Swiss J Geosci (2014) 107:157–175
DOI 10.1007/s00015-014-0167-7

Inherited tectonic structures controlling the deformation style: an example from the Helvetic nappes of the Eastern Alps

Michael Zerlauth · Hugo Ortner · Hannah Pomella · O. Adrian Pfiffner · Bernhard Fügenschuh

Received: 9 July 2013 / Accepted: 3 September 2014 / Published online: 28 November 2014

Abstract Based upon tectonic as well as facies arguments, two different Helvetic nappes can be distinguished in western Austria (Vorarlberg) and in southwestern Germany (Upper Allgäu): the Hohenems nappe and the overlying Vorarlberg Säntis nappe. Both encompass Middle Jurassic to Eocene strata deposited on the internal to external shelf of the southward deepening European margin of the Eurasian plate. Synsedimentary normal faults caused changes in thickness and facies of the various strata, which play a crucial role in deformation behavior. Arcuate fold axes in map view and an almost 3 km thick sequence of stacked Middle Jurassic shales and sandstones drilled below a Jurassic anticlinorium in the southern part of the Bregenzerwald are thought to be indicative of an inverted Jurassic basin. Inversion occurred during the Cenozoic Alpine nappe formation along synsedimentary normal faults, reactivated as ramps and tear faults. A lateral ramp, segmented by tear faults, running along the Iller Valley, and a supposed lateral ramp in the subsurface of the Rhine Valley mark the extension of the inverted former basin. Fault deformation style changes across the Rhine Valley. East of it, i.e. in Vorarlberg, the Vorarlberg Säntis nappe comprises a coherent succession of Jurassic and Cretaceous strata detached along Middle Jurassic sediments. In the west, on the other hand, Cretaceous strata of the Swiss Säntis nappe were largely detached from their Jurassic substrate (Gonzen-Walenstadt imbricates) along the Säntis thrust. This allows to correlate the Helvetic nappe stack of eastern Switzerland, comprising the Swiss Säntis nappe (together with the Gonzen-Walenstadt imbricates) and the underlying Mürtschen nappe, with the Vorarlberg Säntis nappe and the Hohenems nappe of Austria.

Keywords Austria · Germany · Nappe complex · Jurassic basin · Cretaceous facies variations · Seismic and well data

Editorial handling: A. G. Milnes.

Electronic supplementary material The online version of this article (doi:10.1007/s00015-014-0167-7) contains supplementary material, which is available to authorized users.

M. Zerlauth (✉)
alpS Centre for Climate Change Adaptation, Grabenweg 68,
6020 Innsbruck, Austria
e-mail: zerlauth@alps-gmbh.com

M. Zerlauth · H. Ortner · H. Pomella · B. Fügenschuh
Institute of Geology, University of Innsbruck, Innrain 52,
6020 Innsbruck, Austria

O. Adrian Pfiffner
Institute of Geological Sciences, University of Bern,
Baltzerstrasse 1 + 3, 3012 Bern, Switzerland

1 Introduction

The Helvetic nappe system consists of stacked coherent strip-sheets (Trümpy 1969)—the Helvetic nappes proper—, as well as the underlying (par)autochthonous Infrahelvetic complex (Pfiffner 1993, 2010a, 2011) and forms a continuous belt with eastward decreasing width, which can be traced throughout the northern margin of the Alpine arc from Nice (France) to Oberstdorf (Germany). From Oberstdorf eastwards, the Helvetic zone is only exposed as small and discontinuous lenses (Fig. 1).

The Infrahelvetic complex and the Helvetic nappes encompass Mesozoic to Cenozoic shelf and upper slope sediments originally deposited on the southern European passive margin. Towards the lower slope a transition from Helvetic carbonate- and marl-dominated successions to

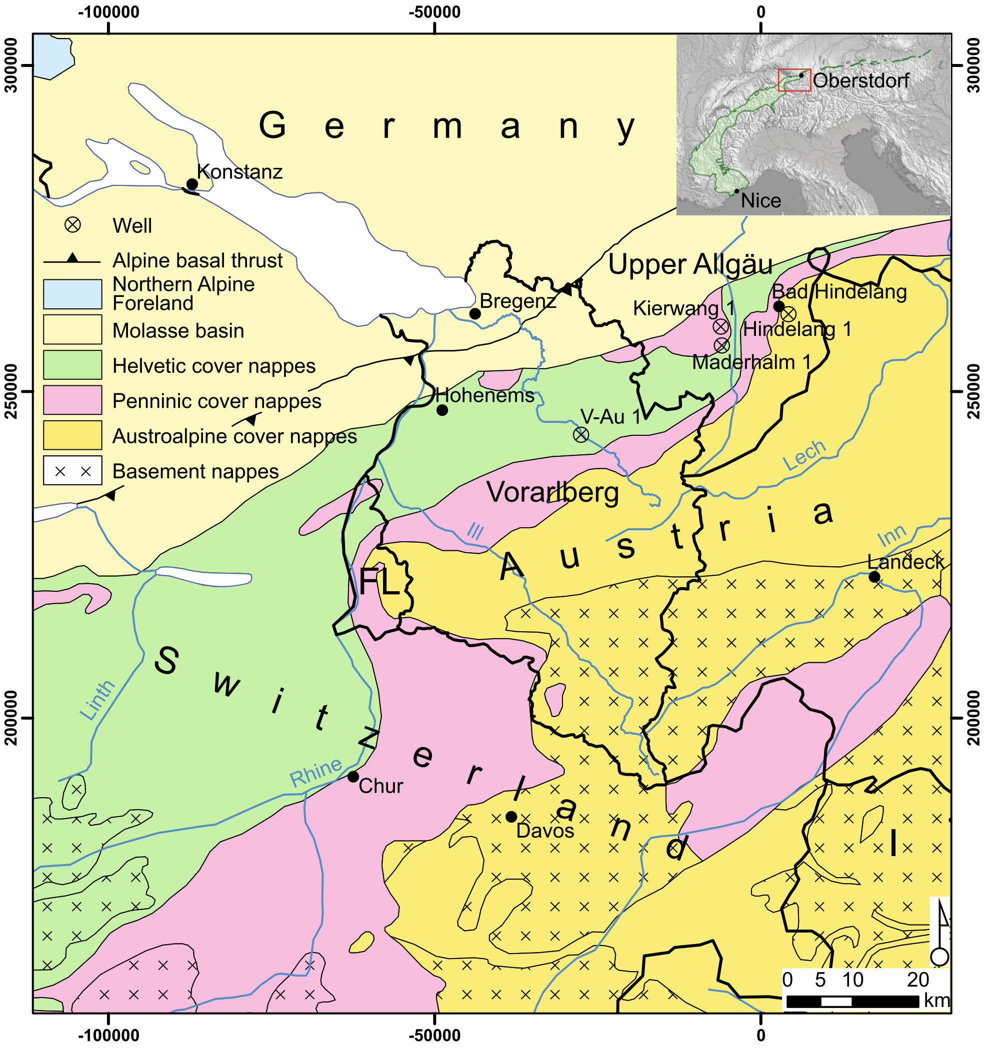

Fig. 1 Simplified tectonic map of eastern Switzerland, Liechtenstein, western Austria, and southwestern Germany based on Scholz and Zacher (1983) and Pfiffner (2010a). *Inset* Digital elevation model of the Alps showing the outcrop pattern of the (Ultra)Helvetic nappe system including the External Massifs in the Alps. Note the substantial decrease in width from west to east. Outlines are redrawn from Egger et al. (1999a, b) and Pfiffner (2010a). *Red rectangle* in the *inset* map indicates the study area proper. MGI Austria GK West coordinate system

shales of the Ultrahelvetic domain occurred. In the course of Cenozoic tectonics, the slope deposits and the adjacent shelf elements were detached from their crystalline substratum and formed the (Ultra)Helvetic nappes. By contrast, the proximal Infrahelvetic complex comprises a complete sequence including pre-Triassic basement and its (par)autochthonous Mesozoic and Cenozoic cover, as well as exotic/allochthonous strip sheets later overridden by the (Ultra)Helvetic nappes. These two domains with overall different structural style, i.e. thin-skinned versus thick-skinned, are separated by the basal thrust of the Helvetic nappes, e.g. the Glarus thrust in eastern Switzerland.

The main focus of this paper lies on the geometry and the internal structure of the Helvetic nappe system of Vorarlberg and Upper Allgäu which is not yet sufficiently understood.

Although numerous authors dealt with its stratigraphy and structure (e.g. Vacek 1879; Messmann 1925; Sax 1925; Schaad 1926; Heim et al. 1933; Oberhauser 1951, 1958, 1963; Felber and Wyssling 1979; Bettenstaedt 1985), it was only Wyssling (1985) who first argued for the existence of two distinct nappes. Apart from the hitherto known Vorarlberg Säntis nappe, distinct facies differences in the Early and Late Cretaceous sequences allowed him to define an underlying nappe, i.e. the Hohenems nappe. Largely based on facies arguments from nearby outcrops in Hohenems and wells Kierwang 1 and Maderhalm 1 (see Fig. 1), the existence of the Hohenems nappe is still a matter of debate (e.g. Oberhauser 1991).

In this study a revised tectonic concept for the Helvetic zone east of the Rhine Valley is presented, taking into account previous results and combining surface geology with “new” seismic and well data: Kierwang 1 (Müller 1985), Maderhalm 1 (Müller 1985), Hindelang 1 (Huber and Schwerd 1995), V–Au 1 (Colins et al. 1989), partly done after 1985 (Fig. 1). First, its structure was worked out, and in the view of our findings, the significance of facies arguments for the definition of the existing nappe stack was checked. Second, the area of investigation was extended across national borders towards Bad Hindelang (Germany) in the east and eastern Switzerland in the west (Fig. 1), which was necessary to examine the lateral continuity of the proposed structures. Finally, parameters decisive for the deformation style moved into focus.

2 Stratigraphy

Stratigraphic nomenclature of the Helvetic units in the Eastern Alps is based on Heim (1916), established in the Churfirsten and Mattstock area in eastern Switzerland, and first applied to the Eastern Alps by Sax (1925) and Schaad (1926). Information concerning the Cretaceous outer shelf to upper slope deposits of the Helvetic-Ultrahelvetic transitional zone as well as the Early Cretaceous Helvetic facies pattern were provided by the work of Felber and Wyssling (1979) and Wyssling (1986), respectively. In the following, an overview of the stratigraphic record of the Helvetic zone of the Eastern Alps, shown in Fig. 2, will be given. For more detailed information the reader is referred to Oberhauser (1951, 1991), Lupu (1972), Zacher (1973), Schwerd and Häussler (1983), Schwerd (1983), Föllmi (1986), Föllmi and Ouwehand (1987), Bollinger (1988), Salomon (1989), Colins et al. (1989), Fessler et al. (1992), Scholz (1984), Huber and Schwerd (1995), Schwerd (1996a, b), Linder et al. (2006), Föllmi et al. (2007), and Friebe (2007a, b).

2.1 Stratigraphic sequence

The Bommerstein Formation, i.e. Middle Jurassic dark shales followed by silt- and sandstones with intercalated calcarenites (Colins et al. 1989; Huber and Schwerd 1995), which was encountered by wells Maderhalm 1 (Müller 1985), Hindelang 1 (Huber and Schwerd 1995) and V–Au 1 (Colins et al. 1989), forms the stratigraphic base of the Helvetic units east of the Rhine Valley. It is overlain by a succession of crinoidal limestones and marls (Reischiben Formation), followed by clayey marls of the Schilt Formation (Colins et al. 1989). Large variations in thickness are characteristic of the Helvetic realm (e.g. Dollfuss 1965; Pfiffner 2010b) and indicate differentiated subsidence due to synsedimentary normal faulting (Trümpy 1969; Pfiffner 2011). During the Late Jurassic, a several hundred meters thick sequence of micritic limestones (Quinten Limestone) was deposited throughout the entire Helvetic shelf. By contrast, the Tros Member, comprising shallow-water carbonates of Tithonian age, is restricted to the northernmost shelf areas (Föllmi et al. 2007). Towards the top of the Quinten Limestone, the limestones rapidly become more marly to sandy, to finally form the Zementstein Formation. The Early Cretaceous is characterized by the development of two partly oolitic southward prograding carbonate platforms and their corresponding marly outer shelf deposits in the Berriasian (Örfla and Palfris Formations, respectively) and Barremian/Aptian (Schrattenkalk Formation and Drusberg Member, respectively). These two platform evolutions were separated by local bioclastic platform resediments (Betlis Formation) and a glauconitic condensation horizon (Gemsmättli Bed/Wildgunten Bed). In the external shelf areas, the latter is overlain by hemipelagic carbonates (Diphyoides Limestone), followed by calcitic cemented arenites and silicious limestones (Kieselkalk Formation), deposited between internal parts of the platform and external shelf areas (Wyssling 1986). Development of the Schrattenkalk-platform is ended by an

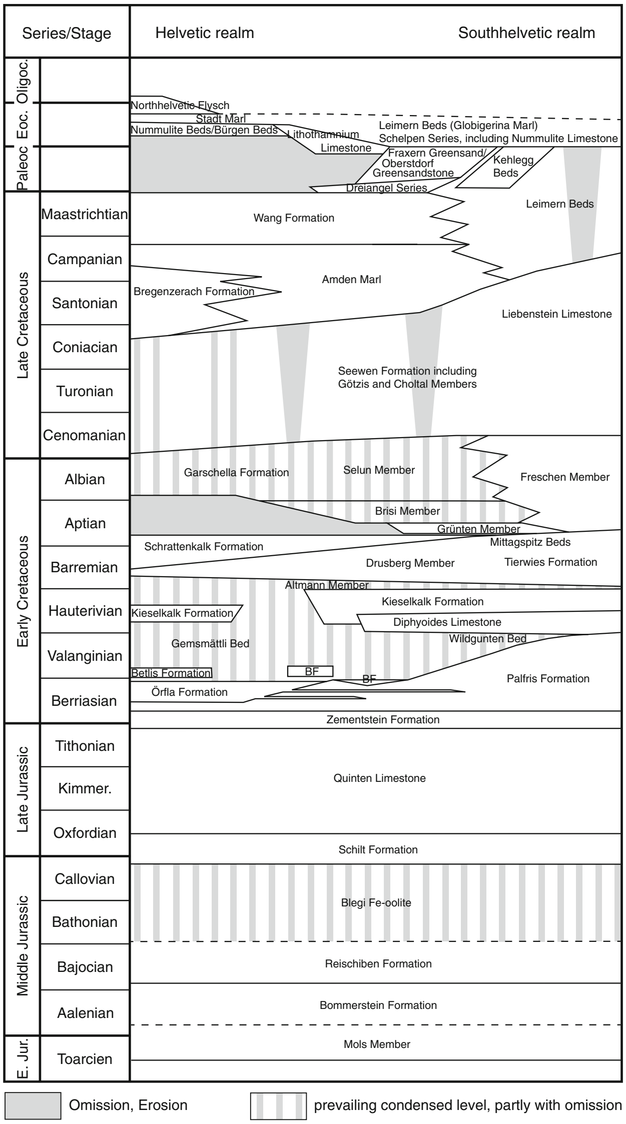

Fig. 2 Stratigraphic succession of the Helvetic nappes of Vorarlberg and Upper Allgäu based on Heim (1916), Felber and Wyssling (1979), Trümpy (1980), Wyssling (1986), Oberhauser (1991), Huber and Schwerd (1995), Linder et al. (2006), and Föllmi et al. (2007). *BF* Betlis Formation

increasing water depth together with an increase in terrigenous input during Aptian times (Bollinger 1988). This gives rise to the deposition of—commonly glauconite-bearing—condensed quartz arenites (Garschella Formation). The overlying pelagic limestones of the Seewen Formation display a relative sea-level highstand during the Late Cretaceous (Schwerd 1996a, b). The stratigraphic sequence of the Cretaceous ceases with marl-dominated successions of the Amden Marl and Wang Formation, indicating a renewed increase in detrital input. Cenozoic sediments, documenting the earliest evolution of the Northalpine Foreland Basin (Allen et al. 1991; Crampton and Allen 1995), are preserved only locally and therefore beyond the scope of this paper.

According to Funk et al. (1993) and Föllmi et al. (2007), the Helvetic realm can be subdivided into three facies zones: (1) The Northhelvetic zone, that is comparatively thin and dominated by carbonates with numerous condensed horizons. Its southern limit is marked by the front of maximum progradation of the Tros Member. (2) To the south follows the Middlehelvetic realm which generally shows increasing thicknesses. This realm is characterized by Cretaceous platform sediments with the most distal Tithonian platform carbonates defining its southern limit. (3) The Southhelvetic sequence is rather thick, prevailing marly, and lacks platform deposits (Richter 1969; e.g. Wyssling 1986). It starts with the first appearance of the Hauterivian Diphyoides Limestone in the north. Towards the south, the slope facies defines the change from the Helvetic to the Ultrahelvetic realm. After orogenesis, the Northhelvetic facies zone became the Infrahelvetic complex, the Middlehelvetic together with the proximal part of the Southhelvetic facies zone (often called just the Helvetic) became the Helvetic nappe complex, and the distal part of the Southhelvetic facies zone became the Ultrahelvetic nappe complex.

3 Tectonic setting

3.1 Overview

The Helvetic nappes proper, carried by the Helvetic basal thrust, display the image of a classical thin-skinned fold-and-thrust belt, with internal deformation resulting in imbricate thrusting, buckle, and/or recumbent folding (e.g. Pfiffner 1993). Detachment of the Mesozoic to Cenozoic sedimentary sequence occurred in the course of thrusting of Austroalpine and Penninic nappes in the Late Eocene, activating the Helvetic basal thrust during the Early Oligocene (Pfiffner 1986). East of the Rhine Valley, the Helvetic basal thrust cuts across Lower Freshwater Molasse deposits at surface, indicating activity at least until the Late Oligocene. In eastern Switzerland, a final increment of thrusting can be assumed to be Early Miocene in age (Ruchi phase of Milnes and Pfiffner 1977), based on the offset of correspondingly young apatite fission track ages (Rahn et al. 1997) and metamorphic isograds (Frey 1988) across the Glarus thrust. Folded thrust planes suggest that thrust propagation generally occurred in-sequence, i.e. from top down or from internal to external parts (Groshong et al. 1984; Pfiffner 2010b), as is typical of thin-skinned fold-and-thrust belts (e.g. Jordan et al. 1993).

3.2 Data

In order to develop a consistent model for the Helvetic nappe system of Vorarlberg and Upper Allgäu, three N–S trending cross sections at upper crustal-scale were constructed. An additional E–W cross section was drawn for better correlation and visualization of the relation between the Helvetic nappes east and west of the Rhine Valley. The cross sections are based on surface geology, logs of nine deep wells [Legau 1 (Schwerd et al. 1995), Sulzberg 1 (Herrmann et al. 1985), Dornbirn 1 (Huf 1963), Immenstadt 1 (Müller 1983), Hohenems 1 (Oberhauser 1991), Kierwang 1 (Müller 1985), Maderhalm 1 (Müller 1985), Hindelang 1 (Huber and Schwerd 1995), and V–Au 1 (Colins et al. 1989)], and reflection seismics for oil and gas exploration. Moreover, two recently acquired seismic sections from Fürstentum Liechtenstein (Naef 2010) were available (Fig. 3). On the basis of vertical seismic profiles (VSP) of wells Sulzberg 1 (Prakla-Seismos 1984), Hindelang 1 (Lettau 1995), and V–Au 1 (Winkler and Cassell 1989), previously interpreted seismic horizons were time-to-depth converted by using statistically determined interval velocities for the corresponding tectonic and/or appropriate thick stratigraphic units.

In general, the resolution of the seismic data decreases to the south. This is caused by the complexity of geologic successions and bedding orientations of the numerous tectonic units stacked. Furthermore, seismic quality is considerably reduced in the area of glacially overdeepened valleys filled with thick unconsolidated sediments, e.g. along the Rhine Valley and the Walgau. North of the Helvetic basal thrust exposed at surface, internal structures within the Subalpine and Foreland Molasse can be quite nicely resolved. Towards the south, on the other hand, interpretation is largely restricted to laterally consistent highly reflective horizons. This is generally the case along (thrust) faults where units with differing seismic velocities and/or densities are in contact. However, the European pre-Triassic crystalline basement together with its Mesozoic cover forms a well-defined seismic feature throughout the area investigated; reflector A, the deepest group of reflections, is attributed to the Triassic Muschelkalk Group, and

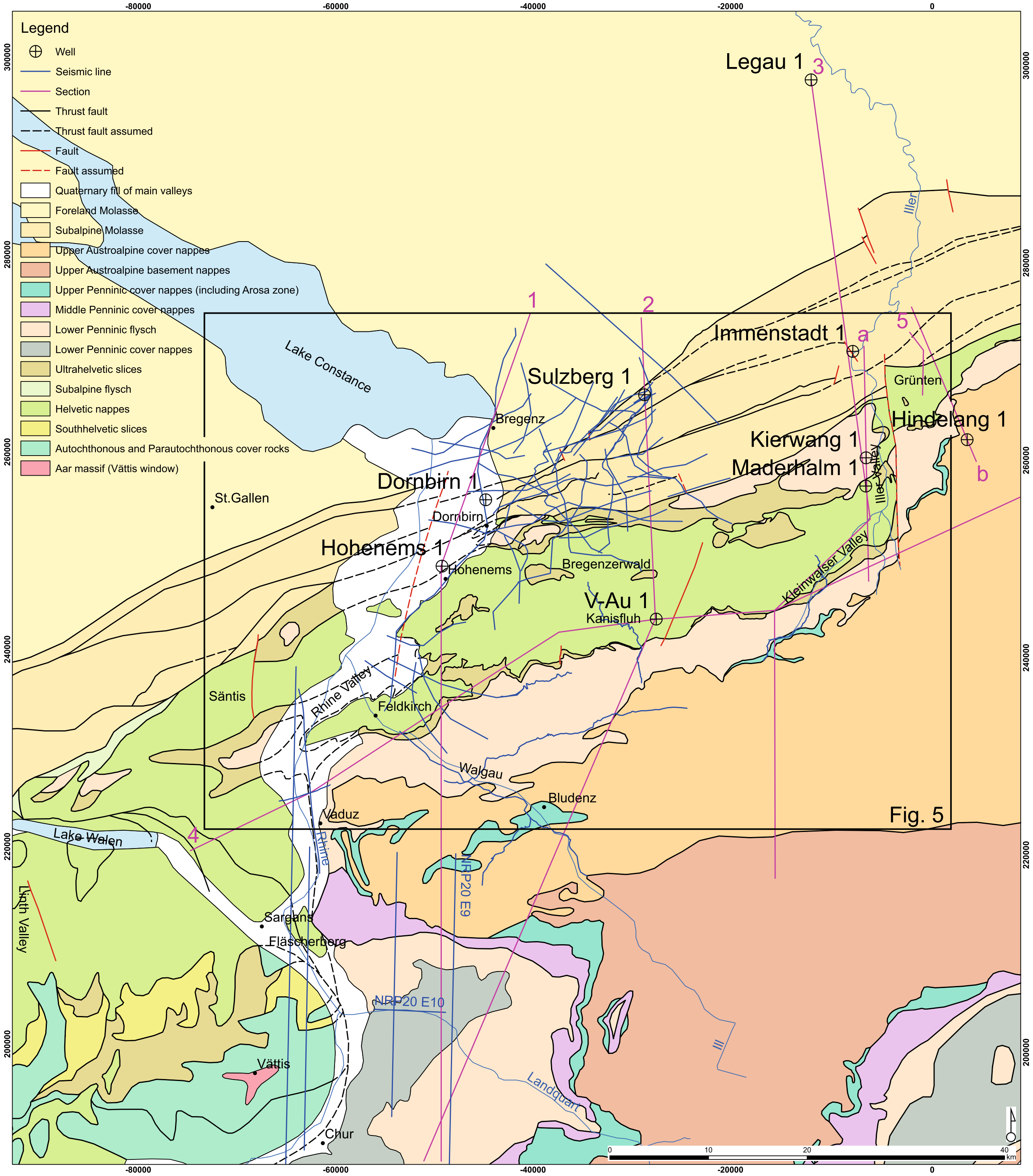

Fig. 3 Tectonic map of the investigated area redrawn after Scholz and Zacher (1983), Oberhauser (2007), and Pfiffner et al. (2010), showing well locations and traces of seismic sections. Note that the Lower Penninic Feuerstätter nappe and the Liebenstein nappe, the latter representing the Ultrahelvetic unit sensu strictu, are grouped together as "Ultrahelvetic slices/nappes" due to their mélange-like structure. Constructed upper crustal-scale cross sections are labeled 1–4 (N–S cross sections 1–3, E–W cross section 4). Section 5 is a surface profile and sections *a* and *b* refer to Fig. 10a, b, respectively. MGI Austria GK West coordinate system

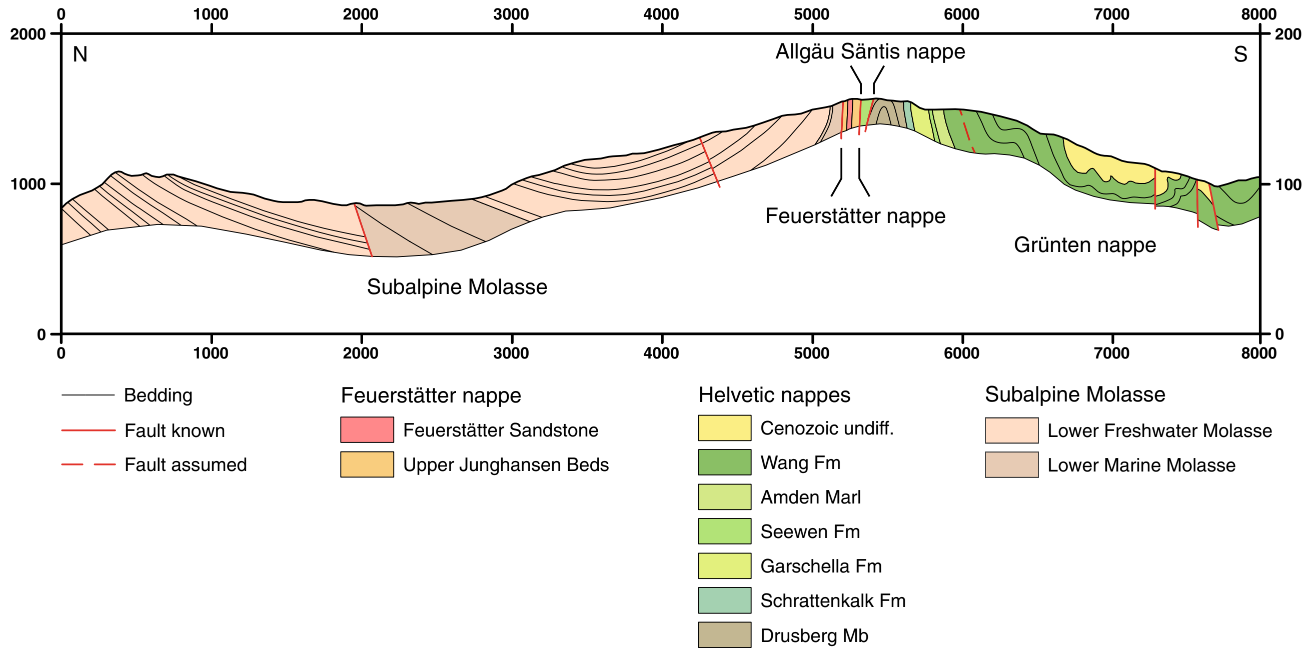

Fig. 4 Section 5 modified from Ebel et al. (1983b) exhibiting the contact between the Subalpine Molasse and the Helvetic nappes with some Penninic remnants in between. Scaling is in Meters. For the trace of the cross section see Fig. 3

reflector B to Cretaceous to Paleogene strata at the base of the foreland basin sequence (e.g. Dohr 1983). The Late Jurassic limestones between reflectors A and B are predominantly seismically transparent.

4 Starting conditions for cross section construction

4.1 Subsurface information

The contact between the southernmost slice of the Subalpine Molasse and the leading edge of the harmonically folded Penninic and (Ultra)Helvetic nappes is commonly marked by a bedding-parallel thrust fault, steeply dipping to the S as well as to the N (e.g. at the Grünten, north of Oberstdorf; see Fig. 4). In some areas, the succession from the basal units of the Lower Marine Molasse towards the underlying youngest Helvetic strata across this doubtless tectonic contact could be mistaken as “normal sequence” (e.g. Ganss and Schmidt-Thomé 1955; Ortner et al. 2011). Evidence for large-scale imbrication of Penninic or (Ultra)Helvetic units is missing from well data and mining galleries (e.g. Ganss and Schmidt-Thomé 1955), as well as from the surface geology. From this, Schwerd (1970) first interpreted this fault as a passive roof thrust at the top of a thrust-bounded wedge in the sense of Price (1986), with the wedge formed by Austroalpine, Penninic, and (Ultra)Helvetic nappes. The Subalpine Molasse in the hanging wall of the passive roof thrust was underthrusted and consequently the southernmost synformal slice formed due to the hanging wall ramp of this buried intercutaneous wedge. In spite of numerous seismic lines crossing this subsurface triangle zone, its exact position and geometry remains unknown. However, late stage out-of-sequence thrusting affecting the aforementioned triangle zone is more than reasonable and thus considered in all N–S trending cross sections (c.f. Schwerd et al. 1995 and Ortner et al. 2011).

In Liechtenstein, at the Fläscherberg—situated in the Rhine Valley east of Sargans (see Fig. 3)—, the Northpenninic Prättigau Flysch nappes are thrust onto the Swiss Säntis nappe along a footwall ramp. The deepest exposed unit cut by the Penninic basal thrust is formed by the Helvetic Kieselkalk Formation (Allemann 2002). Hence, the trailing end of the allochthonous Helvetic units, overlying the Helvetic basal thrust, has to be located not far south of the Fläscherberg, which is in good agreement with the results of the NRP-20 project (Hitz and Pfiffner 1994). For our profiles we projected this point eastwards along trend of the mapped fold axes.

In a next step we determined the longitudinal and vertical extension of the Helvetic units. The vertical extension exceeds the average thickness of the Jurassic (approximately 800 m) and Cretaceous (approximately 1,000 m) strata up to three times. In the area of the Kanisfluh (Fig. 3), the Helvetic basal thrust is located about 6,000 m below the base of the Northpenninic Rhenodanubian Flysch nappes. This fact strongly argues for an imbricated Helvetic nappe stack, in analogy to the Helvetic nappe stack in eastern Switzerland. Following Wyssling (1985, 1986) and Fessler et al. (1992), and using data from wells

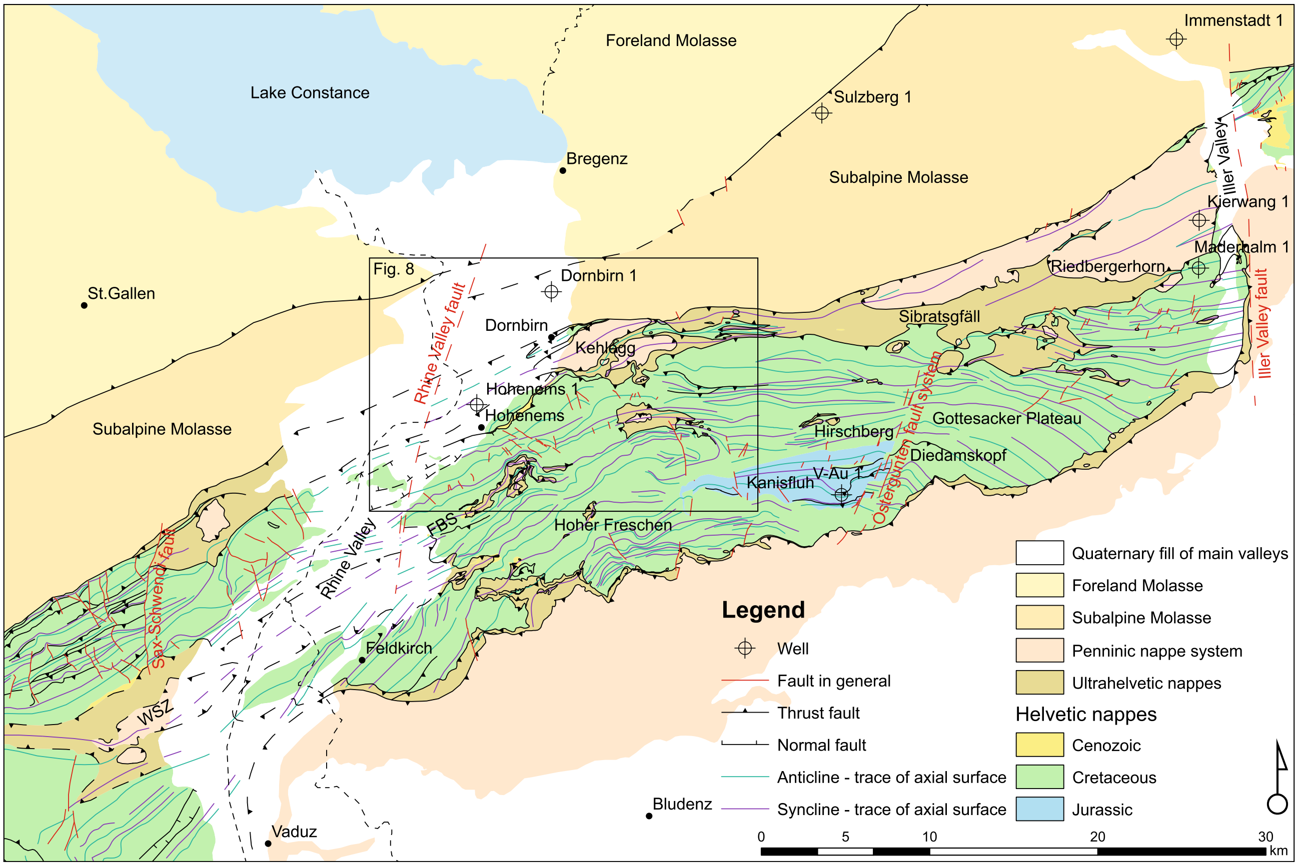

Fig. 5 Detailed tectonic map of the Helvetic zone along the transition between the Central and the Eastern Alps (across the Rhine Valley), showing the traces of axial surfaces of major anticlines and synclines. *WSZ* Wildhauser Schuppenzone, *FBS* Fraxern-Bizau synform. Map compiled from Oberhauser (1982, 1994, 2007), Ebel et al. (1983a), Zacher (1990), Moser (2008), and Pfiffner et al. (2010). *Thin black dashed lines* image national borders

V–Au 1 (Colins et al. 1989) and Hindelang 1 (Huber and Schwerd 1995), another nappe, termed "Hohenems nappe", is considered to be present in the footwall of the well-known exposed Vorarlberg Säntis nappe.

4.2 The problem of the "Rhine Valley fault"

The lateral continuation of the just mentioned units plays a crucial role in the construction of our cross sections and this, on the other hand, provides independent information on the nature of this transition zone across the Rhine Valley. Various authors addressed this question with respect to the Cretaceous Helvetic units cropping out east and west of the Rhine Valley and concluded that they can be connected (e.g. Richter 1969; Zacher 1973; Trümpy 1980; Oberhauser 1991; Trümpy 1992; Funk et al. 2000; Pfiffner 2011). This conclusion is essentially based on two observations. Firstly, although barely possible for individual folds, first order fold-patterns can be traced across the Rhine Valley (Pfiffner 2011). Blumer (1922) already recognized that the synform of Ultrahelvetic and Penninic units in the hanging wall of the Swiss Säntis nappe, termed "Wildhauser Schuppenzone", can be correlated with the "Fraxern-Bizau synform" in Vorarlberg. The same holds true for the Ultrahelvetic and Penninic units east-northeast and west-southwest of Hohenems, which are also located in the core of a synform (Fig. 5).

Secondly, isopach maps from Cretaceous stratigraphic units were compiled, in order to document whether and how thickness changes occur across the Rhine Valley. The use of such maps is reasonable, since the Helvetic units cropping out on both sides of the Rhine Valley are attributed mainly to the Middlehelvetic and Southhelvetic facies realms (Trümpy 1969; Schwerd et al. 1995). Because individual fold trains can be traced across the Rhine Valley, shortening of the Helvetic zone was not taken into account. Isopach maps from the Schrattenkalk Formation and the Drusberg Member (Fig. 6) show that their thickness varies across the Rhine Valley, i.e. along strike of the tectonic structures, as is the case for the entire Helvetic zone in the Eastern Alps (e.g. Richter 1969; Zacher 1973). Due to the resolution of the maps (about 4 km), the

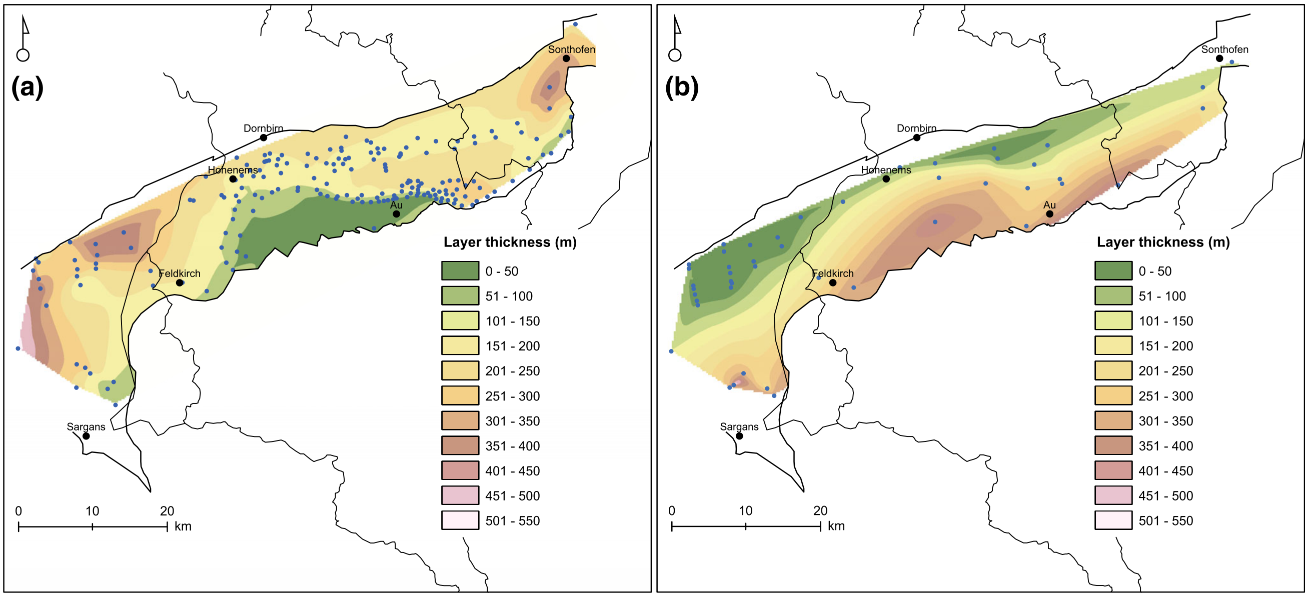

Fig. 6 Isopach line maps for the Early Cretaceous Schrattenkalk Formation (**a**) and Drusberg Member (**b**) based on thickness data from Heim et al. (1933), Briegel (1972), Zacher (1973), Felber and Wyssling (1979), Schwerd and Häussler (1983), Müller (1985), Oberhauser (1991, 1993), Schwerd et al. (1995), Funk et al. (2000), and Goldscheider (2002), indicated by *blue points*. Notice the opposite thickness changes of the platform deposits and the associated basin sediments which verify the interpolation. *Thick black lines* are outcrop limits of the Helvetic nappe system. *Thin black lines* show national borders

isopachs are not offset by the known transfer faults (Ostergunten fault system and Sax-Schwendi fault; see Fig. 5). Therefore, sinistral transfer faults with respective offsets along the Rhine Valley, as supposed by Oberhauser (1991), Funk et al. (2000), and Pfiffner (2011), cannot be excluded. However, it is unlikely that any fold-related faults described by Richter (1969) and Oberhauser (1991) caused a complete separation of the Helvetic zone across the Rhine Valley. Thus, we propose a rather continuous arrangement of the Cretaceous formations in the Helvetic units on either side of the Rhine Valley.

4.3 Shortening estimates: paleolength of the Helvetic realm

Balanced cross sections across the Aar massif published by Trümpy (1969), Blum and Hug (2001), and Pfiffner (2011), yielded highly variable shortening amounts from 15 % up to 70 %. These differences are partly due to the fact that large portions of the different Helvetic nappes have been removed by erosion, and the trailing end of this nappe stack can only be roughly estimated in the subsurface. Consequently, these estimates have to be treated cautiously. In Vorarlberg and Upper Allgäu, reliable shortening estimates can be reported solely for exposed Cretaceous units, and values decrease from 30 % in cross section 1–16 % in cross section 3 (Fig. 7). Balancing the cross section of Trümpy (1969) drawn across the Säntis-Churfirsten massif, which was completed by Blum and Hug (2001), produced some 50 % of overall shortening for the Gonzen-Walenstadt imbricates between Lake Walen and the Fläscherberg. Apart from that, the restored length of the Gonzen-Walenstadt imbricates, which is in the range of 40–45 km, was taken as a minimum value for the length of the appropriate Vorarlberg Säntis nappe. Since the Helvetic basal thrust emerges some 10 km further north to the east of the Iller Valley compared to the Rhine Valley, the Vorarlberg Säntis nappe shows a paleolength of approximately 63 km in cross section 3 (see Fig. 7c). With the general northward decrease in thickness of the Cretaceous strata (e.g. Pfiffner 1979; Funk et al. 1993), an originally 25–35 km long Hohenems nappe can be assumed to fill the space below the Vorarlberg Säntis nappe. The suspected N–S extension coincides more or less with the paleogeographic-palinspastic reconstruction of the Helvetic realm of Kempf and Pfiffner (2004) as well as Pfiffner (2011), where 20–25 km are left between the front of the Swiss Säntis nappe and the (par)autochthonous units at the southeastern end of the Aar massif. To sum up, 72–88 km of the Helvetic shelf is thought to be preserved within the Helvetic nappe stack of Vorarlberg.

4.4 Mechanical stratigraphy

The lateral variation of the number of Helvetic nappes, as well as their varying internal stratigraphy is due to different detachments, which are controlled by mechanical stratigraphy. Occurrence, thickness, and viscosity ratios

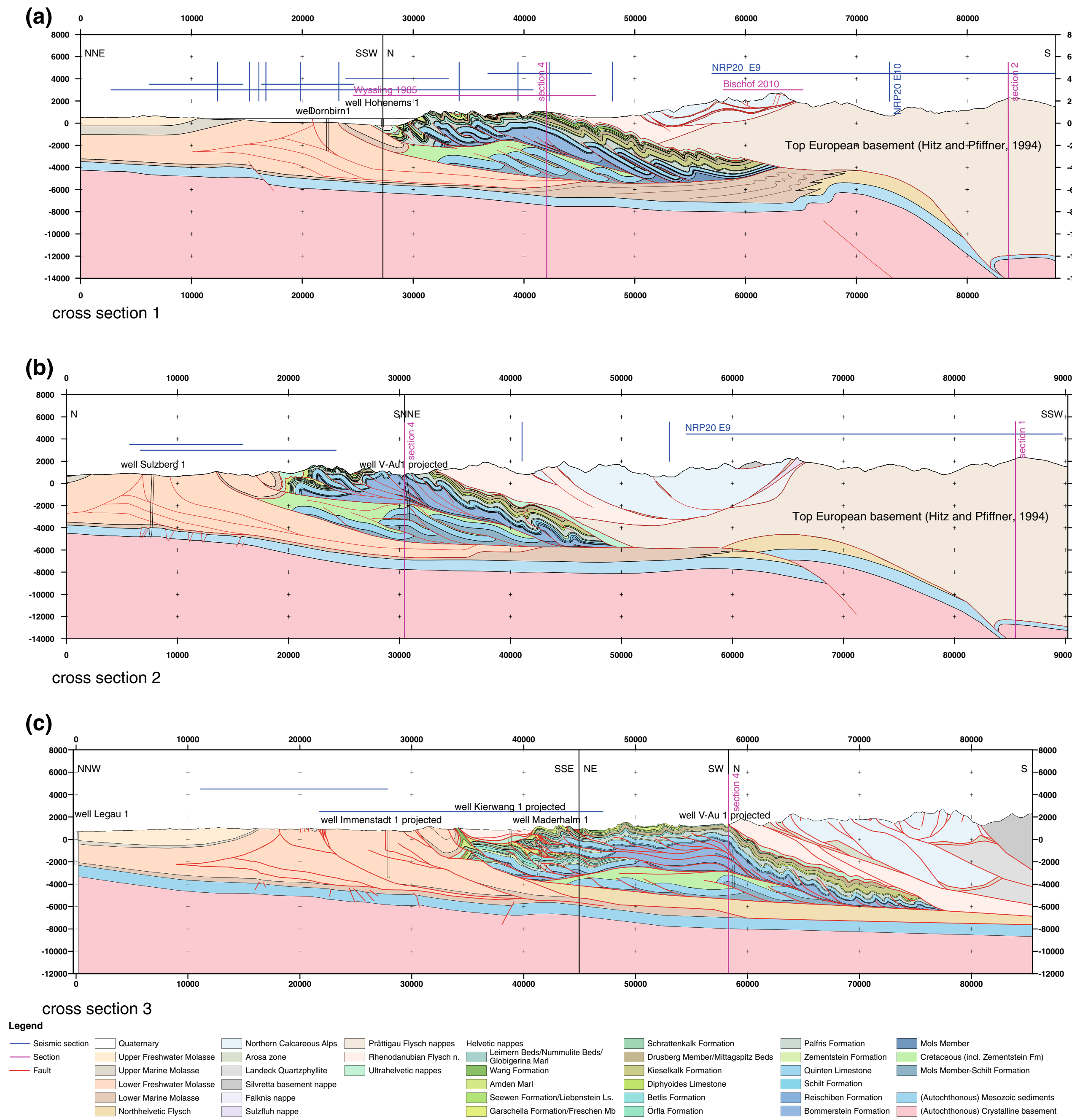

Fig. 7 Interpreted upper crustal cross sections through the Helvetic zone in western Austria and southern Germany: **a** cross section 1, **b** cross section 2, **c** cross section 3 (for locations, see Fig. 3). Surface geology is based on Ampferer and Reithofer (1932), Zacher (1972, 1990), Jerz (1974), Doert and Helmcke (1976), Vollmayr and Ziegler (1976), Zylka and Jacobshagen (1980), Herrmann and Schwerd (1982), Oberhauser (1982, 1994, 2007), Ebel et al. (1983a), Richter (1983), Herrmann (1984), Allemann (1985), Moser (2008), Aichholzer (2010), and Bischof (2010). Scaling is in Meters (Higher resolution figure is available as Electronic supplementary material)

of incompetent and competent units are essential for the development of a detachment along a certain stratigraphic level, for the geometry of the thrust plane itself, and for the internal deformation of the individual horses and nappes (Ramsay and Huber 1987). Following Woodward and Rutherford (1989), a detachment with associated disharmonic folding has to be expected, if the thickness ratio of incompetent and competent units is high. Pfiffner (1993) determined that the transition from imbricate thrusting and harmonic folding to detachment and disharmonic folding occurs at a ratio of 0.5. Polyharmonic folding is given around a value of 0.5.

The Helvetic basal thrust ramps through the stratigraphic sequence towards the north. A detachment (or hanging wall flat) in the Early to Middle Jurassic Mols Member (Bommerstein Formation) is widespread throughout Switzerland. As notable exception the Permian Glarus Verrucano Group forms the base of the Helvetic nappes in eastern Switzerland (e.g. Pfiffner 2010a, 2011). In Vorarlberg and Upper Allgäu, the Bommerstein Formation forms the oldest stratigraphic unit that was drilled above the Helvetic basal thrust. Thick incompetent marls of the Palfris Formation form an additional excellent detachment horizon in the Helvetic nappes, leading to a disharmonic deformation of the Cretaceous and the Jurassic strata. This is, e.g., the case between the Linth and Rhine valleys, where the Cretaceous formations of the Middlehelvetic to Southhelvetic realm were detached along the Säntis thrust. By contrast, in Vorarlberg, north and south of the Kanisfluh anticlinorium, the Jurassic and the Cretaceous strata are polyharmonically folded (e.g. Heim et al. 1933; Felber and Wyssling 1979), which is in agreement with the observed thickness ratios of 0.5 or slightly above (see Table 1). Field observations in Vorarlberg speak against the need for a regional detachment between the Cretaceous and the Jurassic formations, such as is the case for the Säntis thrust in eastern Switzerland. Hence, the eastern branch of the Säntis and the Glarus thrusts (=Helvetic basal thrust in eastern Switzerland) merges towards Vorarlberg. Still further to the east, the Cretaceous strata become increasingly detached from the Jurassic formations again. Since the different detachment levels are only determined from well data of Müller (1985; wells Kierwang 1 and Maderhalm 1) and Huber and Schwerd (1995; well Hindelang 1), their lateral extent is hard to assess. Moreover, individual thrusts cannot be traced across the Iller Valley, with the result that different authors suggest different nappe correlations.

5 Revised view of the Helvetic nappes of Vorarlberg and Upper Allgäu

As stated above, there are several arguments for two distinct Helvetic nappes—the Vorarlberg Säntis nappe and the Hohenems nappe—east of the Rhine Valley. The Hohenems nappe was introduced for the first time by Wyssling (1985), based upon facies analyses. According to this author, the Early Cretaceous units exposed at Hohenems and drilled by wells Kierwang 1 and Maderhalm 1 (Müller 1985) reveal a more proximal facies realm compared to those elsewhere in Vorarlberg. The same applies to the area between Dornbirn and the Bregenzer Ach, where the Late Cretaceous Bregenzerach Formation crops out, a unit which is attributed to the Northhelvetic realm (Fig. 8). In comparison to the Amden Marl, the contemporaneously deposited Bregenzerach Formation reveals a higher amount of sand, indicating a more proximal facies. However, Fessler et al. (1992) point out that an indisputable paleogeographic or a tectonic attribution is impossible since Coniacian to Campanian sandy marls from the Ultrahelvetic zone are almost identical.

Although facies plays a crucial role in later deformation of the Helvetic nappe system (e.g. Pfiffner 1993), facies boundaries do not automatically have to be nappe boundaries. In the southern part of the Bregenzerwald, for example, the exposed transition between the Middlehelvetic and the Southhelvetic facies realms occurs within the Vorarlberg Säntis nappe. Notwithstanding, facies variations within a defined facies zone due to synsedimentary tectonics have to be considered (e.g. Föllmi 1981). Concerning the described Early Cretaceous facies differentiations and the independently-known involved distances, there is no such information from the Helvetic zone of the Eastern Alps. Apart from nappe-scale thrust faults, a combination of recumbent folds, transfer faults,

Table 1 Thickness ratios of prominent incompetent/competent units determined at different locations from south to north

	South					North
	Southhelvetic facies	Grünten nappe	Hirschberg	Gottesacker Plateau	Water Gallery Bezegg	Well Kierwang 1
Drusberg Mb/Cretaceous strata		0.5		0.47		
Palfris Fm/Cretaceous strata	0.5		0.36		0.2	0.3
Palfris Fm/Quinten Ls.	0.7		0.6			
Bommerstein Fm/Quinten Ls.	1.0					

The majority of the values obtained are around 0.5 and they generally decrease towards the north due to the predominance of carbonates in the north of the Helvetic shelf. Solely the ratio of the Bommerstein Formation to the Quinten Limestone in the Kanisfluh area yields a number considerably higher than 0.5 that is indicative of disharmonic folding. Data for calculating thickness ratios were taken from Heim (1919), Heim et al. (1933), Felber and Wyssling (1979), Müller (1985), Wyssling (1986), Colins et al. (1989), and Goldscheider (2002). For locations see Figs. 5 and 8

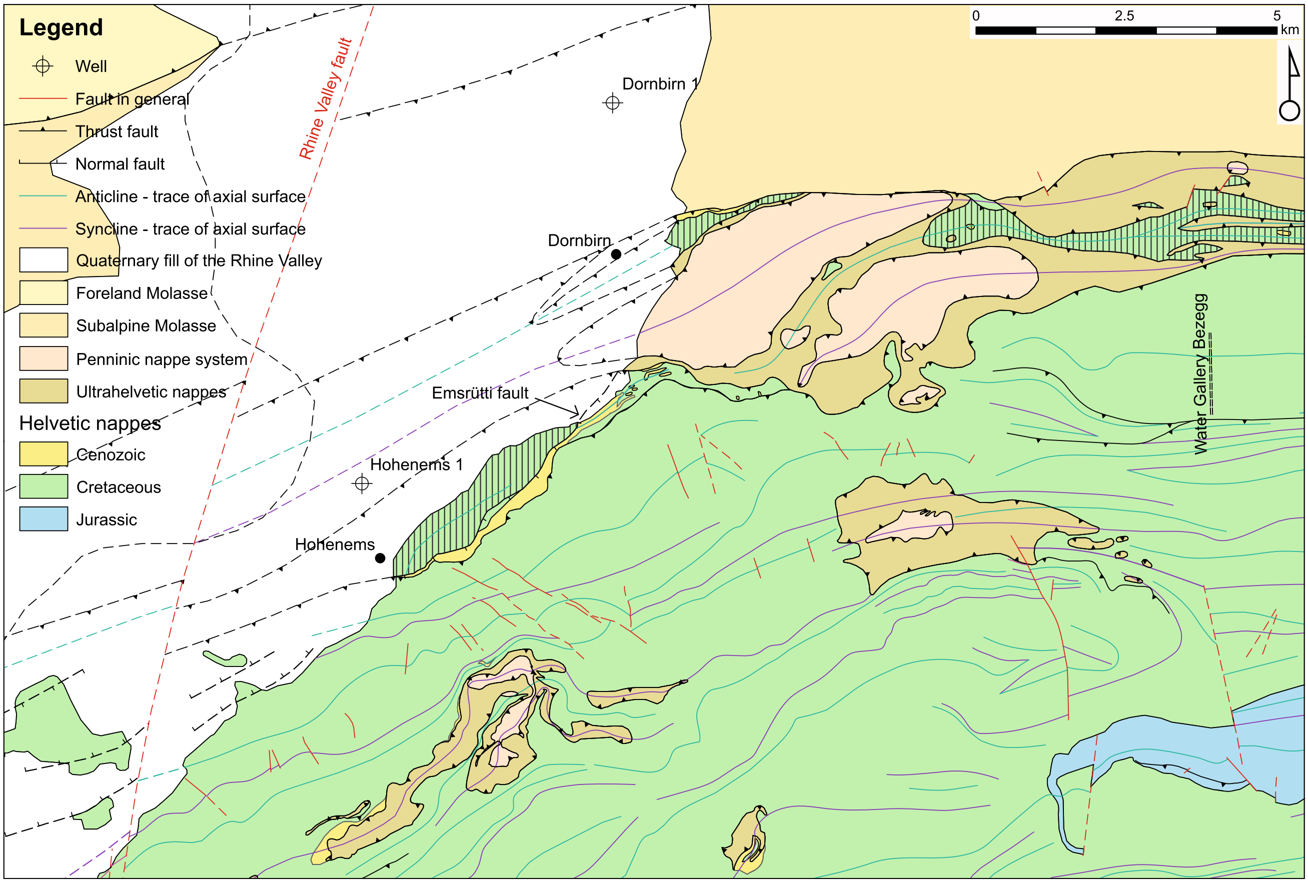

Fig. 8 Detailed tectonic map of the region around Hohenems and Dornbirn, on the eastern side of the Rhine Valley (for location, see Fig. 5). Hatches indicate those areas where the Bregenzerach Formation is exposed, as well as the reference locality of the Hohenems nappe sensu Wyssling (1985, 1986) northwest of the Emsrütti normal fault. Map compiled from Oberhauser (1982, 1994, 2007), Ebel et al. (1983a), Zacher (1990), Moser (2008), and Pfiffner et al. (2010)

and minor thrusts can also bring apparently distant facies realms next to each other. Being aware of this, Oberhauser (1991) interprets the Early Cretaceous units exposed at Hohenems as forming the inverted limb of a recumbent anticline, further known as “Hohenems fold”. This fold is part of the Vorarlberg Säntis nappe and is crosscut by the Emsrütti fault, a SE dipping normal fault with a possible sinistral strike-slip component, following Oberhauser (1991; Fig. 8).

Our revised model for the Helvetic nappes of Vorarlberg largely follows Oberhauser (1991). This implies that the Hohenems nappe, in contrast to the findings of Wyssling (1985, 1986), is not exposed at surface but only drilled by wells Hindelang 1 (Huber and Schwerd 1995) and V–Au 1 (Colins et al. 1989). In well V–Au 1, Colins et al. (1989) ascribe just the lowermost Quinten Limestone to the Hohenems nappe. Due to missing arguments, in cross section 2 (Fig. 7b), the nappe boundary is drawn at the base of the nearly 3 km thick Middle Jurassic sequence. Detailed information on stratigraphy and structure of the Hohenems nappe is poor. Therefore, apart from the Quinten Limestone, the Hohenems nappe is undifferentiated (Fig. 7). Its thickness is taken to be similar to the Mürtschen nappe and the Gonzen-Walenstadt imbricates, as well as to the Infrahelvetic complex (Tolwinski 1910; Oberholzer 1933; Pfiffner 1979), although the projection of distinct thickness values over such distances is hypothetical to some degree (Fig. 9).

To the west of the Iller Valley, Wyssling (1985) argues for two or rather three Helvetic nappes—from top to base, the Vorarlberg Säntis nappe, the Grünten nappe, and the Hohenems nappe—with the central one exclusively represented by Cretaceous and Cenozoic units stripped-off from the Hohenems nappe (Fig. 10a). Interestingly, Wyssling (1985) described the lithological character of the deepest drilled Cretaceous strata as similar to that exposed at Hohenems, i.e. the place where the same author defined the Hohenems nappe. Furthermore, he parallelizes the central Cretaceous units with the Southhelvetic Grünten nappe, first mentioned by Richter (1922) east of the Iller Valley. According to Huber and Schwerd (1995), the Helvetic nappe stack east of the Iller River consists of four nappes:

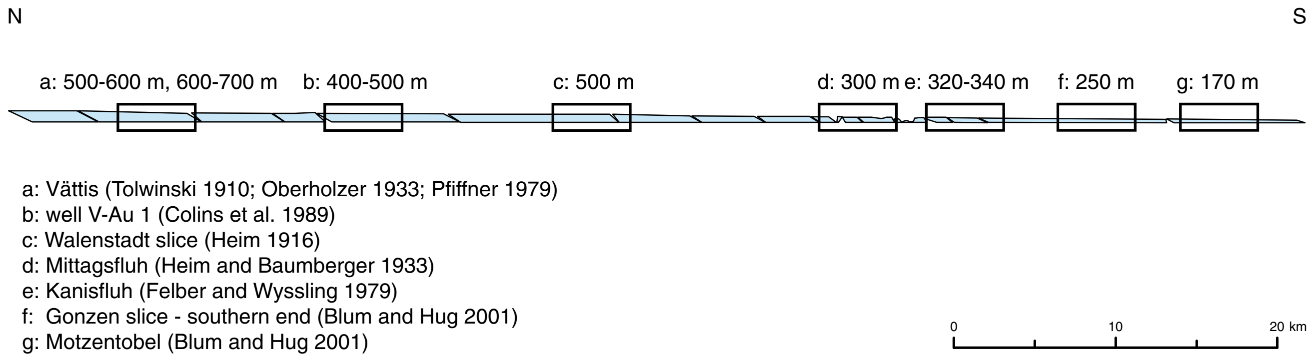

Fig. 9 Restored section of Quinten Limestone along cross section 2. *Small boxes* indicate locations with known thickness used for construction of the Hohenems nappe and the Vorarlberg Säntis nappe

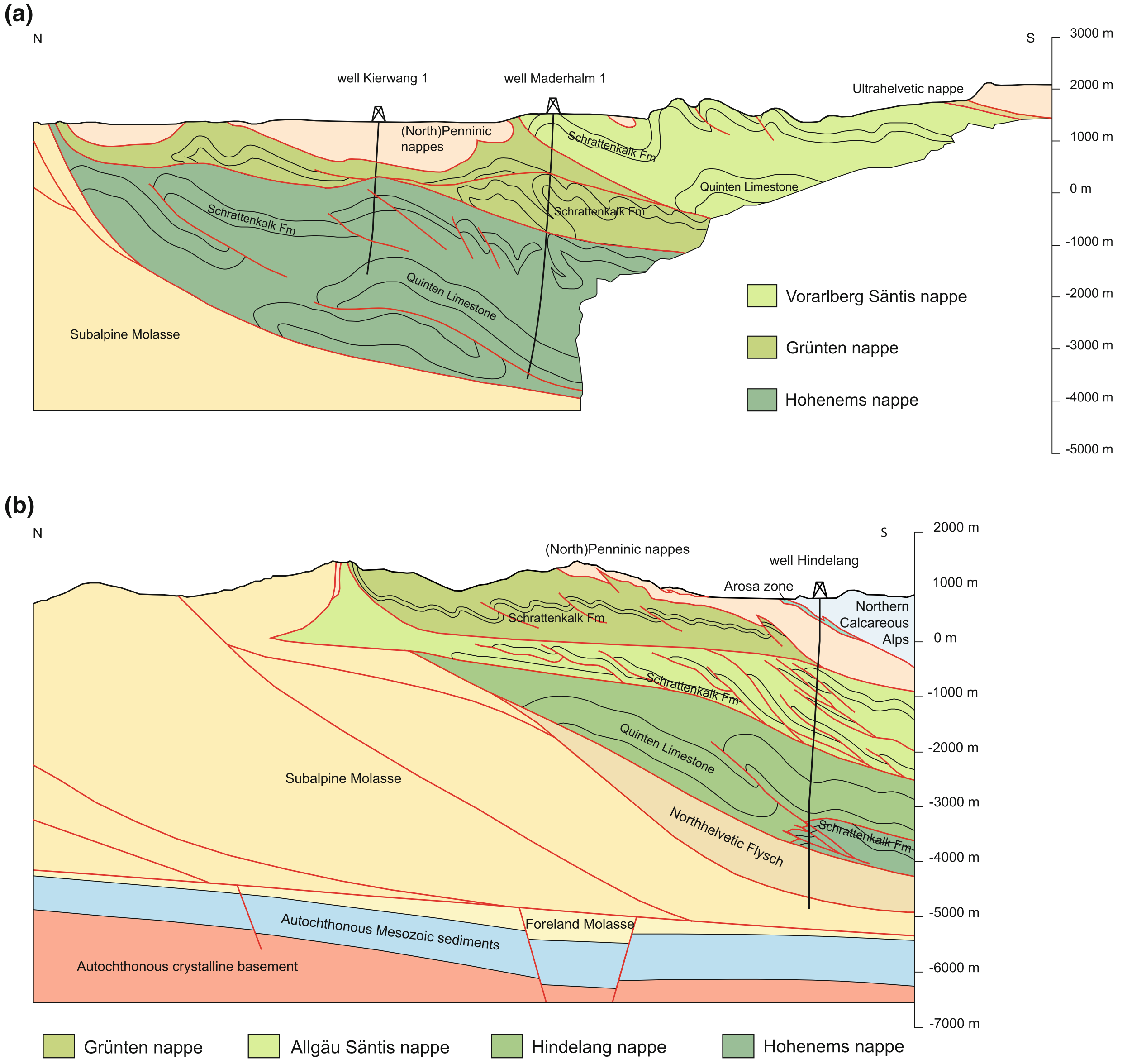

Fig. 10 Contrasting nappe tectonic models presented by various authors. **a** Section modified from Wyssling (1985) running west of the Iller Valley. Cross section 3 in Fig. 7c gives a revised tectonic interpretation of Wyssling's profile. **b** Section modified from Freitag (2003), essentially based on Schwerd et al. (1995), running east of the Iller Valley. For the trace of sections *a* and *b*, see Fig. 3

the Grünten nappe, the Allgäu Säntis nappe, the Hindelang nappe, and the Hohenems nappe (Fig. 10b). The Hindelang nappe, which represents the Jurassic substratum of the Allgäu Säntis nappe, was mainly introduced because of a tectonic contact between the shales of the Palfris Formation and the Quinten Limestone (Huber and Schwerd 1995). There are two points on which Wyssling's interpretation of the Helvetic nappe stack is doubtful. First, the South-helvetic Grünten nappe east of the Iller Valley forms the hanging wall of the Allgäu Säntis nappe, which is derived from the central part of the Helvetic facies realm. Second, the stratigraphic sequence of the lowermost slice observed in well Maderhalm 1 (Müller 1985) shows similarities to the Hindelang nappe, i.e. the uppermost part of the Quinten Limestone is dolomitized, and the Zementstein Formation is lacking in each case (Schwerd et al. 1995). Therefore, well Maderhalm 1 and well Kierwang 1 are interpreted to have exclusively encountered the Vorarlberg Säntis nappe, which is in accordance with the view of Schwerd et al. (1995).

6 Tectonic model: correlation of the Helvetic nappes east and west of the Rhine Valley

Our tectonic model is essentially based on the following findings and data: (1) the exposed Cretaceous Helvetic units can be basically correlated across the Rhine Valley. (2) The deformation style of the Helvetic nappes on both sides of the Rhine Valley differs, a phenomenon which is also true across the Iller Valley. (3) Apart from the nearly 3 km thick pile of Middle Jurassic sediments encountered by well V–Au 1 (Colins et al. 1989), several known and assumed NNE-SSW striking map-scale faults have to be additionally incorporated (e.g. Felber and Wyssling 1979; Liedholz 1983; Oberhauser 1993).

From the structural map (Fig. 5) it becomes obvious that the fold axes between the Säntis area in the west and the Kleinwalser and Iller valleys in the east form an arcuate belt, as already recognized by Pfiffner (1993). From the Säntis area in easternmost Switzerland up to somewhere between the Hoher Freschen and Kehlegg, NE–SW trending folds are prevailing, while further east they are E–W trending. East of the line extending from the Diedamskopf to Sibratsgfäll, the folds splay fanlike. While a NW–SE orientation is obvious at the southeastern border of the Vorarlberg Säntis nappe, the folds of the Ultrahelvetic and Penninic nappes, which can be essentially regarded as harmonically folded together with the Vorarlberg Säntis nappe, trend NE–SW north of the Riedbergerhorn. This latter is in accordance with the orientation of the fold axes from east of the Iller Valley.

Comparable fold arcs have recently been described by Pfiffner (1993, 2011) from the Western and the Central Alps, e.g. from the Chaînes subalpines in Haute Savoie, east of the Kander Valley, as well as from between the Linth and Rhine valleys. The cores of all of these fold arcs are made of remarkably thick sequences of Early and Middle Jurassic shales or Permian clastics (Verrucano Group). They are interpreted to present the infill of former basins that have been scraped out during the Cenozoic nappe formation, a process referred to as "basin inversion" (Gillcrist et al. 1987; Pfiffner 1993). The Vorarlberg fold arc exhibits a similar core which was encountered by well V–Au 1, cutting through an almost 3 km thick sequence of stacked Middle Jurassic sediments (Bommerstein Formation), which can, by analogy, be regarded as the inverted fill of a Middle Jurassic basin, as first supposed by Pfiffner (1993). The Bommerstein Formation, a succession of black shales, silt-, and sandstones, probably forms the basal detachment horizon of the Vorarlberg Säntis nappe far to the south, equivalent to the situation in central Switzerland, where the Helvetic basal thrust (the Axen thrust) runs along the former basin sediments—Triassic evaporites, Early and Middle Jurassic shales—until it climbs up-section in the north.

From Fig. 5 as well as from cross section 4 (Fig. 11), it can be seen that the fold axes of the Vorarlberg arc plunge to the SE at the eastern end and to the SW at the western end. If the basal thrust of the Vorarlberg Säntis nappe is taken to run at an about constant depth, the measured plunge of the exposed Penninic, Ultrahelvetic, and Helvetic units yields a decrease in thickness of the stacked Middle Jurassic strata to both sides. The fact that the plunge decreases from up to 20° towards the Kleinwalser Valley to only 4° towards the Rhine Valley suggests a wedge-shaped geometry in cross section 4 (Fig. 11) to be filled with Middle Jurassic sediments. This can be taken as an indication for the geometry of the former Middle Jurassic basin (Fig. 12), which had to get deeper towards the east according to the greater thickness of the preserved infill at the eastern end of the fold arc. Following the data of Dollfuss (1965), the basin fill can be traced towards Lake Walen, but the basin itself was presumably subdivided by a N–S trending high. To the south, this Middle Jurassic basin had to be bordered by an E–W trending high from the neighboring slope. This is suggested by the decreasing thickness of the Jurassic part of the Helvetic nappe pile towards the south, probably caused by a thinner basin sequence. Alternatively, heterogeneous shortening of the Jurassic strata could explain the observed along-strike axial plunge. However, this alternative possibility seems unlikely, considering the symmetry of the fold arc in map view and because of the lack of a fault cutting across the Vorarlberg Säntis nappe, comparable to the Ostergunten fault system, which could account for bending of the fold axes between Hoher Freschen and Kehlegg.

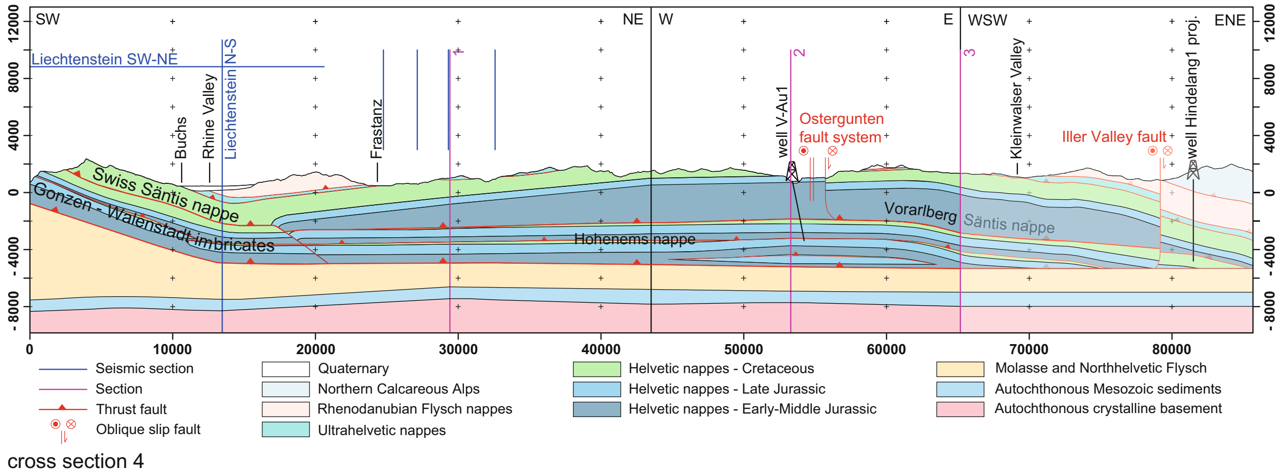

Fig. 11 Cross section 4 running parallel to the traces of the fold axes from eastern Switzerland to the east of the Kleinwalser and Iller valleys (for the trace of the cross section, see Fig. 3). The structure west of the Rhine Valley is based on seismic data taken from Naef (2010). Note that small occurrences of Triassic rocks along the base of the Gonzen-Walenstadt imbricates at the very western end of the cross section cannot be ruled out. The easternmost part of the cross section is *lighter colored* as far as it was largely constructed using surface outcrops and measurements together with data from well Hindelang 1 (Huber and Schwerd 1995). The latter was projected to the SSW without any correction for depth. Scattered W dipping datasets were discounted in order to keep the image simple. Generally, thrust faults within Early to Middle Jurassic units and the Northalpine Foreland Basin sediments are not imaged. The Helvetic basal thrust and the Säntis thrust are highlighted. Scaling is in Meters

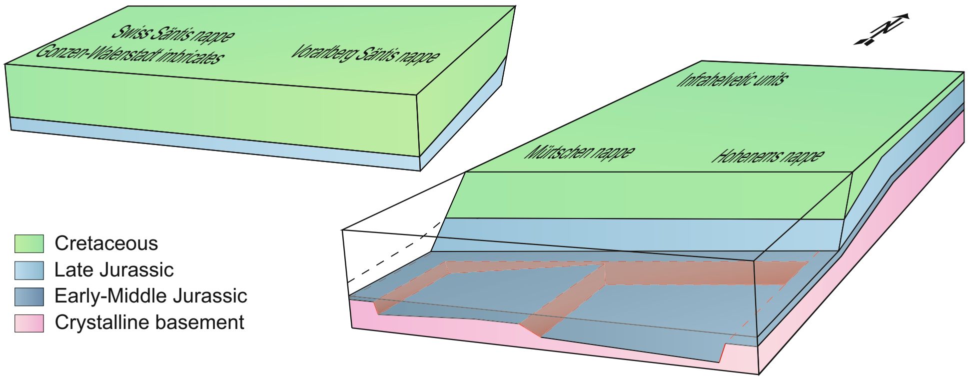

Fig. 12 Simplified block model of the geometry of the Middle Jurassic basin. The block in the upper left (Swiss/Vorarlberg Säntis nappe and Gonzen-Walenstadt imbricates) is shown as removed from the block on the right in order to display the latter's internal structure. The Middle Jurassic basin is located to the south and southeast and interpreted to be bounded by synsedimentary normal faults. The basin fill is thought to form the core of the fold arc of Vorarlberg. Vertical exaggeration: 20×

The abovementioned fan structure east of the line Diedamskopf—Sibratsgfäll may indicate the northeasternmost extension of the inverted Middle Jurassic basin. Accordingly, the absence of a thick sequence of stacked Bommerstein Formation further to the north could reduce the overall thickness of the Vorarlberg Säntis nappe distinctly and therefore account for the notable Ultrahelvetic and Penninic units drilled by well Kierwang 1 (Müller 1985). Apart from that, taking into account the stratigraphically and tectonic insights gained from well Hindelang 1 (Huber and Schwerd 1995), it cannot be excluded that the eastward plunge of the Vorarlberg Säntis nappe is caused by an eastward decrease in thickness of the Hohenems nappe.

According to Pfiffner (1981), the Helvetic nappes of eastern Switzerland were transported roughly in a S–N direction. The obliquity between the nappe transport direction and the NE–SW trend of fold axes arises from the orientation of ramps, which in turn follow facies boundaries, from transfer faults, and from rotation during nappe transport. Although the tip of the Vorarlberg and Allgäu Säntis nappes is buried below the southernmost slice of the Subalpine Molasse, it can be supposed that—equivalent to the Swiss Säntis nappe—their leading edge strikes NE–

SW. Thereby it would parallel the NE–SW trending folds and thrusts of hanging wall units north of the fold arc comprising Ultrahelvetic, Penninic, and Subalpine Molasse thrust sheets as well as the strike of the passive roof thrust above the Helvetic triangle zone. Due to the lack of exposed nappe boundaries east of the Rhine River, no further constraints on the direction of tectonic transport are available. However, the majority of the observed brittle tectonic features (e.g. primary and secondary shear planes, joints, veins, stylolites, parasitic fold axes, and (axial plane) cleavage) are compatible with NNW–SSE to N–S oriented maximum principal compressive stress axes. Provided that they indicate the nappe transport direction, the latter is at an angle to the presumed strike of the leading edge of the Helvetic nappes, comparable to eastern Switzerland. Facies conditions, as demonstrated above, are known to play a crucial role in deformation. However, it is impossible to judge which of the remaining factors (e.g. ramp geometry, transfer faults, thrusting accompanied by rotation) accounts for this obliquity in Vorarlberg and Upper Allgäu.

Apart from thrust faults running approximately parallel to the strike of the Helvetic zone, numerous NNE–SSW to NE–SW striking sinistral transfer faults, downthrowing the southeastern block, are known (Wagner 1950; Felber and Wyssling 1979; Liedholz 1983; Oberhauser 1993) or at least suspected along the Iller (Ebel 1979; Pfiffner 2011) and Rhine valleys (Trümpy 1992; Oberhauser 1993). Folds and thrust faults terminate at an obtuse angle at these faults, which separate independently shortened areas. A bundle of several parallel faults striking NNE–SSW, termed "Ostergunten fault system", delimiting the Kanisfluh anticlinorium towards the east, represents the most prominent transfer fault zone of the Helvetic zone of Vorarlberg. From cross section 4 (Fig. 11) it can be concluded that the eastern block was downthrown for approximately 600 m. Lateral offset is in the order of 3 km as deduced from the exposed Ultrahelvetic units on either side of the Ostergunten fault system. Similar transfer faults are suspected along the Iller and Rhine valleys and are connected with the eastern and western ends of the inverted Middle Jurassic basin infill. As discussed earlier, the occurrence of incompetent units and the thickness ratio of incompetent to competent units have a decisive influence on the deformation style. Therefore, the described differences concerning the stratigraphic thickness and the associated deformation style of the Helvetic nappes between eastern Switzerland and Upper Allgäu are probably due to the highly variable thickness of the Bommerstein Formation. Towards the Rhine Valley, a dramatic decrease in thickness of the Bommerstein Formation is obvious (compare data in Colins de Tarsienne et al. 1988 with Blum and Hug 2001). Because of thick Palfris shales west of the Rhine Valley, the Säntis thrust climbs along a lateral ramp from the Jurassic level east of the Rhine Valley to the Cretaceous level in the west (Fig. 11). This lateral ramp acted as a transfer fault and represents the reactivated normal fault at the western side of the Middle Jurassic basin of Vorarlberg. It is quite possible that similar faults emerge from this subsurface structure and cut through the Cretaceous strata to finally reach the surface. The Emsrütti fault at Hohenems (Oberhauser 1991) could be one of them. However, the Cretaceous units cropping out west and east of the Rhine Valley are not completely separated across the valley, as are the Jurassic ones. Our subsurface lateral ramp is located deeper down and separates the Hohenems nappe from the Gonzen-Walenstadt imbricates (Fig. 13).

In contrast to the situation in the Rhine Valley, the Jurassic and the Cretaceous stockwerks seem to be partly separated in cross-sectional view across the Iller Valley. A transfer fault can be suspected from digital elevation models and aerial photographs and traced along the Iller Valley. From the tectonic map as well as by comparing Fig. 10a + b and cross section 3 (Fig. 7c), it can be seen that the thickness of the Helvetic zone decreases substantially across the Iller Valley. Accordingly, the front of the Austroalpine and Penninic units in the hanging wall of the Helvetic nappes is significantly offset across the Iller Valley and located much further north on its eastern side. The missing Middle Jurassic basin infill is mainly thought to account for this observation. Additionally, seismic data indicate that the Hohenems nappe does not continue east of the Iller Valley. The Iller Valley fault is therefore assumed to delimit the eastern edge of the Middle Jurassic basin infill and to present the master fault segmenting the eastern lateral culmination wall (in the sense of McClay 1982) of the Hohenems nappe (Fig. 14). Penninic and Austroalpine folds and thrusts in the hanging wall changing from an ENE–WSW towards a NE–SW orientation (see Scholz and Zacher 1983) probably image the latter. Similar to the situation at the western end of the basin infill, the transfer fault in the Iller Valley is thought to cut the entire Helvetic nappe stack.

7 Conclusions

Deformational structures of the Helvetic units of Vorarlberg and Upper Allgäu are largely controlled by the geometry of a former basin with its highly variable facies conditions. In general, the southeastern European shelf deepened towards the Ultrahelvetic slope. Permo-Carboniferous and Jurassic horsts and grabens caused along-strike internal segmentation. During the Cenozoic nappe formation the thick basin infill became scoured out and former synsedimentary normal faults were reactivated as lateral

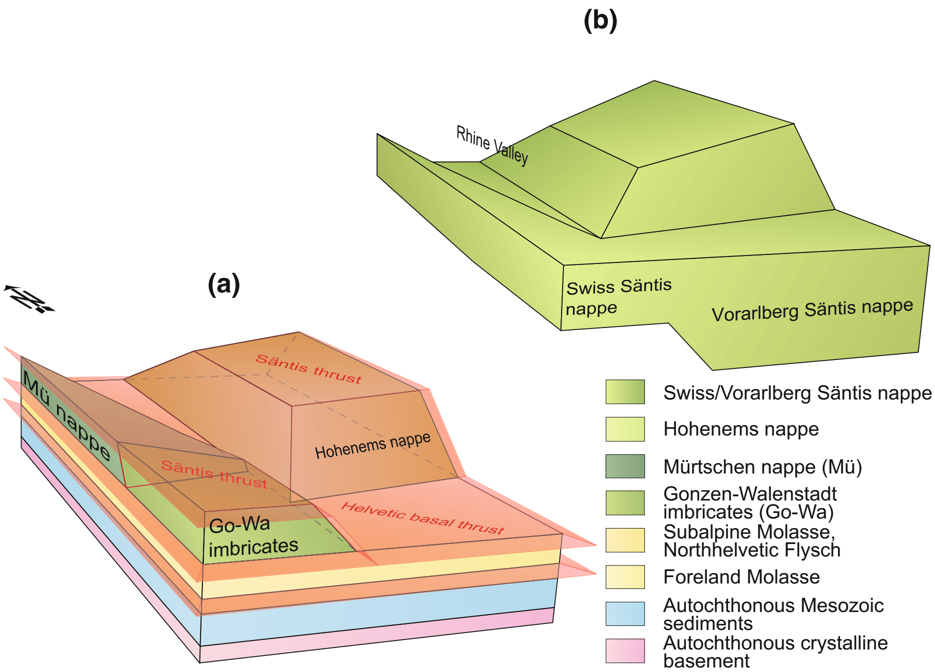

Fig. 13 Schematic 3D view (2 × vertical exaggeration) to illustrate the geometry of the Helvetic nappe system along the Rhine Valley. **a** Lower Helvetic nappe complex, Subalpine Molasse, and Autochthonous. The upper limit of this block corresponds to the base of the Swiss/Vorarlberg Säntis nappe. **b** Upper nappe complex consisting of Cretaceous and Jurassic strata (the latter restricted to the Vorarlberg Säntis nappe). Block **b** fits on top of **a**. Note that the upper limit of block **b** does not represent the current ground level

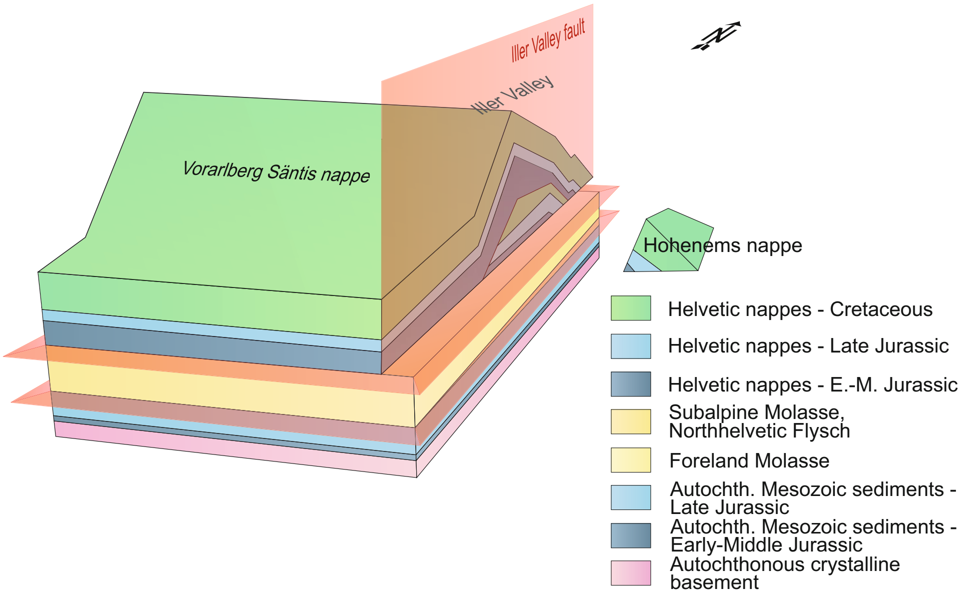

Fig. 14 Schematic 3D view (2 × vertical exaggeration) to illustrate the subsurface geometry of the Helvetic nappe system along the Iller Valley

ramps. Nowadays these sediments form the core of the various Helvetic fold arcs observed in the Western, Central, and Eastern Alps. The Iller Valley and the Rhine Valley mark the eastern and western ends, respectively, of the inverted Middle Jurassic basin present in Vorarlberg. The basin geometry influenced the internal structure of the Helvetic nappes and explains the remarkable changes that occur along strike. Moreover, the presence and absence of detachment levels controlled the number of Helvetic nappes stacked at different locations. The Iller Valley and Rhine Valley transfer faults are deep-seated structures, responsible for the disappearance of the lower nappe (Hohenems nappe). In the case of the Rhine Valley transfer fault, the uppermost unit (Cretaceous strata of the Swiss/Vorarlberg Säntis nappe) is hardly affected by the fault, whereas major changes are present across the Iller Valley transfer fault.

Acknowledgments This research was done in the framework of the COMET program of the alpS Centre for Climate Change Adaptation. Thanks to the Austrian Research Promotion Agency (FFG) and the Illwerke-Alternativenergie GmbH for funding this project, as well as to the rest of the working group (Lothar Mähr and Peter Niederbacher). Careful and critical corrections of the manuscript by two anonymous reviewers are highly appreciated and thanked.

References

Allemann, F. (1985). *Geologische Karte des Fürstentums Liechtenstein 1: 25 000*. Liechtenstein: Regierung des Fürstentums Liechtenstein.

Allemann, F. (2002). *Erläuterungen zur Geologischen Karte des Fürstentums Liechtenstein 1:25 000* (p. 129). Bern: Regierung des Fürstentums Liechtenstein.

Allen, P. A., Crampton, S. L., & Sinclair, H. D. (1991). The inception and early evolution of the North Alpine foreland basin. *Basin Research, 3*, 143–163.

Ampferer, O., & Reithofer, O. (1932). *Geologische Karte der Lechtaler Alpen: Klostertaler Alpen 1:25 000*. Wien: Geologische Bundesanstalt.

Bettenstaedt, F. (1985). Zur stratigraphischen und tektonischen Gliederung von Helvetikum und Flysch in den Bayerischen und Vorarlberger Alpen aufgrund mikropaläontologischer Untersuchungen. *Zeitschrift der Deutschen Geologischen Gesellschaft, 109*, 566–592.

Blumer, E. (1922). Notiz über die nördlichsten Kreideketten der Alpen zu beiden Seiten des Rheins; Nachtrag zur geol. Monogr. des Säntisostende. *Eclogae Geologicae Helvetiae, 17*, 166–168.

Bollinger, D. (1988). Die Entwicklung des distalen osthelvetischen Schelfs im Barremian und Früh-Aptian. Drusberg-, Mittagsspitz- und Schrattenkalk-Fm. im Vorarlberg und Allgäu. Ph.D. dissertation, Univ. Zürich, Schweiz, 136 pp.

Briegel, U. (1972). Geologie der östlichen Alvierkette (Helvetische Decken der Ostschweiz) unter besonderer Berücksichtigung der Drusberg- und Schrattenkalkformation. *Eclogae Geologicae Helvetiae, 65*, 425–483.

Colins de Tarsienne, E., Niederbacher, P., & Winkler, G. (1988). Geologisch-geophysikalische Grundlagen der Kohlenwasserstoff-Exploration in Vorarlberg. In G. B. Fettweis, F. Weber, & A. Weiß (Eds.), *Bergbau im Wandel : Tagungsbericht und Vorträge zum Thema: Der Bergbau im Strukturwandel der Anforderungen von Wirtschaft, Umwelt und Technik - Tendenzen von Forschung, Entwicklung und Betrieb* (pp. 681–687). Graz: Akademische Druck- und Verlagsanstalt.

Colins, E., Niederbacher, P., & Sauer, R. (1989). Kohlenwasserstoffexploration in Vorarlberg - Ergebnisse der Bohrung Vorarlberg-Au 1. *Mitteilungen der Österreichischen Geologischen Gesellschaft, 82*, 91–104.

Crampton, S. L., & Allen, P. A. (1995). Recognition of forebulge unconformities associated with early stage foreland basin development: Example from the North alpine foreland basin. *American Association of Petroleum Geologists Bulletin, 79*, 1495–1514.

Doert, U., & Helmcke, D. (1976). Geologie des Flexenpasses (Vorarlberg, Österreich). *Geologica et Paleontologica, 10*, 181–200.

Dohr, G. (1983). Reflexionsseismik und Gravimetrie im Rahmen der Erdölexploration. In Bayerisches Geologisches Landesamt (Ed.), *Geologische Karte von Bayern 1:25 000 - Erläuterungen zum Blatt Nr. 8427 Immenstadt i. Allgäu* (pp. 201–207). München: Bayerisches Geologisches Landesamt.

Dollfuss, S. (1965). Über den Helvetischen Dogger zwischen Lindth und Rhein. *Eclogae Geologicae Helvetiae, 58*, 453–554.

Ebel, R. (1979). Geologie der Alpenrandzone bei Immenstadt im Allgäu beiderseits des Illertales, unter Berücksichtigung der Faltenmolasse. Ph.D. dissertation, Univ. Deutschland, München, 131 pp.

Ebel, R., Häussler, H., Jerz, H., Schwerd, K., & Zacher, W. (1983a). *Geologische Karte von Bayern 1:25 000 - Blatt Nr. 8427 Immenstadt i. Allgäu.*. München: Bayerisches Geologisches Landesamt.

Ebel, R., Schwerd, K., & Zacher, W. (1983b). *Geologische Karte von Bayern 1:25 000 - Profiltafel zum Blatt Nr. 8427 Immenstadt i. Allgäu*. München: Bayerisches Geologisches Landesamt.

Egger, H., Krenmayr, H. G., Mandl, G. W., Matura, A., Nowotny, A., Pascher, G., Pestal, G., Pistotnik, J., Rockenschaub, M., & Schnabel, W. (1999a). *Geologische Übersichtskarte der Republik Österreich 1: 1 500 000 (ohne Quartär)*. Wien: Geologische Bundesanstalt.

Egger, H., Krenmayr, H. G., Mandl, G. W., Matura, A., Nowotny, A., Pascher, G., Pestal, G., Pistotnik, J., Rockenschaub, M., & Schnabel, W. (1999b). *Geologische Übersichtskarte der Republik Österreich 1: 2 000 000*. Wien: Geologische Bundesanstalt.

Felber, P., & Wyssling, G. (1979). Zur Stratigraphie und Tektonik des Südhelvetikums im Bregenzerwald (Vorarlberg). *Eclogae Geologicae Helvetiae, 72*, 673–714.

Fessler, U., Kiessling, T., Rische, H., & Zacher, W. (1992). Die vorquartäre Geologie des Andelsbucher Becken (Vorarlberg). *Jahrbuch der Geologischen Bundesanstalt, 135*, 825–843.

Föllmi, K. B. (1981). Sedimentäre Hinweise auf oberkretazische Tektonik im Vorarlberger Helvetikum. *Eclogae Geologicae Helvetiae, 74*, 175–187.

Föllmi, K. B. (1986). Die Garschella- und Seewer Kalk-Formation (Aptian-Santonian) im Vorarlberger Helvetikum und Ultrahelvetikum. Ph.D. dissertation, Eidg. Techn. Hochsch. Zürich, Schweiz, 391 pp.

Föllmi, K. B., Bodin, S., Goded, A., Linder, P., & Van de Schootbrugge, B. (2007). Unlocking paleo-environmental information from Early Cretaceous shelf sediments in the Helvetic Alps: stratigraphy is the key! *Swiss Journal of Geosciences, 100*, 349–369.

Föllmi, K. B., & Ouwehand, P. J. (1987). Garschella-Formation und Götzis-Schichten (Aptian-Coniacian): Neue stratigraphische Daten aus dem Helvetikum der Ostschweiz und des Vorarlbergs. *Eclogae Geologicae Helvetiae, 80*, 141–191.

Frey, M. (1988). Discontinuous inverse metamorphic zonation, Glarus Alps, Switzerland: Evidence from illite "crystallinity" data. *Schweizerische Mineralogische und Petrographische Mitteilungen, 68*, 171–183.

Friebe, G. J. (2007a). Helvetische Decken. In G. J. Friebe (Ed.), *Geologie der Österreichischen Bundesländer—Vorarlberg* (pp. 71–85). Wien: Geologische Bundesanstalt.

Friebe, G. J. (2007b). Ultrahelvetische Decken. In G. J. Friebe (Ed.), *Geologie der Österreichischen Bundesländer—Vorarlberg* (pp. 69–71). Wien: Geologische Bundesanstalt.

Funk, H., Föllmi, K. B., & Mohr, H. (1993). Evolution of the Tithonian-Aptian Carbonate Platform along the Northern Tethyan margin, Eastern Helvetic Alps. *American Association of Petroleum Geologists Bulletin, 56*, 387–407.

Funk, H., Habicht, K. J., Hantke, R., & Pfiffner, A. O. (2000). *Blatt 1115 Säntis. - Geologischer Atlas der Schweiz 1:25 000, Erläuterungen 78* (p. 61). Bern: Bundesamt für Wasser und Geologie.

Ganss, O., & Schmidt-Thomé, P. (1955). Die gefaltete Molasse zwischen Bodensee und Salzach. *Zeitschrift der Deutschen Geologischen Gesellschaft., 105*, 402–495.

Gillcrist, R., Coward, M., & Mugnier, J.-L. (1987). Structural inversion and its controls: examples from the Alpine foreland and the French Alps. *Geodinamica Acta, 1*, 5–34.

Goldscheider, N. (2002). Hydrogeology and vulnerability of karst systems—examples from the Northern Alps and the Swabian Alb. Ph.D. dissertation, Universität Karlsruhe, Deutschland, 259 pp.

Groshong, R. H. J., Pfiffner, A. O., & Pringle, L. R. (1984). Strain partitioning in the Helvetic thrust belt of eastern Switzerland from the leading edge to the internal zone. *Journal of Structural Geology, 6*, 5–18.

Heim, A. (1916). Monographie der Churfirsten-Mattstock-Gruppe. 3.Teil. *Beiträge zur Geologischen Karte der Schweiz [Neue Folge], 20*, 369–573.

Heim, A. (1919). Zur Geologie des Grünten im Allgäu. *Vierteljahresschrift der Naturforschenden Gesellschaft in Zürich, 64*, 458–486.

Heim, A., Baumberger, E., & Fussenegger, S. (1933). Jura und Unterkreide in den helvetischen Alpen beiderseits des Rheins (Vorarlberg und Ostschweiz). *Denkschriften der schweizerischen Naturforschenden Gesellschaft, 68*, 156–220.

Herrmann, P. (1984). *Geologische Karte von Österreich 1: 25.000 - Blatt 83 Sulzberg*. Wien: Geologische Bundesanstalt.

Herrmann, P., Draxler, I., & Müller, M. (1985). *Erläuterungen zu Blatt 83 Sulzberg* (p. 20). Wien: Geologische Bundesanstalt.

Herrmann, P., & Schwerd, K. (1982). *Geologische Karte der Republik Österreich 1: 25.000 - Blatt 82 Bregenz*. Wien: Geologische Bundesanstalt.

Hitz, L., & Pfiffner, A. O. (1994). A 3D crustal model of the Eastern External Aar Massif interpreted from a network of deep seismic profiles. *Schweizerische Mineralogische und Petrographische Mitteilungen, 74*, 405–420.

Huber, K., & Schwerd, K. (1995). Das Geologische Profil der Tiefbohrung Hindelang 1 (Allgäuer Alpen). *Geologica Bavarica, 100*, 23–55.

Huf, W. (1963). Die Schichtenfolge der Aufschlussbohrung "Dornbirn 1" (Vorarlberg, Österreich). *Bulletin der Vereinigung Schweizerischer Petroleumgeologen und Petroleumingenieure, 29*, 9–10.

Jerz, H. (1974). *Geologische Karte von Bayern 1: 25 000 - Blatt Nr. 8427 Buchenberg*. München: Bayerisches Geologisches Landesamt.

Jordan, T. E., Damanti, J. F., & Drake, R. E. (1993). Chronology of motion in a complete thrust belt: The Precordillera, 30–31°S, Andes Mountains. *Journal of Geology (Centennial issue), 101*, 135–156.

Kempf, O., & Pfiffner, A. O. (2004). Early Tertiary evolution of the North Alpine Foreland Basin of the Swiss Alps and adjoining areas. *Basin Research, 16*, 549–567.

Lettau, O. (1995). Geophysikalische Untersuchungen im Bereich der Tiefbohrung Hindelang 1 (Allgäuer Alpen). *Geologica Bavarica, 100*, 131–151.

Liedholz, J. (1983). Helvetikum und Nördliche Flyschzone im Allgäu westlich der Iller, an der Breitach und im Balderschwanger Tal (Exkursion E am 7. April 1983). *Jahresberichte und Mitteilungen des Oberrheinischen Geologischen Vereins, Neue Folge, 65*, 61–83.

Linder, P., Gigandet, J., Hüsser, J.-L., Gainon, F., & Föllmi, K. B. (2006). The Early Aptian Grünten Member: Description of a new lithostratigraphic unit of the Helvetic Garschella Formation. *Eclogae Geologicae Helvetiae, 99*, 327–341.

Lupu, M. (1972). Mikrofazielle Untersuchungen eines Quintnerkalk-Profils der Mittagsfluh in Vorarlberg. *Verhandlungen der Geologischen Bundesanstalt, 1972*(2), 281–287.

McClay, K. R. (1982). Glossary of thrust tectonics terms. In K. R. McClay (Ed.), *Thrust tectonics* (pp. 419–433). London: Chapman and Hall.

Messmann, P. (1925). Geologische Untersuchungen der Kreideketten des Alpenrandes im Gebiet des Bodenseerheintales. *Verhandlungen der Naturforschenden Gesellschaft in Basel, 37*, 1–112.

Milnes, G. A., & Pfiffner, A. O. (1977). Structural development of the infrahelvetic complex, eastern Switzerland. *Eclogae Geologicae Helvetiae, 70*, 83–95.

Moser, M. (2008). *Zusammenstellung ausgewählter Archivunterlagen der GBA 1:50 000 - Blatt 112 Bezau: Stand 2008, Ausgabe: 2009/06*. Wien: Geologische Bundesanstalt.

Müller, M. (1983). Der Bau des tieferen Untergrunds (Tiefbohrung Immenstadt 1). In Bayerisches Geologisches Landesamt (Ed.), *Geologische Karte von Bayern 1 : 25 000 - Erläuterungen zum Blatt Nr. 8427 Immenstadt i. Allgäu* (pp. 191–200). München: Bayerisches Geologisches Landesamt.

Müller, M. (1985). Maderhalm 1 und Kierwang 1 - Zwei Tiefbohrungen in das Helvetikum des bayerischen Allgäus. *Jahrbuch der Geologischen Bundesanstalt, 127*, 639–641.

Oberhauser, R. (1951). Zur Geologie des Gebietes zwischen Canisfluh und Hohem Ifen (Bregenzerwald). Ph.D. dissertation, Leopold-Franzens Universität Innsbruck, Österreich, 45 pp.

Oberhauser, R. (1958). Neue Beiträge zur Geologie und Mikropaläontologie von Helvetikum und Flysch im Gebiet der Hohen Kugel (Vorarlberg). *Verhandlungen der Geologischen Bundesanstalt, 1958*, 121–140.

Oberhauser, R. (1963). Die Kreide im Ostalpenraum Österreichs in mikropaläontologischer Sicht. *Jahrbuch der Geologischen Bundesanstalt, 106*, 1–88.

Oberhauser, R. (1982). *Geologische Karte der Republik Österreich 1: 25.000 - Blatt 110 St. Gallen Süd und 111 Dornbirn Süd*. Wien: Geologische Bundesanstalt.

Oberhauser, R. (1991). *Geologische Karte der Republik Österreich 1: 25.000 - Erläuterungen zu Blatt 110 St. Gallen Süd und 111 Dornbirn Nord* (p. 72). Wien: Geologische Bundesanstalt.

Oberhauser, R. (1993). Molasse, Helvetikum, Flysch und Kalkalpen längs eines Schnittes vom Bodensee durch den Bregenzerwald zum Großwalsertal (Exkursion F am 16. April 1993). *Jahresberichte und Mitteilungen des Oberrheinischen Geologischen Vereins, Neue Folge, 75*, 137–153.

Oberhauser, R. (1994). *Geologische Karte der Republik Österreich 1: 25.000 - Blatt 110 St. Gallen Nord und 111 Dornbirn Nord mit Anteilen von 81 Bodensee und 82 Bregenz*. Wien: Geologische Bundesanstalt.

Oberhauser, R. (2007). *Geologische Karte von Vorarlberg 1: 100 000*. Wien: Geologische Bundesanstalt.

Oberholzer, J. (1933). Geologie der Glarner Alpen. *Beiträge zur Geologischen Karte der Schweiz [Neue Folge], 28*, 1–626.

Ortner, H., Fügenschuh, B., Zerlauth, M., & Von Hagke, C. (2011). Geometry, Sequence and Amount of Thrusting in the Subalpine Molasse of Austria and Bavaria. CorseAlp 2011, 10–16 April 2011, Saint-Florent (Corsica), Abstract Volume, 67.

Pfiffner, A. O. (1981). Fold-and-thrust tectonics in the Helvetic Nappes (E Switzerland). In K. R. McClay & N. J. Price (Eds.), *Thrust and Nappe tectonics, Geological Society, London, Special Publications 9* (pp. 319–327). Oxford: Blackwell Scientific Publications.

Pfiffner, A. O. (1986). Evolution of the north Alpine foreland basin in the Central Alps. In P. A. Allen & P. Homewood (Eds.), *Foreland basins, International Association of Sedimentologists, Special Publication 8* (pp. 219–228). Oxford, UK: Blackwell Scientific Publications.

Pfiffner, A. O. (1993). The structure of the Helvetic nappes and its relation to the mechanical stratigraphy. *Journal of Structural Geology, 15*, 511–521.

Pfiffner, A. O. (2010a). *Geologie der Alpen* (p. 359). Stuttgart: UTB Haupt Verlag.

Pfiffner, A. O. (2010b). The Helvetic nappe system and landscape evolution of the Kander valley. *Swiss Bulletin für angewandte Geologie, 15*, 53–61.

Pfiffner, A. O. (2011). *Structural map of the Helvetic Zone of the Swiss Alps, including Vorarlberg (Austria) and Haute Savoie (France), 1: 100 000. Geological Special Map 128* (p. 128). Explanatory notes. Wabem: Federal Office of Topography swisstopo.

Pfiffner, A. O., Burkhard, M., Hänni, R., Kammer, A., Kligfield, R., Mancktelow, N. S., Menkveld, J. W., Ramsay, J. G., Schmid, S.

M., & Zurbriggen, R. (2010). Structural Map of the Helvetic Zone of the Swiss Alps, including Vorarlberg (Austria) and Haute Savoie (France), 1: 100 000. Geological Special Map 128. Wabem: Federal Office of Topography swisstopo.

Price, R. A. (1986). The southeastern Canadian Cordillera: thrust faulting, tectonic wedging and delamination of the lithosphere. *Journal of Structural Geology, 8*, 293–310.

Rahn, M. K., Hurford, A. J., Frey, M. (1997). Rotation and exhumation of a thrust plane: Apatite fission-track data from the Glarus thrust, Switzerland. *Geology*, *25*(7), 599–602

Ramsay, J. G., & Huber, M. I. (1987). *The techniques of modern structural geology, Volume 2: Folds and Fractures* (p. 391). London: Academic Press.

Richter, M. (1922). Der Flysch in der Umgebung von Oberstdorf im Allgäu. *Jahrbuch der Geologischen Bundesanstalt, 72*, 49–80.

Richter, M. (1969). *Sammlung geologischer Führer - Vorarlberger Alpen* (p. 177). Berlin–Stuttgart: Gebrüder Borntraeger.

Richter, M. (1983). Geologische Karte von Bayern 1: 25.000 - Blatt Nr. 8527 Oberstdorf (Unveröffentlichte Manuskriptkarte). München: Bayerisches Geologisches Landesamt.

Salomon, D. (1989). Sedimentäre Entwicklung und Stratigraphie der helvetischen mittleren und oberen Kreide (Spät-Apt bis Maastricht) im Bereich der Gottesackerwände (Allgäu/Vorarlberg). *Berliner Geowissenschaftliche Abhandlungen, A106*, 385–407.

Sax, H. (1925). Geologische Untersuchungen zwischen Bregenzer Ach und Hohem Freschen (Vorarlberg). Ph.D. dissertation, Univ. Zürich, Schweiz, 38 pp.

Schaad, H. (1926). Zur Geologie der jurassischen Canisfluh-Mittagsfluh Gruppe im Bregenzerwald. *Vierteljahresschrift der Naturforschenden Gesellschaft in Zürich, 70*, 49–84.

Scholz, H. (1984). Bioherme und Biostrome im Allgäuer Schrattenkalk (Helvetikum, Unterkreide). *Jahrbuch der Geologischen Bundesanstalt, 127*, 471–499.

Scholz, H., & Zacher, W. (1983). *Geologische Übersichtskarte 1: 200 000—CC 8726 Kempten (Allgäu)*. Hannover: Bundesanstalt für Geowissenschaften und Rohstoffe.

Schwerd, K. (1983). Ultrahelvetikum-Zone. In Bayerisches Geologisches Landesamt (Ed.), *Geologische Karte von Bayern 1: 25 000–Erläuterungen zum Blatt Nr. 8427 Immenstadt i. Allgäu* (pp. 37–40). München: Bayerisches Geologisches Landesamt.

Schwerd, K. (1996a). Helvetikum. In Bayerisches Geologisches Landesamt (Ed.), *Erläuterungen zur Geologischen Karte von Bayern 1: 500 000, 4* (pp. 195–205). München: Bayerisches Geologisches Landesamt.

Schwerd, K. (1996b). Ultrahelvetikum. In Bayerisches Geologisches Landesamt (Ed.), *Erläuterungen zur Geologischen Karte von Bayern 1: 500 000, 4* (pp. 205–206). München: Bayerisches Geologisches Landesamt.

Schwerd, K., & Häussler, H. (1983). Helvetikum-Zone. In Bayerisches Geologisches Landesamt (Ed.), *Geologische Karte von Bayern 1: 25 000 - Erläuterungen zum Blatt Nr. 8427 Immenstadt i. Allgäu* (pp. 40–78). München: Bayerisches Geologisches Landesamt.

Schwerd, K., Huber, K., & Müller, M. (1995). Tektonik und regionale Geologie der Gesteine der Tiefbohrung Hindelang 1 (Allgäuer Alpen). *Geologica Bavarica, 100*, 75–115.

Tolwinski, K. (1910). Die Grauen Hörner. *Vierteljahresschrift der Naturforschenden Gesellschaft in Zürich, 55*, 1–62.

Trümpy, R. (1969). Die helvetischen Decken der Ostschweiz: Versuch einer palinspastischen Korrelation und Ansätze zu einer kinematischen Analyse. *Eclogae Geologicae Helvetiae, 62*, 105–142.

Trümpy, R. (1980). *Geology of Switzerland—a guide-book. Part A An Outline of the Geology of Switzerland* (p. 104). Basel, New York: Wepf & Co.

Trümpy, R. (1992). Ostalpen und Westalpen—Verbindendes und Trennendes. *Jahrbuch der Geologischen Bundesanstalt, 135*, 875–882.

Vacek, M. (1879). Über Vorarlberger Kreide. Eine Localstudie. *Jahrbuch der Kaiserlich-Königlichen Geologischen Reichsanstalt, 29*, 659–758.

Vollmayr, T., & Ziegler, J. H. (1976). *Geologische Karte von Bayern 1:25 000 - Blatt Nr. 8425 Weiler i. Allgäu*. München: Bayerisches Geologisches Landesamt.

Wagner, G. (1950). *Rund um Hochifen und Gottesackergebiet: eine Einführung in die Erd- und Landschaftsgeschichte des Gebietes zwischen Iller und Bregenzer Ach* (p. 116). Öhringen: Verlag der Hohenloheschen Buchhandlung Ferdinand Rau.

Winkler, G. R., & Cassell, B. R. (1989). Deep VSP study in a complex Alpine overthrust area. *First Break, 7*, 111–124.

Woodward, N. B., & Rutherford, E. J. (1989). Structural lithic units in external orogenic zones. *Tectonophysics, 158*, 247–267.

Wyssling, G. (1985). Palinspastische Abwicklung der helvetischen Decken von Vorarlberg und Allgäu. *Jahrbuch der Geologischen Bundesanstalt, 127*, 701–706.

Wyssling, G. (1986). Der frühkretazische helvetische Schelf in Vorarlberg und im Allgäu - Stratigraphie, Sedimentologie und Paläogeographie. *Jahrbuch der Geologischen Bundesanstalt, 129*, 161–265.

Zacher, W. (1972). *Geologische Karte von Bayern 1: 100 000 - Blatt Nr. 670 Oberstdorf*. München: Bayerisches Geologisches Landesamt.

Zacher, W. (1973). Das Helvetikum zwischen Rhein und Iller (Allgäu - Vorarlberg). *Geotektonische Forschungen, 44*, 1–74.

Zacher, W. (1990). *Geologische Karte der Republik Österreich 1: 50.000 - Blatt 113 Mittelberg*. Wien: Geologische Bundesanstalt.

Zylka, R., & Jacobshagen, V. (1980). Das Karhorn bei Lech/ Vorarlberg - eine Deckscholle. *Annalen des Naturhistorischen Museums in Wien, 83*, 387–398.

Unpublished work

Aichholzer, S. (2010). Strukturgeologische Bearbeitung der Subalpinen Molasse im Raum Bregenzer Wald und Westallgäu. Diploma thesis, Leopold-Franzens Universität Innsbruck, Österreich, 102 pp.

Bischof, M. (2010). Zur Geologie und Tektonik im südwestlichen Rätikon (Vorarlberg). Diploma thesis, Leopold-Franzens Universität Innsbruck, Österreich, 114 pp.

Blum, A., & Hug, R. (2001). Geologische Untersuchungen im Raum Sargans (inkl. 3D-Geometrie des Gonzenerzlagers). Diploma thesis, Universität Bern, Schweiz, 310 pp.

Freitag, U. (2003). Abwicklung eines Strukturprofils über den Nordrand der Alpen (Molasse bis Nördliche Kalkalpen) im Bereich der Bohrungen Legau und Hindelang. Diploma thesis, Friedrich-Schiller-Universität Jena, Deutschland, 68 pp.

Naef, H. (2010). Tiefengeothermie im Fürstentum Liechtenstein: Geologische Interpretation der Testseismik 2010—Bericht Nr. FL 10-03 vom 8. Oktober 2010, 18 pp.

Pfiffner, A. O. (1979). Stratigraphische Profile im Infrahelvetikum der Ostschweiz. ETH Zürich, 58 pp.

Prakla-Seismos (1984). Seismische Geschwindigkeitsmessung Sulzberg 1. Interner Bericht NR. 843 626 an das Konsortium des Aufsuchungsgebietes VEF Vorarlberg.

Schwerd, K. (1970). Stratigraphische, sedimentpetrographische und tektonische Spezialuntersuchungen in der Subalpinen Molasse am Westende der Murnauer und Rottenbucher Mulde zwischen Kranzegg und Immenstadt im Allgäu. Diploma thesis, Techn. Hochsch. München, Deutschland, 43 pp.