. In the southern URG, the area of strongest seismicity, extension is oriented WSW-ENE. Compression may be NNW-SSE as well as vertical. Further north a slight rotation towards NW-SE compression and NE-SW extension occurs (Plenefisch & Bonjer 1997).

Recent stress from in-situ stress measurements show the same general trend of the maximum principal stress orientation perpendicular to the Alpine chain. Stresses rotate from N-S in southern Bavaria to NW-SE in western Switzerland (Heidbach et al. 2008, Reinecker et al. 2010). The world stress map shows NNW-SSE compression for the study area (Heidbach et al. 2008, Heidbach & Reinecker 2012, Fig. 20), though recent near-surface stress locally deviates in and around the Jura Mountains (Becker 2000). While it shows the general Central Europe NW-SE orientation in the basement, near-surface stress is slightly rotated and apparently decoupled (Becker 1989, 1987). In front of the eastern termination of the Jura Mountains Becker (1989, 2000) reports E-W orientation of in-situ stress. Interpolated near-surface maximum horizontal stress orientations are WNW-ESE in the Hegau and southern Black Forest (Becker 2000).

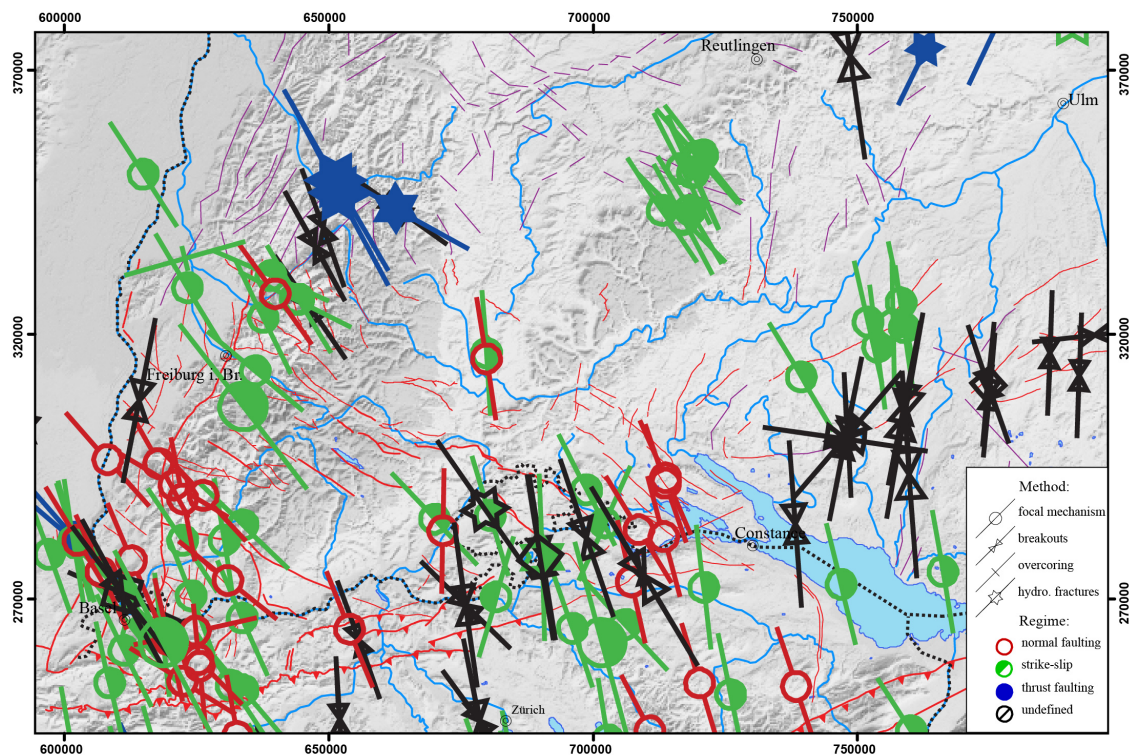


Fig. 20: Recent stress indicators within the study area according to the World Stress Map compilation (Heidbach & Reinecker 2012)

7.2 Geodetic aspects

A comparison of several levelling campaigns was done by Zippelt & Dierks (2007) for the region between the southern URG and Lake Constance region, covering nearly exactly the area of this study. The authors present point data on levelling lines as well as an interpolated map of relative subsidence and uplift with respect to a reference point at Laufenburg (Swiss-German border in the High Rhine Valley). The Black Forest region appears as stable with respect to the reference point, while the URG and the Dinkelsberg subside. Further east towards the Hegau and Upper Swabia vertical movement mostly gets insignificant with respect to their increasing standard deviation, which is due to increasing distance from the reference point (Zippelt & Dierks 2007). Nevertheless, zones of uplift and subsidence striking roughly NNE-SSW can be recognised. Localised uplift centres in the Feldberg area, the Neustadt area and the Blumberg area are important to note since they are situated along the trace of the FBBFZ.

In contrast to Zippelt & Dierks (2007), detailed levelling comparison in the southern Black Forest, covering a 30 year time span, revealed almost no movement across the URG border fault and N-S striking faults in the southwestern Black Forest, but significant movement across NW-SE striking faults (Demoulin et al. 1998). This was interpreted by the authors as due to predominantly seismic behaviour of the N-S striking and predominantly aseismic behaviour of the NW-SE striking faults. From this point of view the normal faults of the HELC region probably contain a considerable amount of recent aseismic tectonic activity.

Analyses of permanent GPS measurements at the scale of Western Europe reveal the larger study area to be in a state of negative dilatation (Tesauro et al. 2006).

7.3 Geomorphic aspects

The literature on the evolution of the Lake Constance basin often concentrates on discussions of tectonic versus glacial erosion origin. While the mouth of the Alpine Rhine Valley is overdeepened below sea level by glacial erosion (Oberhauser 1998) and the Lake Constance amphitheatre in the sense of Ellwanger et al. (2011) is clearly shaped by glacial advance and retreat, the orientation of the lake itself fits surprisingly well with the strike of the Hercynian type FBBFZ. Especially in the western part of the lake the strike of several shorelines and shoreline kinks as well as straight, steep slopes of the lake bottom (IGB 1990) can be attributed to common fault orientations (Schalch 1901, Schmidle 1911, 1931). This has lead authors to propose the basin to be almost completely of very young tectonic origin (Schmidle 1911, Erb 1932, Carlé 1955). It was especially Lake Überlingen that was inferred to have formed under the influence of tectonic processes; however, Ernst (1969) and Schreiner (1979, 1992) found no evidence of faulting at its eastern termination. Erb (1932) thus already distinguished between mainly Tertiary subsidence in the Hegau and Quaternary subsidence in the lake itself. Based on the interpretation of a seismic survey on the lake, Müller & Gees (1968, 1970, 1971) attributed the trough-like geometry of the top Tertiary in the Upper Lake and Lake Überlingen to glacial erosion only. From the known fault distribution (Fig. 14 and b, Encl. 3) it can be stated that the basin of Lower Lake Constance is indeed underlain by faults that form a graben structure (Schreiner 1979, Zaugg et al. 2008). However, in the case of the morphologically more pronounced basin of Lake Überlingen a clear relation to faulting is not obvious. Here Variscan and Rhenish type faults crossing the lake basin are probably more important than Hercynian type faults parallel to it (Fig. 14a and b, Encl. 3). Such crossing faults might be responsible for the regular kinking of the shorelines of Lake Überlingen. Due to the very young age of the lake basin itself (Keller 1994, Ellwanger et al. 2011) and the absence of clear indicators for very young tectonic activity, most modern authors describe an evolution driven by fluvial and glacial

erosion. Erosion was presumably guided by pre-existing weak zones most likely representing faults in prolongation of the FBBFZ in the Hegau (Schreiner 1979).

The younger Deckenschotter (Mindel age) of the Friedinger Schlossberg is located in the central part of the Hegau (Schreiner 1989). Its basis was found to be 30 m lower than the reconstructed basal plane of the younger Deckenschotter, pointing to 30 m of late Pleistocene normal faulting between the Mindelsee fault and the Schienerberg fault (Frei 1912, Schreiner 1989, 1992). Reconstruction of the ancient river bed of the Radolfzeller Aach suggests 10 m of syn to post-Würmian normal faulting along the nearby Buchberg fault (Schreiner 1989).

The well accentuated but small-scale horsts and grabens of the Sipplingen field (Encl. 3, Schalch 1901) are not smoothed by the Würm-age glacier that followed the Lake Überlingen basin and were therefore attributed to post-glacial tectonic activity (Schmidle 1911). Clear field evidence proof the tectonic nature of the N-S and NE-SW striking faults of the Sipplingen field (Schreiner 1992). The faults oriented parallel to the lake basin are most likely atectonic since repeated slope instabilities are recorded in the area (Geyer et al. 2011, Wagenplast 2005). Post-glacial vertical movements therefore most likely took place in form of gravitational gliding only (Penck & Brückner 1909), but were nonetheless located along pre-existing faults in a tectonically complicated zone (Schreiner 1992).

Very young and recent tectonic activity can potentially be recorded in the glacial deposits or in the recent sediments of Lake Constance. Schmidle (1916) reported several indicators of normal faulting in glacial deposits along the northern shore of Lower Lake Constance. These, as well as other structures in glacial deposits are, however, not clearly distinguishable from glacio-tectonic features that are also described as being abundant in the region (e.g. Schreiner 1997). Along the lower Lake Constance, sagging lines that formed in the course of the mid-European earthquake of November 16th, 1911 were originally attributed directly to rupturing faults (Lauterborn 1912, Rüetschi 1913, Schmidle 1918). A trench that opened at the bottom of Lake Überlingen in prolongation of known onshore faults (the Weiherholz fault and the N-S striking segment of the Beurenhof fault, Knupfer 1912) was also attributed to active faulting (Wasmund 1933).

7.4 Gas exhalations in the Hegau and Lake Constance area

Some faults in the Hegau and Lake Constance area, for example those recorded along the Hochbühl fault and the Beurenhof fault (see Encl. 3) are characterised by enhanced soil gas exhalations along their traces (Carlé 1955, Ernst 1969, 1971). In sub-aquatic environments gas exhalation can lead to pockmarks (Hovland et al. 2002). If aligned such pockmarks can be related to faults (Cartwright et al. 2004). The occurrences of pockmarks in Lake Überlingen were interpreted accordingly (Wessels et al. 2010). Onshore, a correlation between nest sites of red forest ants and gas exhalation spots along faults has been recorded (Schreiber et al. 2009) and attributed to active faulting (Schreiber & Berberich 2011). A neotectonic study using the approach of mapping nest sites of forest ants is currently in progress on the Bodanrück (Berberich 2012, pers. comm.).

In marine environments, enhanced gas exhalation and associated pockmark formation is well known to occur as side-effects during earthquakes (Hovland et al. 2002). However, in the first place gas exhalations primarily indicate the existence of fluid pathways along fault zones, not necessarily current fault activity as such.

8 Summary: Nature of larger structural elements, implications from the literature review

8.1 Freiburg-Bonndorf-Bodensee Fault Zone

This deformation zone consists of a series of WNW-ESE, E-W and NW-SE striking faults generally showing normal offsets. Along strike it affects all stratigraphic levels from the basement of the Black Forest to the Miocene Molasse, which may indicate its crustal scale. The fault zone extends from the URG in the west to the Alpine Front in the southeast and shows two larger irregularities along strike. The first one is the Bonndorf graben segment, where faults strike E-W. This segment corresponds to the intersection of the lineament with the Triassic West-Swabian Basin which is characterised by salt deposits in the middle Muschelkalk (Rupf & Nitsch 2008, Wild 1968, Simon 2003, Bock & Simon 2009). Such spatial correlation indicates tectonic decoupling, which would be expressed by counter-clockwise rotation of the segment. This rotation corresponds to left-lateral shear along the axis of the West-Swabian Basin (Nitsch 2011, pers. Comm.). The second irregularity occurs in the western Hegau tectonic region, whose southern border is formed by the Randen normal fault zone. Towards the north NW-SE striking faults are widely scattered, but all are synthetic in offset with Randen fault zone, featuring a step-fault geometry instead of a graben structure in cross section. By contrast, the fault pattern in the eastern Hegau and across Lower Lake Constance forms a 10 km wide graben structure with a few hundred meters of tectonic subsidence in its central part.

8.2 Permo-Carboniferous trough of northern Switzerland

The Permo-Carboniferous trough of northern Switzerland strikes ENE-WSW and presumably extends into the Lake Constance region. Its overall strike is apparently deviated towards E-W, which is most likely caused by repeated right-lateral offset along NW-SE striking faults, similarly observed further west (Eggberg fault and Vorwald fault, e.g. Diebold et al. 1991, Nagra 2008). It seems likely that the eastern termination is due to the crossing FBBFZ. However, the corresponding faults in the HELC region are situated just south of the well Dingelsdorf 1, which supplies the easternmost evidence of the deep trough. No irregularity is obvious along the trace of the FBBFZ at the intersection of both structures in the Lower Lake Constance area. The volcanic province of the Hegau is situated north of the Permo-Carboniferous trough of northern Switzerland, implying that the localisation of volcanic activity is not linked to the trough.

8.3 Albstadt shear zone

The Albstadt shear zone has been proposed to reach from north of Stuttgart to the northern border of the Alps (Schneider 1993). A more realistic view suggested it to be linked to the trace of the western border of the paleogeographic Mid-Swabian Basin (Rupf & Nitsch 2008). Seismicity is concentrated in the area of the Zollernalb, where a tectonic decoupling between strike-slip in the basement and normal faulting in the cover units above the mid-Muschelkalk salt is inferred (Reinecker & Schneider 2002). While the paleogeographic lineament given by the Mid-Swabian Basin continues into the northwestern Hegau and the Kanton Schaffhausen, the salt occurrences do not (Rupf & Nitsch 2008, Wild 1968, Simon 2003, Bock & Simon 2009). Furthermore, N-S to NNE-SSW striking elements in the Hegau, such as basaltic dykes, occur in the centre of the ancient Mid-Swabian Basin rather than at its western border. If the Albstadt shear zone represents a larger shear zone continuing into the Hegau, it cannot be strictly linked to the western border of the mid-Swabian paleogeographic basin.

8.4 Fault zones in the Molasse Basin of Upper Swabia

The prominent basin parallel faults in the Molasse Basin of Upper Swabia are parallel to the long axes of the Permo-Carboniferous troughs. In the study area, however, they are not underlain by such a trough. The main pulse of faulting is concurrent with the Molasse sedimentation, but occurs earlier than along the FBBFZ. The fault zones are right-laterally offset in places by roughly E-W striking (Hercynian) faults. In the southeastern part there is poor evidence for the existence of N-S striking faults.

8.5 Molasse Basin of Northeastern Switzerland

With respect to tectonics, the Molasse Basin of northeastern Switzerland is the least investigated region of the larger study area, and postulated fault traces are highly speculative. The only well-documented fault zone is the N-S striking one, recently discovered in the subsurface near St. Gallen. It remains speculative if this fault zone is related to the poorly constrained N-S striking faults that occur in the southeast of the Molasse Basin of Upper Swabia.

9 References

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Personal communications:

Berberich, G. (2012): Universität Duisburg-Essen, Fakultät für Biologie und Geographie,

Heuberger, S. (2011): geosfer AG, St. Gallen

Nitsch, N. (2011): Landesamt für Geologie, Rohstoffe und Bergbau Baden-Württemberg (LGRB), Freiburg im Breisgau

Northwest Hegau

Central Hegau

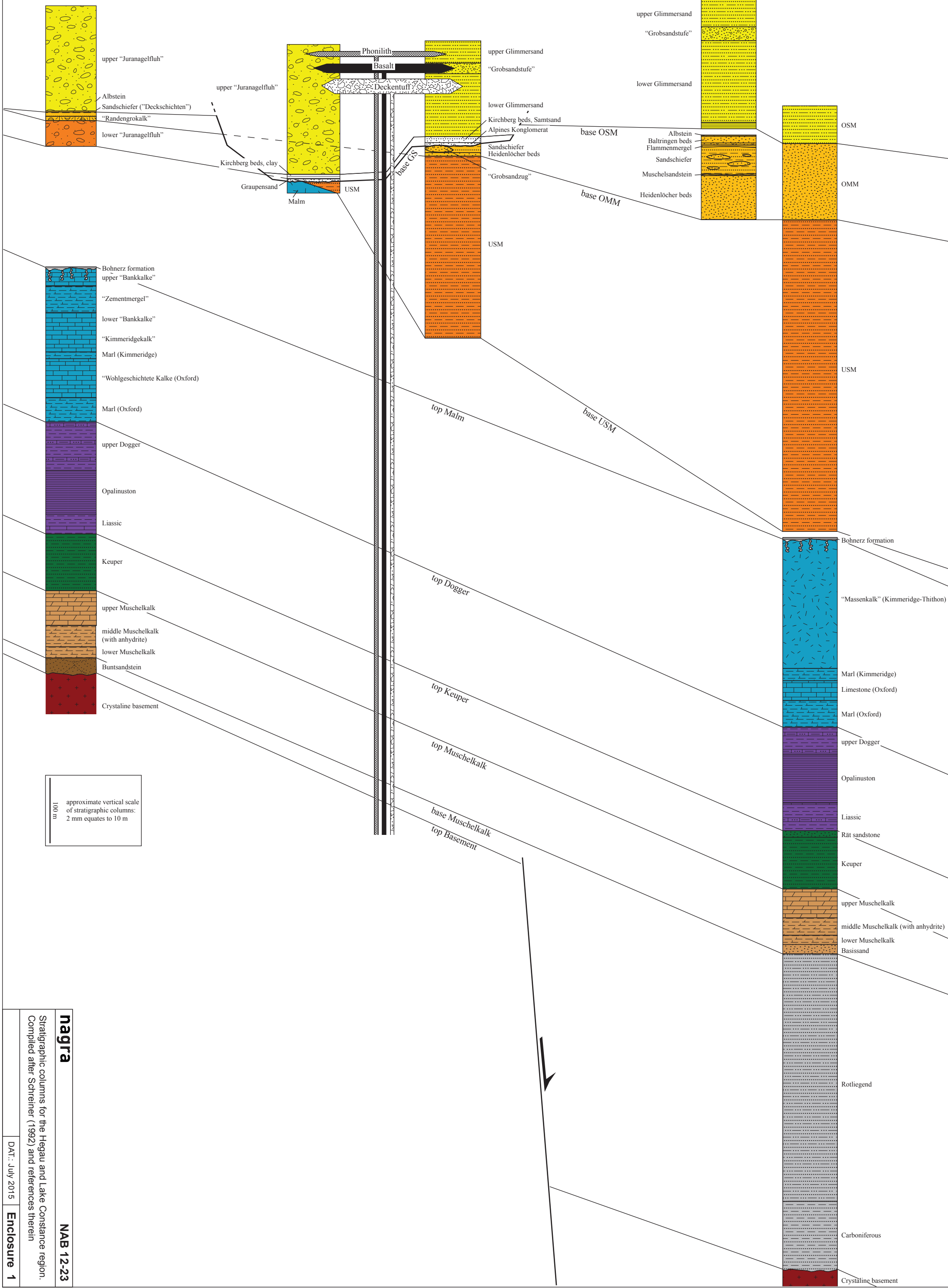
Southeast Hegau

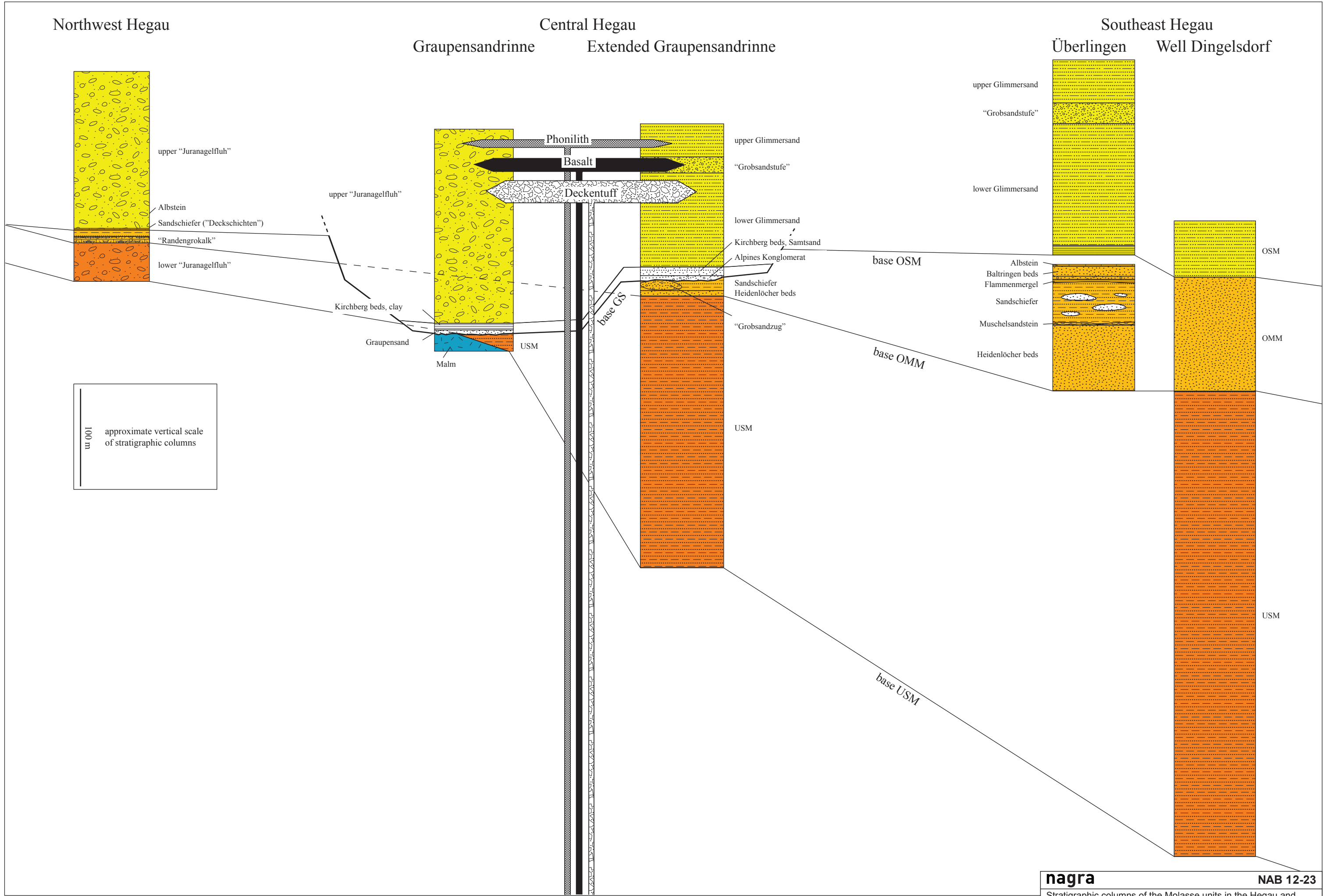
Graupensandrinne

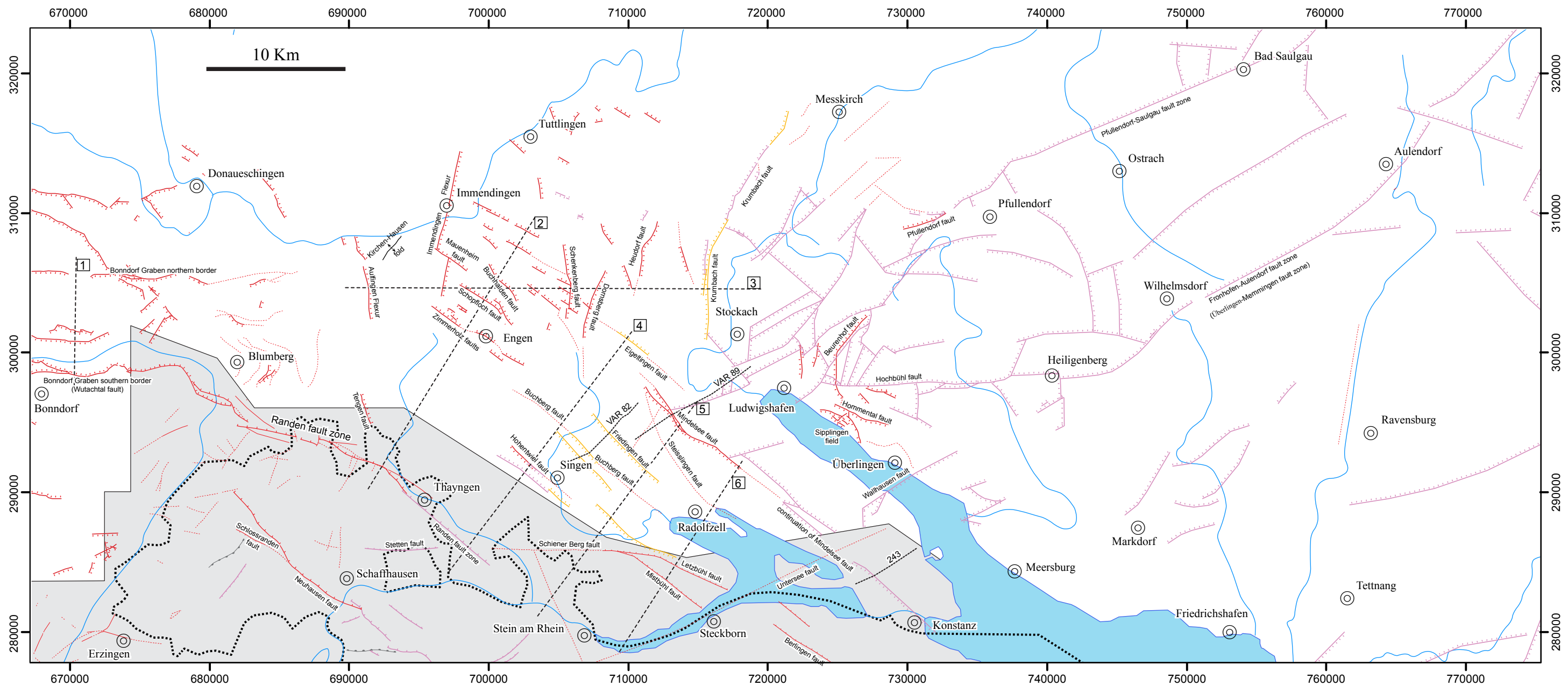
Extended Graupensandrinne

Ueberlingen

Well Dingelsdorf







Faults compiled from literature (this study)

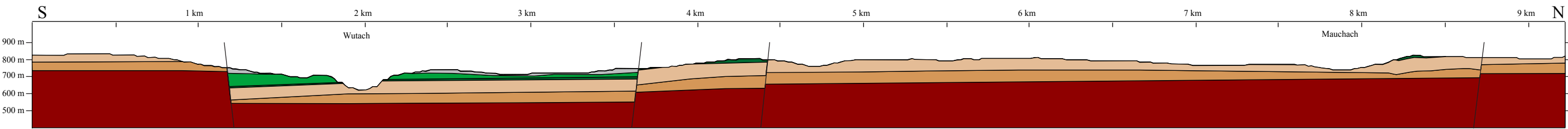
- faults mapped at surface
- faults derived from seismic interpretation
- faults derived from stratigraphic correlation
- faults assumed

Faults from the Nagra dataset (grey area)

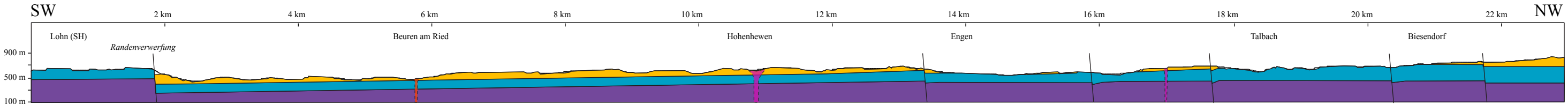
- major normal faults mapped at surface
- normal faults mapped at surface
- faults mapped at surface
- faults assumed
- thrust mapped at surface
- flexure derived from seismic interpretation
- major normal faults derived from seismic interpretation
- normal faults derived from seismic interpretation
- thrust derived from seismic interpretation
- local thrust derived from seismic interpretation

6 Cross-section with number given in appendix 4
243 seismic line with number given in figure 16

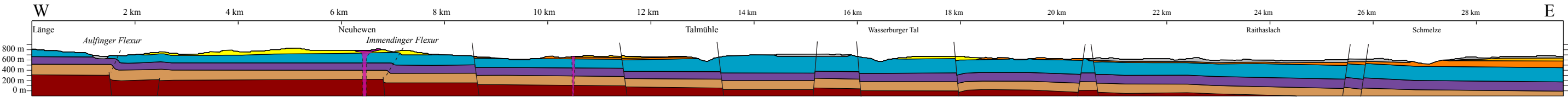
Known faults of the Hegau and Lake Constance region as compiled from literature (Bertleff 1986; Geyer et al. 2011; Interreg IIIA 2007; Reinecker & Schneider 2002; Schreiner 1992; Volz 1959; Zaugg et al. 2008; and the corresponding map sheets of the Geologische Karte von Baden-Württemberg 1:25 000) and as provided by Nagra (grey area). Although the compiled faults outside the Nagra dataset are nearly exclusively designated as normal faults in the literature they are often subvertical in orientation and some of them are flexures. Therefore the small ticks point to the side of relative downthrow in general.



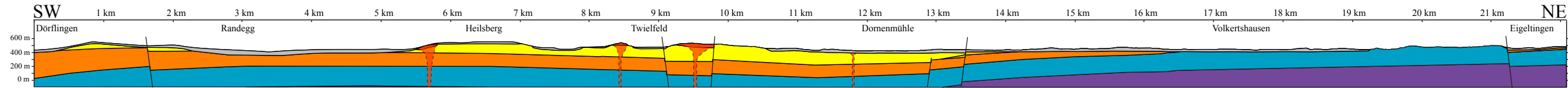
1 Bonndorf Graben



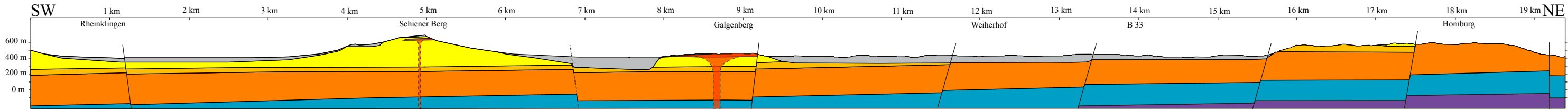
2 Randen - Emmingen



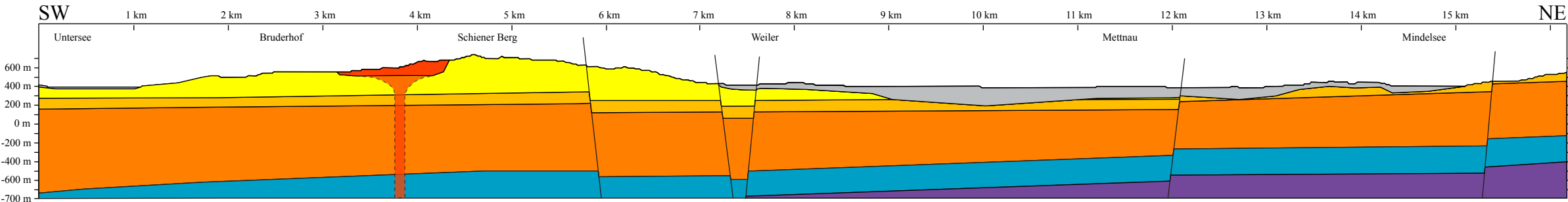
3 Länge - north of Stockach



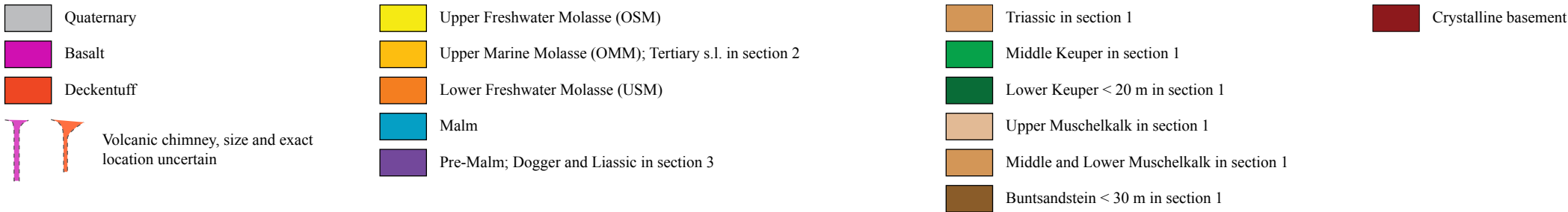
4 Singen Basin north



5 Singen Basin south



6 Schiener Berg - Lower Lake Constance



Cross sections constructed based on surface geology as given in published geological maps of Geologische Karte von Baden-Württemberg 1:25.000, and seismic interpretations(Interegg IIIA 2007). Stratigraphic thicknesses as shown in Enclosure 1. See Enclosure 3 for cross section traces.