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The Grenchenberg conundrum in the Swiss Jura: a case for the centenary of the thin-skin décollement nappe model (Buxtorf 1907)

HANS LAUBSCHER

Key words: Jura, décollement, Grenchenberg tunnel, asperities, reactivation, collision

ABSTRACT

When Buxtorf in 1907 proposed his décollement hypothesis which visualized the Jura fold belt as a "folded décollement nappe" pushed by the Alps, he met with both fervent support of a few and skepticism by the many. As an illustration of recalcitrant problems within the Jura décollement nappe, that remain after 100 years, a model of the Grenchenberg complex is presented within the frame of 3D décollement kinematics, based on a set of rules gleaned from recurrent features in the Jura: (1) that generally progression of décollement was in sequence from south to north, (2) that in any given structure thrusting (with attendant ramp folding) preceded more generalized folding, (3) that progression of décollement was held up at "anchor points" (asperities) where the emerging thrusts and folds developed inflections with dextral transpression in the western and sinistral transpresssion in the eastern flank, (4) that at such asperities more southerly structures, riding piggyback on the moving décollement sheet, often collided with more northerly ones and even merged with them. The asperities occur on fault/flexure lines of Paleogene origin, the Pierre Pertuis anchor point on the Vicques and the Grenchenberg extended anchor domain on the "Schwarzwald" Line (the continuation of the eastern border of the Rhinegraben). These lines produced deformations of the décollement surface in the middle Triassic evaporites which acted as boundary conditions at the bottom boundary of the décollement nappe, which led to stress concentrations and the nucleation of faults. Although it is now widely recognized that these lines were reactivated during late Miocene Jura décollement, it ought to be stressed that this reactivation affected the décollement nappe only and there individual asperities or groups of asperities rather than the lines as a whole. Because in the course of nappe displacement the originally autochthonous asperities as expressed in the sedimentary cover moved into an allochthonous position, their original autochthonous location in the basement has to be found by retrodeformation enabled by a map-aspect kinematic model. The Grenchenberg structure developed by collision of the Montoz and Chasseral ranges and was affected by at least three different anchors. At one of these anchors a belt of brachyanticlines developed along which material was dextrally transferred from the Montoz- to the Chasseral fold, resulting in the disappearance of the former and the strengthening of the latter, which in turn merged with the rising Weissenstein fold.

ZUSAMMENFASSUNG

Als Buxtorf 1907 seine Abscherungshypothese vorstellte, in der der Faltenjura als eine von den Alpen her geschobene „gefaltete Abscherdecke" konzipiert war, stiess er bei Wenigen auf begeisterte Zustimmung; die Mehrheit blieb skeptisch. Um zu illustrieren, dass es auch heute noch, nach hundert Jahren, widerspenstige Probleme im abgescherten Jura gibt, wird unter Verwendung einer Anzahl von Regeln der Versuch unternommen, ein 3D-kinematisches Abschermodell des Grenchenberg-Komplexes zu entwickeln. Die Regeln sind (1) dass generell (d. h. mit Ausnahmen) Abscherung und Faltenbildung „in Sequenz", d. h. progressiv von S nach N erfolgten; (2) dass in jeder individuellen Kontraktionsstruktur zuerst Überschiebungen (begleitet von den obligaten Rampenfalten) entstanden, gefolgt von einer allgemeinen Verfaltung; (3) dass die Ausbreitung der Abscherung an Ankerpunkten aufgehalten wurde, wo die in Bildung begriffenen kontraktiven Strukturen einen nach S konvexen Knick erfuhren mit einer dextral-transpressiven Westflanke und einer sinistral-transpressiven Ostflanke; (4) dass an solchen Ankerpunkten südlichere, schon bestehende Strukturen, die passiv auf der sich bewegenden Abscherdecke nach N ritten, mit den sich bildenden Strukturen kollidieren und sich sogar mit ihnen vereinigen konnten; (5) dass den kontraktiven transpressive Elemente überlagert sein können, vor allem bedingt durch die örtlichen Unregelmässigkeiten an der Basis der Abscherdecke. Diese Ankerpunkte befinden sich auf eo-oligozänen Deformationslinien, und zwar der Pierre Pertuis Anker auf der Viques-, die etwas ausgedehntere Ankerdomäne des Grenchenbergs auf der „Schwarzwald" Linie (südliche Fortsetzung des Rheingraben-Ostrands). An den Ankerpunkten wurde der spätere Abscherhorizont während des Eozän-Oligozäns und Untermiozäns deformiert, und diese Deformationen wirkten als spezielle Randbedingungen an der Basis der spätmiozänen Abscherdecke. Daran entstanden Spannungskonzentrationen, welche Störungen aller Art auslösten. Obwohl nun allgemein anerkannt ist, dass diese Palaeolinien in der spätmiozänen Jurafaltung reaktiviert wurden, so ist hervorzuheben, dass nicht die Linien selbst sondern vielmehr die darauf befindlichen Ankerpunkte oder Gruppen von Ankerpunkten wirksam waren, und zwar nur in der Sedimenthaut. Weil im Verlauf der Deckenbewegungen die ursprünglich autochthonen Anker in der Abscherdecke um grosse Beträge in allochthone Positionen verfrachtet wurden, kann die ursprüngliche autochthone Position im Grundgebirge nur mit Hilfe eines kinematischen Modells (in Kartenansicht) durch Retrodeformation ermittelt werden. Der Grenchenberg entstand durch Kollision der Chasseral- mit der Montozkette, wobei mindestens drei Ankerpunkte mitwirkten. An einem solchen Ankerpunkt entstand eine dextrale Transferzone, markiert durch einen en-échelon Gürtel von Brachyantiklinalen. An diesem Gürtel wurde die Montozfalte abgebaut und dafür die Chasseralfalte aufgebaut, wobei sie in die aufsteigende Weissensteinfalte überging.

Introduction

A conundrum is a problem that is difficult or impossible to solve. There are numerous such problems even in a modest fold-and-thrust belt such as the Jura (Fig. 1), in spite of the efforts of generations of geologists. One particular problem of this kind is the structure of the Grenchenberg complex ("G" in Fig. 1).

Wenkenstrasse 26, CH-4125 Riehen, Switzerland. E-mail: laubscherh@bluewin.ch

It is the purpose of this article commemorating the centennial of the Jura décollement model to investigate, in the guise of a case study involving the Grenchenberg complex already worked on by Buxtorf (1916), the more obvious difficulties remaining for the application of the model. It addresses some fundamental and general problems of the ambiguities of data sets and of interpolations and extrapolations, and offers the application of an updated model to the Grenchenberg structure.

When Buxtorf (1907) first published his décollement hypothesis of Jura tectonics, his only data set consisted of moderately accurate surface maps and cross sections based on them plus shallow railroad tunnels. His crucial point was that nowhere in the Jura strata older than middle Triassic evaporites had been observed, even in the most deeply eroded folds, and that even crudely constructed cross sections left room for little more than the Triassic strata. It stood to reason that the folds had been sheared off in the apparently easily deformed evaporites. However, this data set was considered by many too paltry to permit a rather sweeping generalization such as a thin-skin décollement nappe model for the entire Jura system.

Some fundamental problems of tectonics as applied to the Jura

Tectonics, a synthetic science, strives to integrate the sundry static data sets collected in a given region into a kinematic and finally a dynamic entity. "Integration", not "compilation" is the key word: Tectonics has to go beyond the facts, its goal is the presentation of evolutionary models respecting the constraints imposed by the data.The first fundamental problem of the tectonics of the Jura system is that it is not stringently constrained. To constrain it more effectively, an updated model may be built with additional stipulations based on empirical rules inferred from an extended region. Required is a trial-and-error procedure, beginning with a simple first model, whose implications may be tested for plausibility. This model may then be refined in a number of steps. The step attempted in this paper aims at an updated qualitative model without striving at quantitative perfection.

A first application of the décollement model: the Grenchenberg structure

Buxtorf's 1907 hypothesis, which visualized the Jura as a décollement nappe pushed from the Alps (for location see Fig. 1) may be seen as such an initial simple model. His first series of cross-sections, which illustrated the model, were quite crude and called for improvement in a second step of the trial-and-error procedure. An opportunity for such an improvement presented itself when the Grenchenberg railroad tunnel was excavated (Buxtorf 1916). The section across the eastern Jura based on the tunnel data became world famous and circulated widely as support for the décollement model. It did not, however, convince the many skeptics who doubted the physical feasibility of the décollement process and particularly the implied allochthony of the Molasse basin. Buxtorf's interest in physics was limited, he was an observational geologist of the old school. However, later progress in experimental rock mechanics (e.g. Urai et al. 1986, Jordan 1994) demonstrated, that objections on mechanical grounds were unfounded**:** Décollement was possible, although this did not prove that it had actually taken place, particularly on the scale of the Jura system. Other problems remained unsolved. The most important one was the actual, detailed position of the décollement surface. For his 1916 cross-section Buxtorf relied on traditional techniques based mainly on experience, style and personal aesthetics. However, he also added a first version of section balancing, including fault-bend (ramp-) folding and a kinematic sequence. As one of his assistants, the late Justus Krebs, told the author decades ago, Buxtorf gave him instructions to use colored strings of equal length, representing formation boundaries, and to deform each one of them by the same amount. He then proceeded to fit in the actual stratigraphic column, estimating the position of an uncomplicated décollement horizon, filling in empty spaces with accumulations of evaporites and eliminating the evaporites where there was no room for them.

However, this procedure did not prove very satisfacory, as it left too many points to arbitrary decisions. Modern computer-assisted techniques of section balancing offered the hope of further refinement of the model, particularly with a view to improving the geometry of the décollement horizon (e.g. Bitterli 1992, Philippe 1994, Philippe et al. 1996, Pfiffner et al. 1997, Wilkerson & Dicken 2001, Laubscher 2003b, 2008a, 2008b).

The success of these efforts, however, was limited mainly because of four essential uncertainties. The first concerned the exact stratigraphic thicknesses at each point; they might be estimated on regional isopachs, but this was not very accurate and rather impracticable as efficient construction required constant thicknesses at least for a confined region. The second pertained to the 3D nature of many of the Jura structures: Section balancing ideally required profiles in the direction of the kinematic vector. Strike-slip and rotation about vertical axes, manifestly abounding in the Jura (e.g. Bitterli 1992, Laubscher 2003b), did not conform to the techniques. A third uncertainty arose from the problem, that Jura structures were assembled in a succession of steps with not necessarily constant direction of the kinematic vectors (Laubscher 2003b). And a fourth and rather crucial problem is implied in the allochthony of the décollement nappe: Original irregularities in the shape of the décollement horizon would be deformed and transported by considerable amounts from their original, autochthonous position and could not be found by downward extrapolation in a cross-section (Fig. 2; compare Laubscher 2008b).

The allochthony issue

Addressing the allochthony problem, Laubscher (1965) proposed a first, rough, map-view kinematic model, particularly for the Rheintal Jura south of the Rhinegraben. For this model, published cross sections were examined for amounts of short-

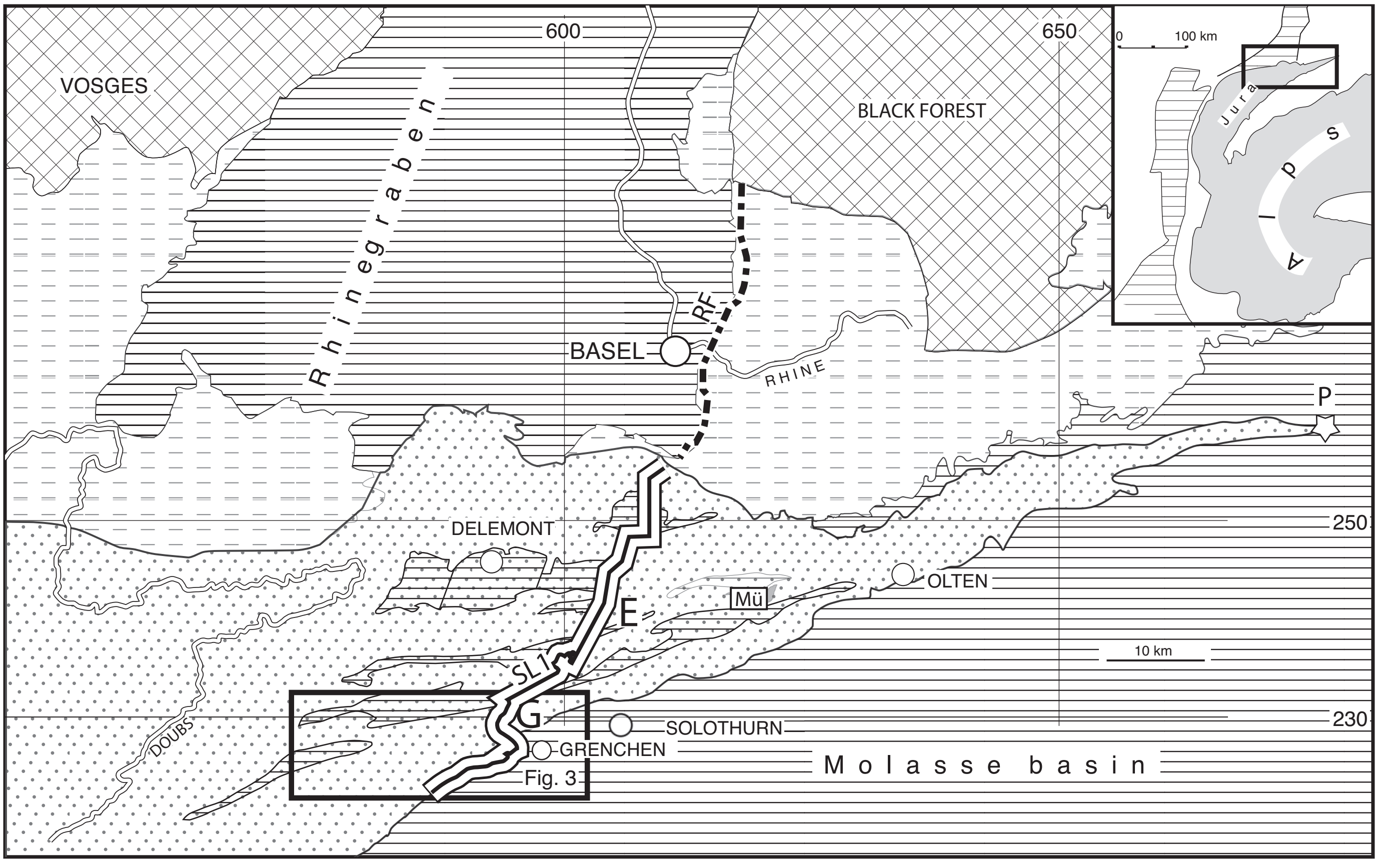


Fig. 1. The location of the Grenchenberg complex (bold rectangle) within the Jura system. Inset: The Jura within its tectonic surroundings. Horizontal ruling: major Tertiary (mostly Oligocene) depressions; dashes: tabular array of sediments (mostly Mesozoic); cross-ruled: pre-Mesozoic of Vosges and Black Forest; stippled: late Miocene Jura fold-thrust belt; G: Grenchenberg; E: Envelier inflation; Mü: Mümliswil; RF: Rheintal flexure; SL1: Schwarzwald line (allochthonous); P: Pivot for dextral rotation of the eastern Jura. Coordinates (of all figures) are those of the Swiss Topographic Office.

ening by subjecting them to simple modifications to assure a minimum of balancing ("curvimetric-volumetric harmony"). He then fitted these amounts into rotational kinematics with a pivot at the eastern end of the Jura ("P" in Fig. 1). Attempts at improving the model with modern balancing techniques (Bitterli 1992, Laubscher 2003b, 2008a, 2008b) have proved difficult if not impossible because of the fundamental uncertainties mentioned above. Discrepancies in the estimated amounts of shortening would still have to be smoothed out by fitting them into a more or less plausible model.

However, the old 1965 model turns out to be still useful for estimating allochthony, as established by the working out of some particular cases (Laubscher, 2008a, 2008b; compare Fig. 2).

Balancing problems: Promises and limitations

Material balance is a fundamental aspect of deformation. In the brittle domain it may be equated with volume balance, and in a cross-section even with area balance. Balancing techniques, aided by computer software, are used to check the "validity" of cross-sections, "validity" merely meaning the maintenance of some balancing rules, preferably maintaining bed lengths and thicknesses in addition to areas. However, cross-sections may be valid in this sense without being kinematically viable, i.e. respecting a pre-ordained sequence of events. This, however, is what is at stake in tectonic synthesis. As far as the author can see, kinematic validity can be approximated only by forward modeling, which faces the difficulty that first inputs are conjectural and may cause the following steps to go astray (Laubscher 2003b). It is here that the somewhat fuzzy concept of "style" is important: Attempts at guessing the most useful first input in a number of kinematic models have convinced the author that there is such a thing as a "default style", which should be envisaged first, unless it contradicts data. In view of the time consuming efforts required for forward modeling, a point of diminishing returns will eventually force the modeler to accept a result with not very satisfactory limits of balancing error. The author opines that for the issues discussed in this paper a default style, as proposed by Laubscher (2003b), is of first and foremost importance, and that quantitative balancing errors are acceptable in the interest of arriving at temporary conclusions in affordable time. Balancing in the cross-sections shown in the present paper is therefore reduced to estimates based on Laubscher (2003b).

On the other hand, default assumptions are used, and their consequences are examined. They are (1) a basal decollement surface in the middle Triassic evaporites with an average south-dip of 2.5°; (2) in sequence propagation of décollement; (3) a fold style beginning with a thrust and attending ramp fold, which is folded in turn by kink bands in the hanging wall and disharmonious deformation of the foot wall or core (Laubscher 2003b); (4) nucleation of thrusts beginning at asperities in the décollement horizon, that line up at paleofaults and temporarily impede décollement as "anchors".

Revisiting the Grenchenberg

One of the more challenging problems of 3D kinematics concerns the classical Grenchenberg complex of Buxtorf's (1916) publication. The Grenchenberg is, in extreme geometrical simplification, the "triple junction", where three of the most important Jura folds merge ("G" in Fig. 1, "Gre" in Fig. 2). Buxtorf's illustrations concern the cross-sectional aspect only, and consequently are limited to a 2D analysis. In this paper an attempt is made to address the 3D problem, amalgamating cross-sectional and map-view kinematics.

The observational data sets used for this paper are, in addition to the tunnel profile of Buxtorf (1916): (1) the published sheets of the Geological Atlas of Switzerland 1 : 25'000 (Moutier 1106 (96) by Pfirter et al. (1996), Büren a.A. 1116 (109) by Antenen et al. (2004) and unpublished recent mapping by J. Aufranc (personal communication 2005, 2006). However, the paper is mainly concerned with interpretation, particularly kinematic synthesis.

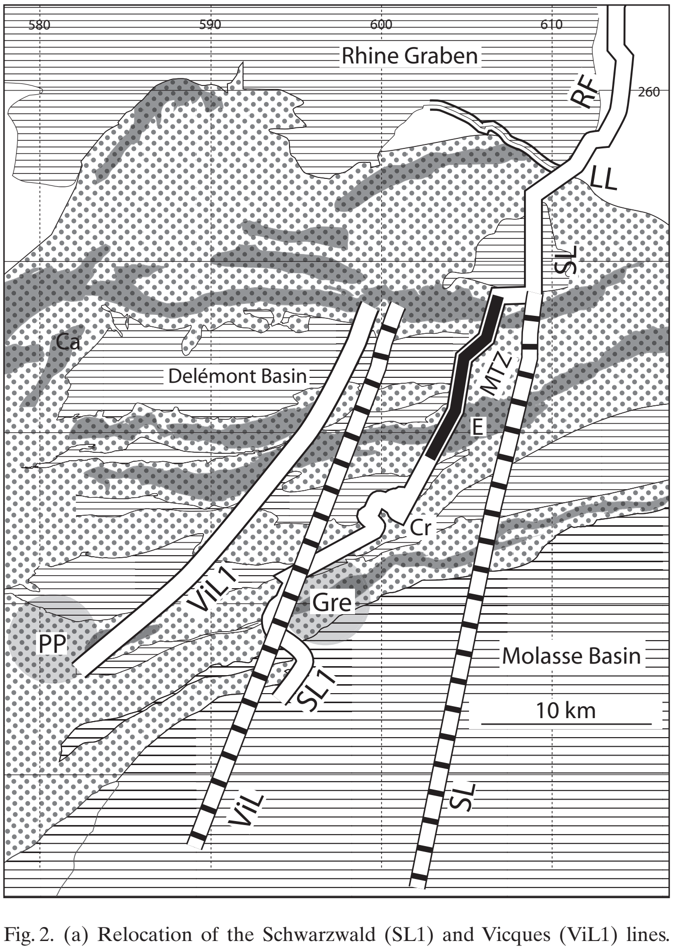


Fig. 2. (a) Relocation of the Schwarzwald (SL1) and Vicques (ViL1) lines. SL, ViL: autochthonous position, retro-deformed, using the simple rotational model of the eastern Jura of Laubscher (1965). PP: Pierre Pertuis; Gre: Grenchenberg; Cr: Crémines; E: Envelier; MTZ: Mervelier transfer zone; LL: Landskron line; RF: Rheintal flexure; dots: Jura fold belt; ruled: Tertiary; gray: middle Jurassic and older (core of folds).

Approaching the Grenchenberg from the west

To approach the problem of the eastwards merging Chasseral and Montoz anticlines, the structure of the still separated individual anticlines west of the Bürenschwängli triple junction (Fig. 3) would have to be known. Fig. 3 is a simplified map of the pertinent area, and Fig. 4 is a series of cross-sections of the Chasseral and Montoz folds according to the newest mapping by J. Aufranc (1985 and personal communication 2005), beginning at a transect, where they still are separated by the wide St.Imier syncline. Fig. 4d is intended to illustrate a first transitory collision of the anticlines in the the Pierre Pertuis transect (location in Fig. 3).

The most obvious features of the Chasseral anticline in cross-section (a) are a gently dipping (~20°) very broad south limb and an intensely folded and faulted north limb of late Jurassic to early Cretaceous beds, thrust on the Tertiary molasse of the St. Imier syncline. Decisive for the construction of this cross section is the identification of the south limb as the trailing limb of a fault-bend fold (or, simplified, of a ramp fold; Suppe 1983), in accordance with the assumed default style. The other principal features of the structure then take shape almost automatically, except that the stratigraphic column and the position of the décollement horizon have to be fixed to complete an essential set of constraints, and that the deformation of the core is disharmonious and in detail somewhat arbitrary. In the north limb of the Montoz structure of Fig. 4a collision of the Montoz and Les Places structures is symbolically suggested, but the discussion of such collisions is deferred to the analysis of the Pierre Pertuis and Grenchenberg areas farther east.

As to stratigraphy, the tunnel profile of Buxtorf (1916), which might be expected to provide the most accurate information, is rather disappointing, as it shows quite variable thicknesses. Obviously, this fact has rather unsatisfactory consequences. It leaves a not negligible margin of error particularly for the position of the basal décollement surface. However, these errors are irrelevant for the issue at stake in this paper, which is the collision problem in, first, the Pierre

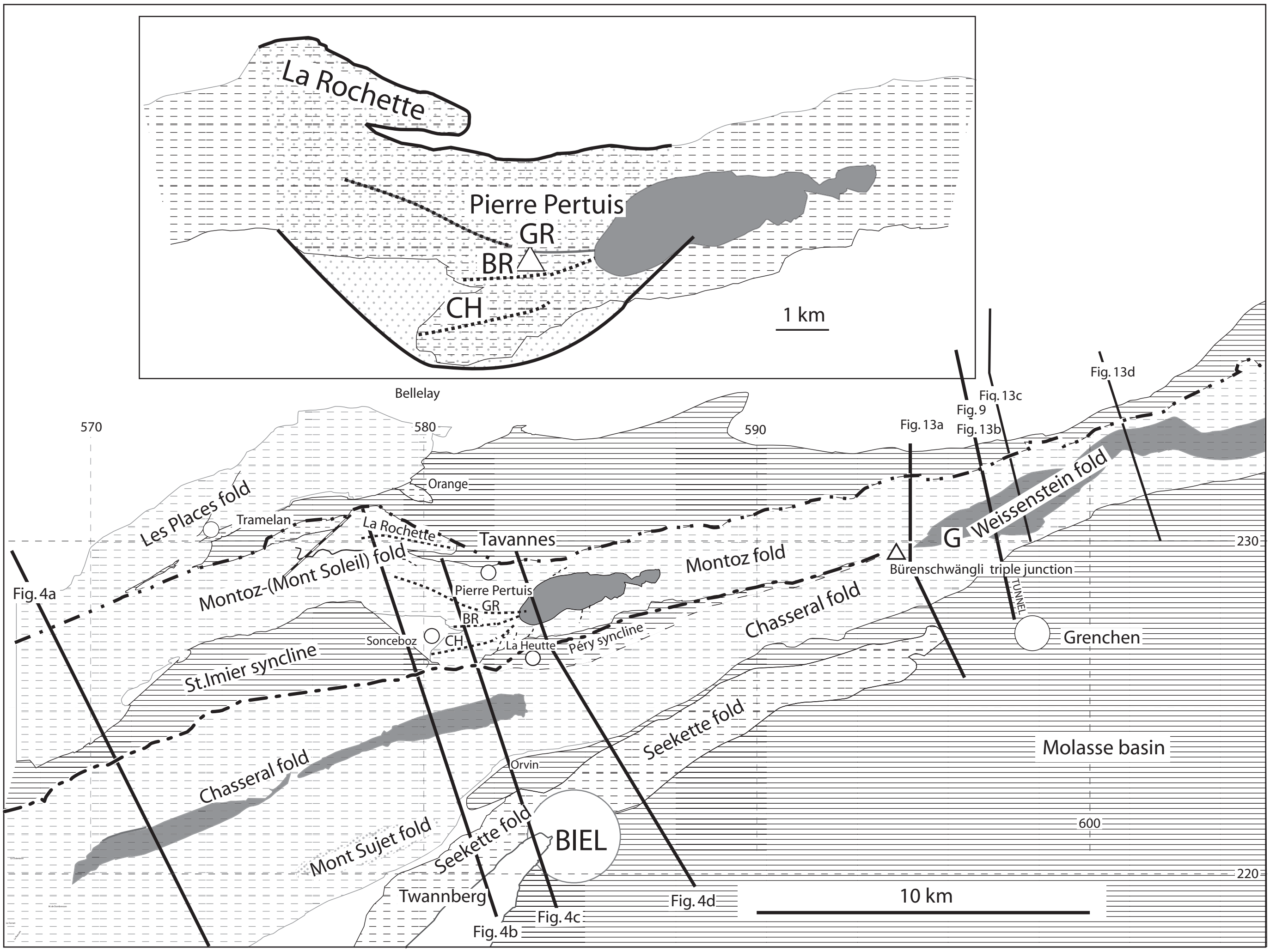


Fig. 3. Simplified map of the tectonic units discussed in this article, with the tracks of cross-sections. Shading: Middle Jurassic; dashes: upper Jurassic and lower Cretaceous; ruled: Tertiary; heavy dash-dot line: Chasseral thrust; heavy dash-dot-dot line: Montoz thrust; heavy dotted lines: axes of Pierre Pertuis brachyanticlines with GR = Grimm (-Mt. Soleil) fold; BR = Brahon fold; CH = Châtillon fold; G = Grenchenberg. Inset: the Pierre Pertuis segment of the Montoz range, enlarged; stippled: segment of fold wrapped around the anchor (triangle). Explanations in the text.

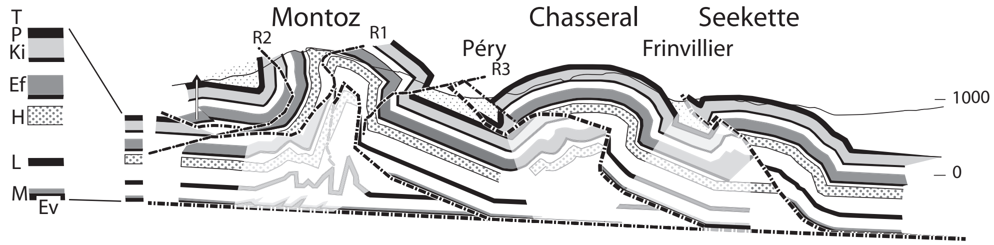
Pertuis transect, but particularly in the Grenchenberg complex.

Default position of the décollement horizon is set, as postulated above, in the middle Triassic evaporites below the Hauptmuschelkalk ("M") with a dip of 2.5° south, passing through the estimated southern hinge of the south limb. In Fig. 4b the base of the Tertiary is at a lower position than in Fig. 4a. This is due to various factors, but primarily because the flat roof of the Grim (Gr in Fig. 3) fold was used for fixing the position of the Montoz thrust. However, position and dip of the thrust may be varied without, on the other hand, greatly influencing the relation of the Montoz and Chasseral folds. Similar considerations also concern the other sections.

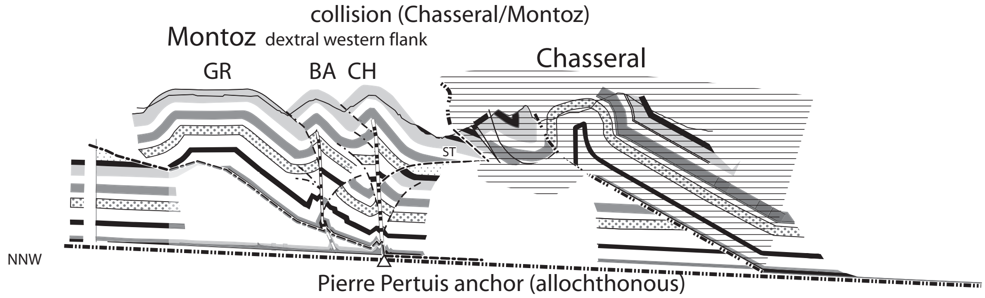
Of paramount importance in this context, however, is the style of deformation, the default style as defined above. The prevalence of this style may be inferred time and time again in many parts of the Jura (compare, e.g., Mühlberg 1914b, at least in outlines, Sommaruga 1999, Laubscher 2003b).

The Pierre Pertuis (Fig. 3; PP in Fig. 2) anchor point and the problem of asperities at the base of the décollement nappe

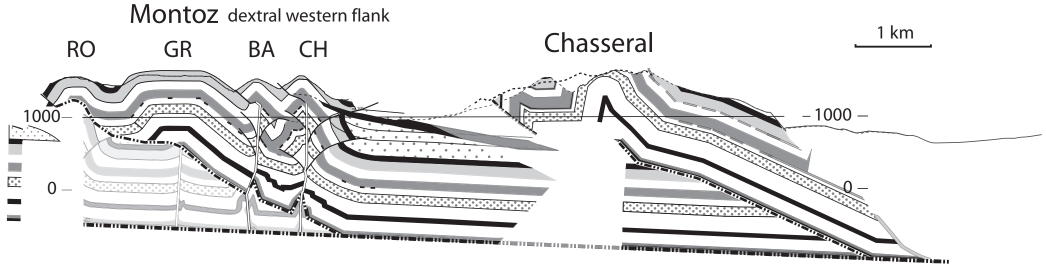
The Chasseral and Montoz folds continue without major changes until they approach the Pierre Pertuis transect (Fig. 3). There, both folds change character, in particular the Montoz fold. In map view (Fig. 3) it executes a sharp bend to the south, at the same time developing a belt of narrow subsidiary folds (brachyanticlines). Apparently the progress of décollement had been halted at what may be termed the "Pierre Pertuis pindown" or "anchor".



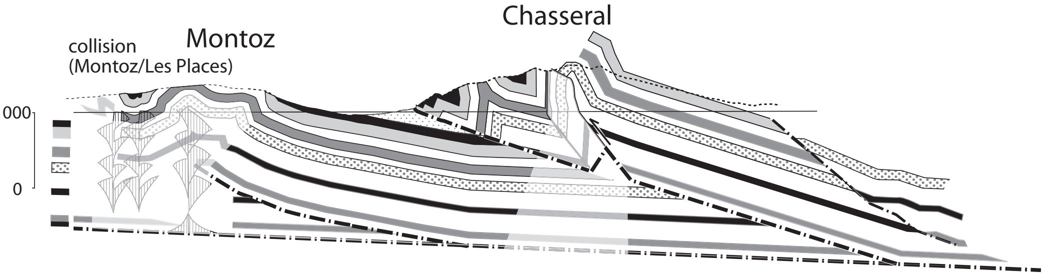
d) Tubelochschlucht (data from Aufranc, personal communication 2005)



c) Sonceboz E (data from Aufranc, personal communication 2005)



b) Sonceboz W (data from Aufranc, personal communication 2005)



a) Petit Chasseral (data from Aufranc, personal communication 2005)

Fig. 4. Cross-sections of the Chasseral-Montoz anticlinorium from the Petit Chasseral to the Tubelochschlucht (for locations see Fig. 3). Qualitatively balanced sections according to the rules of Laubscher (2003b). Stratigraphic columns: T = Tertiary, P = "Portlandian" (Tithonian) and lower Cretaceous, Ki = Kimmeridgian, E = Effingen beds, H = Hauptrogenstein, L = lower Liasssic, M = Hauptmuschelkalk, Ev = Mid-Triassic evaporites; white or matted: Areas of no or questionable projection, mainly core of folds. (a) Profile through Petit Chasseral. Vertically ruled: symbolic flower structures. (b) Section passing through the dextrally transpressive western flank of the Pierre Pertuis anchor. Data from Schneider (2005) and Aufranc (1985 and personal communications 2005, 2006). (c) Profile Sonceboz-E passing through the beginning of the sinistrally transpressive eastern flank of the Pierre Pertuis anchor. Source of data as above. The kinematic rules laid down in the text require collision and consequent adaptive tectonics of the two ranges (qualitatively suggested by indenting of the Châtillon flower structure). Horizontally ruled: Chasseral range. (d) Tubelochschlucht, data from Antenen et al. (2004) and the revised map of Aufranc (personal communication 2005). The revised data include a north-vergent thrust of the Montoz range intimated by a drillhole; a south-vergent (back)thrust, folded by the vertical north-limb; complications in the north-limb of the Chasseral fold; small-scale wrinkling in the north-limb of the Seekette. While exposures in the Tubeloch gorge are uncommonly good, the all-important Tertiary beds in the synclines are practically not exposed at all. Therefore, one is at liberty to choose the bottom of the synclines to conform to the position of the default décollement surface.

Such anchor points are quite frequent in the eastern Jura, as even a casual glance at regional maps such as the Tectonic Map of Switzerland 1 : 500'000 (Spicher 1980) reveals. In his atttempts to unravel the origin of tectonic knots in the area he had mapped in the eastern Jura, Laubscher (2005, 2008a, 2008b) arrived at new concepts, particularly as to reactivation of pre-existing structures. Anchors are indicators that the décollement surface is far from smooth, being rather riddled with asperities which had to be overwhelmed by the Jura nappe. It is to be kept in mind, however, that the currently observable probable anchor points, particularly in the southern ranges, are allochthonous by considerable amounts (compare Fig. 2).

Anchor points and the reactivation of paleofaults

Traditionally (e.g. Laubscher 1948), paleofaults are viewed as continuous surfaces, and their reactivation as a process affecting these surfaces as continuous entities. However, faults (and flexures) generally and the paleofaults of the Rhinegraben system in particular are zones of fractured and displaced bedding rather than linear breaks (Fig. 5). Their tectonic relief changes from point to point. During décollement those points or clusters of points with the highest relief are the most prominent obstacles for décollement and will have to be overwhelmed first, when décollement progresses into the foreland (Fig. 6). It goes without saying that, as a rule, the most important paleofault zones contain the most important anchors. As décollement proceeds, the anchors tend to be connected by breaks in the thin skin to form a neofault zone, at first restricted to the neighborhood of the anchor, and resembling but not generally coinciding with the paleofault one (Laubscher 2008a, b). How this affects the moving thin-skin may be inferred from field evidence as illustrated in the cited articles and, as a schematic model, in this paper (Fig. 6). For instance, one area recently remapped in detail is that of the anchor of Mümliswil in the eastern Graitery range (Laubscher 2008a; for location see Fig. 1). Another one is the Mervelier transfer zone at the eastern margin of the Delémont basin, a segment of the eastern margin of the Rhinegraben as it appears, allochthonous, in the folded Jura (Laubscher 2008b; location in Fig. 2). A cluster of anchor points marks its southern end in the Envelier area ("E" in Fig. 2). Its complex influence on nappe kinematics resulted in a local inflation of the Raimeux and Passwang folds, and this phenomenon has been termed the "Envelier inflation structure". While, in Fig. 2, the neotectonical MTZ ends at E, another rather isolated inflation structure developed within the Graitery fold at Crémines ("Cr" in Fig. 2), and yet another in the Weissenstein range in the Grenchenberg area ("Gre" in Fig. 2). When they are moved into an autochthonous position, they line up in the southern projection SL of the Rheintal flexure ("R" in Fig. 1; Laubscher 2008b).

As to the kinematics at anchor points, some rules may be inferred from regional evidence and used for an updated décollement model (Fig. 6). One rule stipulates that anchors are flanked by transpressional structures, dextral ones in the west and sinistral ones in the east; they often are asymmetrical. For instance, the western flank of the Pierre Pertuis anchor (Fig. 3) shows a dextral drag accentuated by brachyanticlines; its eastern flank is characterized by a sinistral bend of the belt of brachynticlines as well as by sinistral drag of the core and minor NNE striking sinistrally transcurrent faults (Aufranc, personal communication 2005). The Châtillon brachyanticline occupies the position of a backfold (Fig. 3 and Fig. 6).

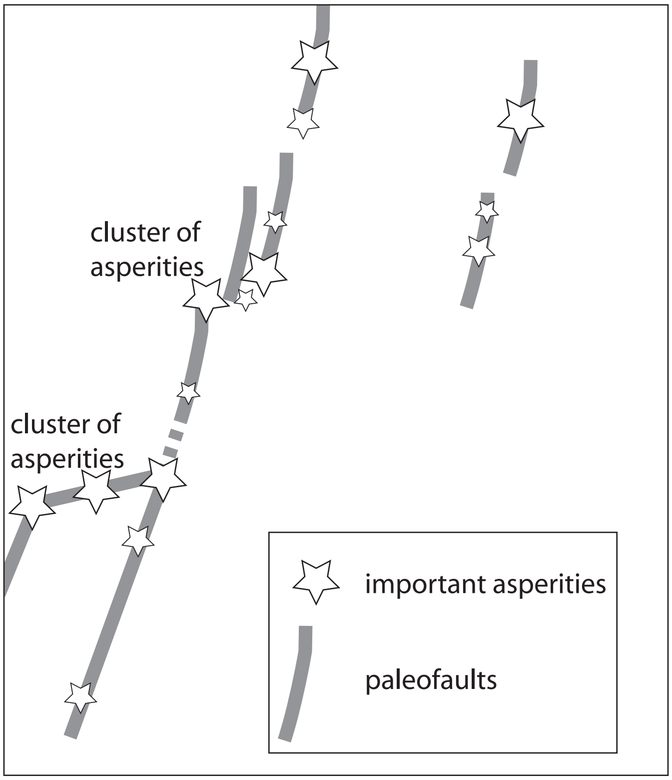


Fig. 5. Schematic figure illustrating the relation of paleofaults and asperities (map view). Paleofaults are fault segments arranged in more or less continuous zones with varying tectonic relief. Their more prominent points constitute asperities of unequal importance that develop into anchors during décollement.

Collisional tectonics at the Pierre Pertuis anchor point

While the inflection of the Montoz-(Mont-Soleil) fold at the PP anchor is evident, the role of the Chasseral fold at this point requires a special analysis. It takes some- though not much- imagination to visualize how the Chasseral structure moved piggyback on the décollement nappe till it collided with the developing Montoz structure, which was held back at the Pierre Pertuis anchor, and even developed a backfold (Fig. 6, 7), resulting in a complex of accommodating structures.

In detail their 3D structure is not predictable, but arguments may be put forth for at least a plausible solution. We first note that according to the remapping by Aufranc (personal communication 2005) the Chasseral structure retains a north-vergent overthrust at this point, although the footwall here is the Pierre Pertuis part of the Montoz fold with its brachyanticlines (particularly the Châtillon brachyanticline backfold) rather than the St. Imier syncline (Fig. 3). How does this look on a cross-section?

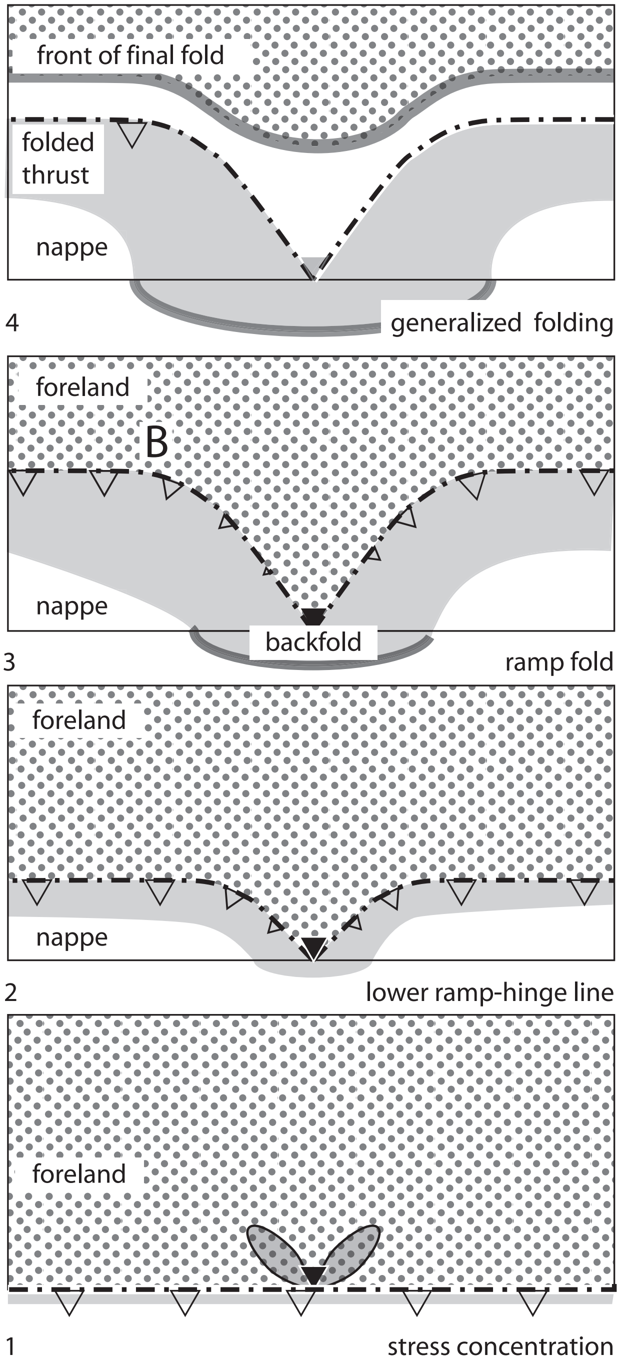


Fig. 6. Stages in the fold development at anchor points. (1) Stress concentration at the indenting point with the usual shearing stress lobes. (2) The still stable foreland skin breaks in the direction of the lobes, followed by an advance of the décollement sheet on both flanks and a backfold south of the anchor; the development of the breaks is facilitated by pre-existing faults. (3) With increasing advance a thrust ramp forms and starts climbing towards the surface, at a few hundred meters from the anchor as a thrust, closer to the anchor as an increasingly steep "lateral ramp", finally as a rank vertical transfer fault. The lateral ramp has a lateral thrust component that results in the overriding of the thrust over the transfer fault: This phenomenon is observed time and time again. Additionally, the proximity of the anchor is characterized by adaptive deformations such as transpressional brachyanticlines. (4) In the final overall folding stage the anchor starts yielding but adaptive deformations continue.

The deep structure of brachyanticlines and the collision of ranges

Brachyanticlines cannot be projected harmoniously as far down as the décollement horizon, their limbs converge at shallower levels. Where simple projective techniques fail, guiding models may have to suffice. Such models have been proposed elsewhere on the basis of seismic evidence (Harding & Lowell 1979) and have also been imitated by analog experiments (e.g. Richard et al. 1995, who modeled a wide range of transpressional and transtensional arrangements). The gist is that they represent 3D transpressive deformations, but that in cross-sections they are commonly shaped as a sort of "flower structure" (Harding & Lowell 1979). The petals of these flowers are three-dimensionally contorted strike-slip faults passing into thrusts, which permit wedging of the brachyanticline into its surroundings. However, as cross-sections cannot reveal their true nature, in this article the flower structures occasionally are represented as schematic pictures (e.g. in Fig. 4a). Nevertheless, en-échelon arrangements of brachyanticlines interpreted as surficial expression of strike-slip components may help in constructing plausible solutions.

The profile series of Fig. 4 illustrates such a "plausible solution". Assuming in sequence propagation of décollement and a flower structure for the Châtillon brachyanticline, the proper style governing the collision would appear to be a wedge of the young Châtillon flower penetrating the older frontal thrust masses of the Chasseral range as what has been termed a "delta" or "triangle" structure (Fig. 4c). As the proposal of such a structure is rather novel in the Jura generally and in the Pierre Pertuis complex in particular it demands some discussion.

Different philosophies in the construction of cross-sections

The problem of extrapolation from a given set of discrete data points in order to construct an image of continuous lines, surfaces, or bodies is no trivial problem but hinges on profound questions of the epistemology part of philosophy, the study of justified knowledge or belief. Thus, downward extrapolation of surface data rests on more or less plausible conceptual models, as the set of observational data in itself is insufficient for a unique solution of the problem, permitting considerable latitude. To further constrain extrapolation, a number of default assumptions gleaned from a wide range of surface observations have been postulated above.

These considerations are of crucial importance in the neighborhood of the Pierre Pertuis anchor. In particular the assumption of in-sequence propagation of décollement requires an alternative solution, differing from recently proposed ones (e.g.

Schneider 2005, who is, to my knowledge, the only author who constructed down-to-basement cross-sections of the Pierre Pertuis area). The cross-sections (b), (c) and (d) of Fig. 4 are based on the surface information of Aufranc (oral communication, 2006). The crucial importance is due to the fact that surface maps show a sort of barrier of Mesozoic strata across the Tertiary of the St. Imier syncline. If the Chasseral and Montoz folds are to be followed to the Grenchenberg area, the crossing of this barrier on the basis of general décollement in the middle Triassic is a fundamental problem. It turns out to be possible, when the default assumptions as stated above are respected, and even necessary, when in-sequence propagation of décollement is valid.

For comparison with profile (4c) consider the closely adjacent profile (4d). In both profiles the style is the default style adopted for this article (ramp folds modified by kinking and brachyanticlines) and the structures originated in sequence, with the brachyanticlines of the Montoz fold shown as qualitative, schematic flower structures that belong to the western flank of the Pierre Pertuis anchor and its backfold.

In profile (4d) recent improvements in the surface geology by Aufranc (oral communication 2005) have been included. The picture that now presents itself is as follows: The Chasseral thrust, deformed by subsequent thrusting and folding (Fig. 4c), is assumed to continue from Fig. 4a to this section, as data do not demand otherwise. This means that according to recent mapping the frontal thrust may be followed across the Pierre Pertuis barrier. As to the Montoz fold, it is assumed that in principle it retains its default style, particularly its initial thrust and attending deformations. However, it turns out that this basic scheme needs to be substantially modified in order to respect the recently added observational data. There are small back thrusts, deformed (overturned) by folding, but as their branch-off points at the décollement horizon come to lie far north of that of the main thrust, they should be younger and dissect it. The surfacing of the dissected main thrust may be placed north of the drill hole which encountered the upper Jurassic at such a high position that a large north-verging thrust is unavoidable (data from Aufranc, personal communication 2005).

As an aside it may be noted that between Fig. 4c and Fig. 4d both the Chasseral and Montoz structures change their shape, the Chasseral losing and the Montoz gaining tectonic relief, suggesting an out-of-sequence transfer zone. It would appear that in this instance the default assumptions would have to be softened. However, as the problem does not touch the main issue of this paper, it is left for later investigations.

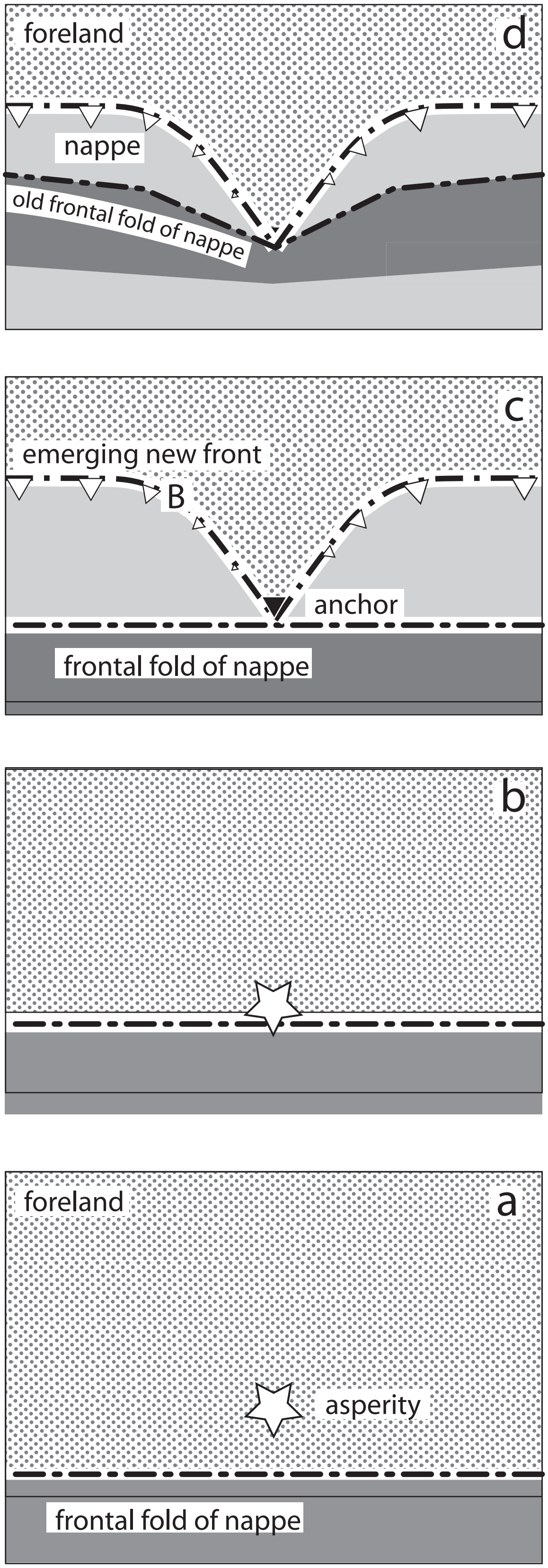


Fig. 7. Fold collision at anchor points (map view). Compare with Fig. 5.

The collisional tectonics in the Grenchenberg anchor domain

Beyond the Pierre Pertuis barrier the Chasseral and Montoz folds continue, separated by the narrow strip of Tertiary in the Péry syncline (Fig. 3), an equivalent of the St.Imier syncline (Fig. 8). The Tertiary sediments finally disappear at Bürenschwängli (Fig. 3), where in Atlas sheet Büren (Antenen et al. 2004) the Kimmeridgean Reuchenette formation enigmatically

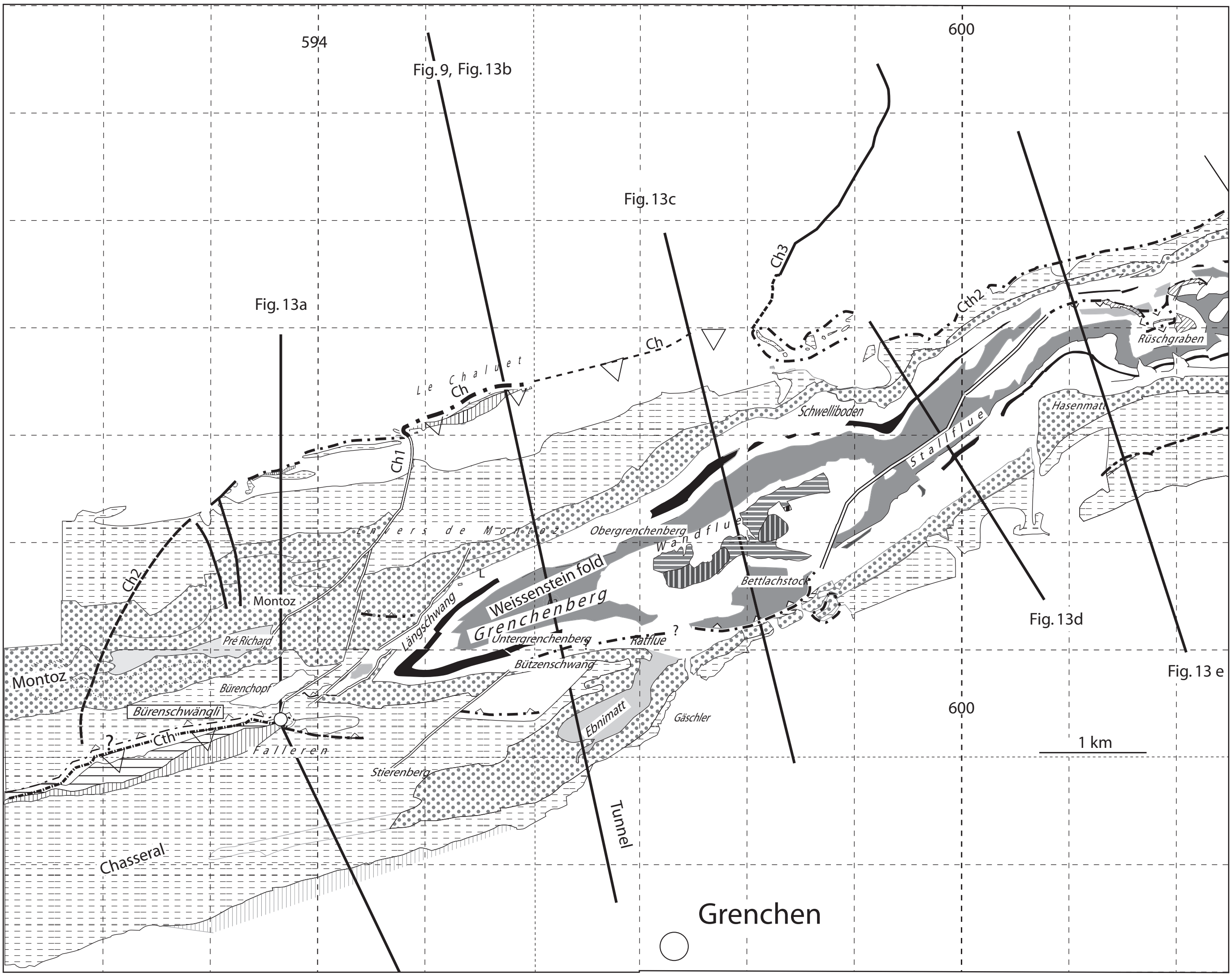
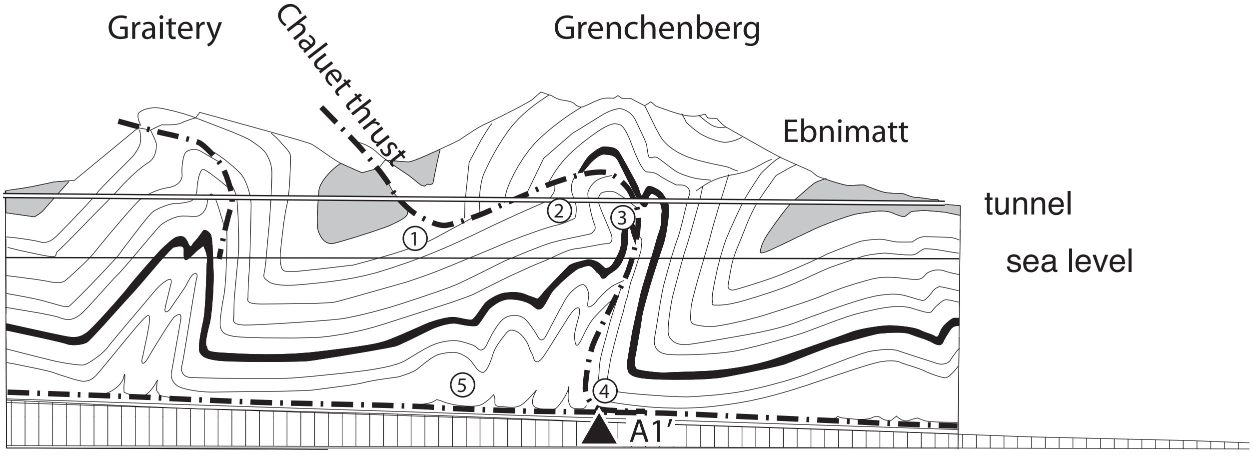


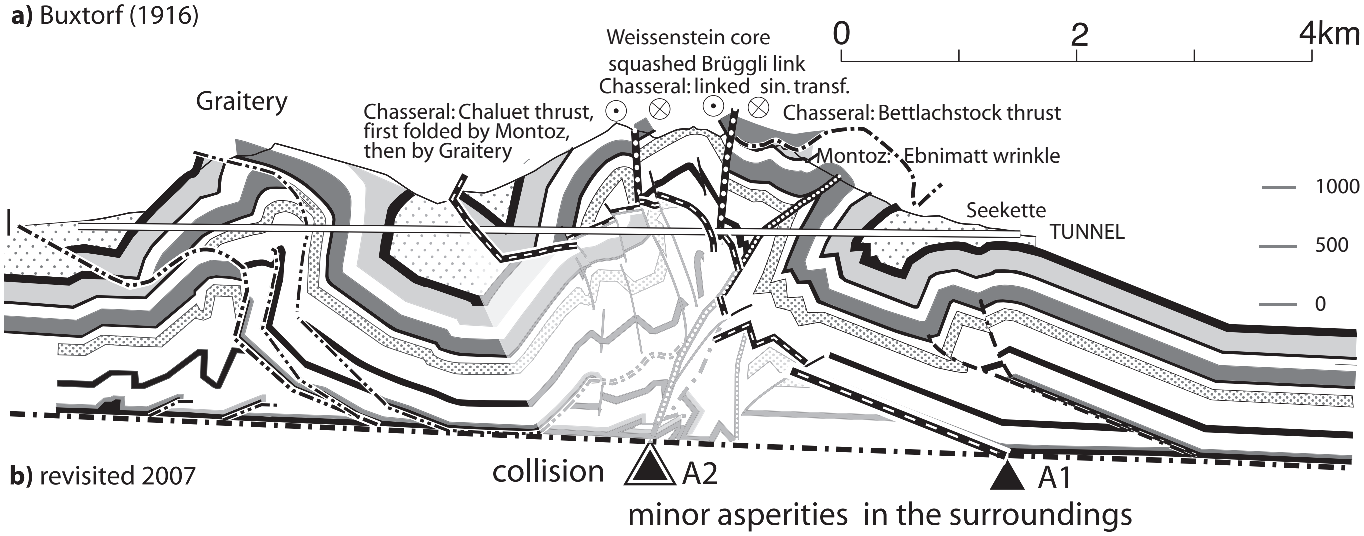
Fig. 8. Simplified map of the Grenchenberg complex, compiled on the basis of Pfirter et al. (1996), Antenen et al. (2004) and Aufranc (personal communication 2005). Black with white ruling: lower Liassic; gray with horizontal white ruling: Opalinus shales; gray: Hauptrogenstein; black: Birmenstorf beds; light gray: Effingen beds of the Ebnimatt and Pré Richard brachyanticlines; dots: "Sequanian"; dashes: Kimmeridgian; vertical ruling: Portlandian (Tithonian) and Cretaceous; wide horizontal ruling: Tertiary; light gray with white vertical ruling: wrinkles of the Stierenberg area; heavy lines with teeth: important thrusts; black lines with white cores: tranpressional faults; Cth: Chasseral thrust; Ch1, Ch2: conjectured Chaluet-Chasseral connections; Ch: Chaluet thrust; L: Längschwang farm.

crosses over from the Chasseral to the Montoz fold. Such an undisturbed cross-over, however, is contradicted not only by the default assumptions but also by the data of the Grenchenberg tunnel (Buxtorf 1916), where the Montoz strata below the Chaluet thrust and the Chasseral strata above the thrust are strictly kept apart, except that apparently a certain mass transfer took place along the Pré Richard-Ebnimatt belt of brachyanticlines (see below and Fig. 9, 10, 11, and, particularly, Fig. 12). These findings, in turn, support the above interpretation of the Pierre Pertuis barrier.

Besides the Bürenschwängli enigma, the Grenchenberg complex contains a number of other special features. In Fig. 12 some of these features have been isolated. They consist of two groups. The first one comprises the Ebnimatt fold (E) and a series of wrinkles in the upper Jurassic extending as far as the brachyanticline of Pré Richard NW of Bürenschwängli. The second one is principally composed of the Bettlachstock backthrust (Fig. 12) and a series of sinistral transfer faults. There is considerable latitude in the interpretation of some mapped features (maps are not collections of observational facts but interpretations- including erroneous ones- based on them; to quote a colleague: "All maps are wrong, but some are wronger than others").



a) Buxtorf (1916)



b) revisited 2007

Fig. 9. The Grenchenberg tunnel profile after Buxtorf (1916) and according to this work. A1 is the conjectured anchor point at the base of the Chasseral thrust in profile (b), A1' is at the base of the thrust in Buxtorf's interpretation in profile (a); A2 is a possible anchor point at the projected base of the Ebnimatt wrinkle in the Montoz domain. Explanations in the text.

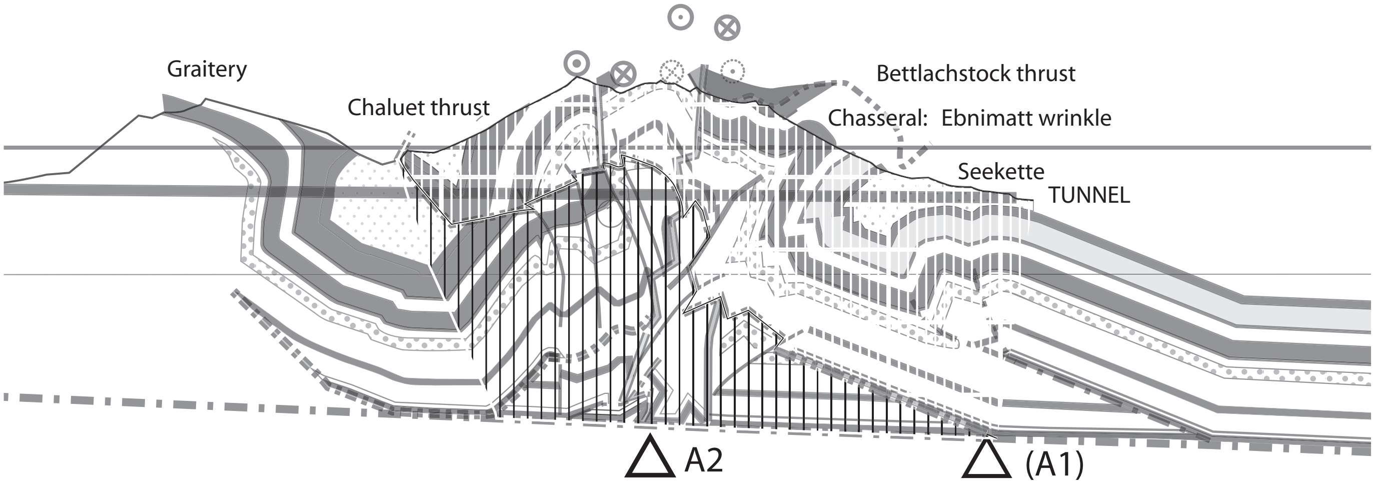
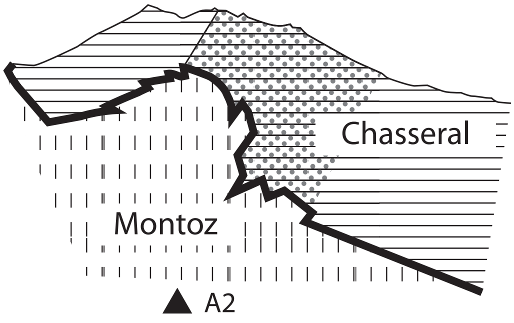
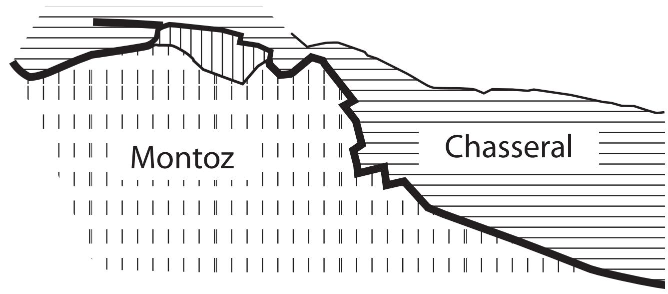


Fig. 10. The Grenchenberg collision: Structural levels. Black ruling: main part of Montoz; white ruling: originally Chasseral part. The shortening of the Chasseral domain due to deformation by the Montoz fold and the Ebnimatt-Pré Richard belt are a part of Montoz stage shortening. Explanations in the text.



b) Tunnel: Montoz: axially plunging



a) Bürenschwängli: Montoz emerging

Fig. 11. Grenchenberg collision – axial plunge of Montoz from profile (a) to profile (b) of Fig. 13. Vertically ruled: Possile subsidiary sliver of Chasseral mass; dotted: domain of mass transfer from the Montoz to the Chasseral-Weissenstein entity by the Ebnimatt-Pré Richard belt of brachynticlines. Explanations in the text.

Two such interpretations, that were disregarded in the published maps, concern the extent of the Bettlachstock backthrust and its connection with lateral sinistral strike-slip faults. The problem is evident in sheet Moutier (Pfirter et al. 1994), where in the middle Jurassic of the Weissenstein fold the south limb is clearly sinistrally displaced (at "Brüggli" in Fig. 12), the Bettlachstock backthrust ending at the postulated transfer fault. This transfer fault heads toward the fold axis of the Stallflue structure, a very anomalous segment of the Weissenstein fold (compare Fig. 13, profile (d)): Its strike is NNE, the core is exceptionally narrow, the two limbs abruptly abut against each other, at its northern end it hooks up with the Rüschgraben thrust. All of these peculiarities point to the existence of a transfer fault as shown in Fig. 12. More problematic is the southwestern end of the backthrust, where it enters the Pré Richard-Ebnimatt belt of wrinkles. A possible pro tempore interpretation is that in the Stierenberg area there is a superposition of Montoz structures (the belt of wrinkles) and the earlier Chasseral stage structures (the faults and backthrusts) As to the belt of wrinkles, the map permits several interpretations, the most promising one being that it provided a dextral mass transfer from the Montoz to the Chasseral units, thereby simultaneously contributing to the emergence of the Weissenstein fold and the decline of the axially plunging Montoz fold (Fig. 11).

Three approaches towards deciphering Grenchenberg kinematics

The first approach towards deciphering Grenchenberg kinematics consists in trying to project the Chaluet thrust (Ch in Fig. 8, 12), as revealed by the Grenchenberg tunnel (Fig. 9), to the west. Inasmuch as the Chaluet thrust to all appearances roots in the Chasseral domain, that area above the thrust ought to be attributed to the Chasseral unit. It stands to reason that the folded unit beneath, which to the west passes into the north limb of the Montoz fold, is a part of the younger Montoz structure. However, the Montoz fold emerges in the Bürenschwängli area, and the Chaluet thrust on its top ought to emerge there too. Yet, no such emerging thrust appears in the published maps.

On the other hand, the front of the Chaluet thrust (Ch in Fig. 8, 12) in Pfirter et al. (1994) is kinked immediately west of the Chaluet syncline ("K" in Fig. 12), bending into a SSW trending fault (Ch1 in Fig. 8, 12). This is the first manifestation of a borderline separating the Chasseral and Montoz units. Significantly, it heads towards the Bürenschwängli triple point, although in the maps the connection is merely suggested by fragments of little faults. In Fig. 12a tentative conjectural connnection is shown. At Bürenschwängli it joins the postulated Chasseral thrust (Cth). The simplest explanation for this geometry would seem to be an initial sinistral transfer link within the Chasseral thrust, folded first by the Chasseral fold and subsequently again by the Montoz fold.

However, west of of fault Ch1 there are other faults – particularly the one labeled "Ch2" in Fig. 12 – taking off from the northern front of the Montoz range and crossing it towards the merely fractionally exposed south limb, which is steep to overturned. These steep dips are interpreted as an indication of a possible backthrust in Atlas sheet Büren a.A. (Antenen et al. 2004). However, an altogether different interpretation is shown in Fig. 13a, where, at Bürenschwängli (framed area) the Chasseral thrust is synclinally folded by the south limb of the Montoz fold. That this is no outlandish speculation is demonstrated in the Grenchenberg tunnel profile (Fig. 9), where the front of the Chasseral thrust is folded by the south-limb of the adjacent Graitery fold.

With this insight in mind, the tectonics of the Bürenschwängli area appears in a new light. An essential part of the Péry syncline belongs to the hanging wall of the Chasseral thrust, in exact analogy to the Chaluet syncline in the hanging wall of the Chaluet thrust, which, because of the sinistral Ch1 transfer, was transported into the domain of the younger Graitery fold and there was infolded by that fold.

As to the Ch2 fault (Fig. 12), a possible interpretation is that the Chasseral thrust was split into a main branch (Ch1) and an accessory branch (Ch2) in the cluster of asperities in the Grenchenberg area (compare Fig. 11; also see Laubscher 2008b, where at the Envelier cluster of asperities a number of sinistral transfer faults affect the Passwang thrust).

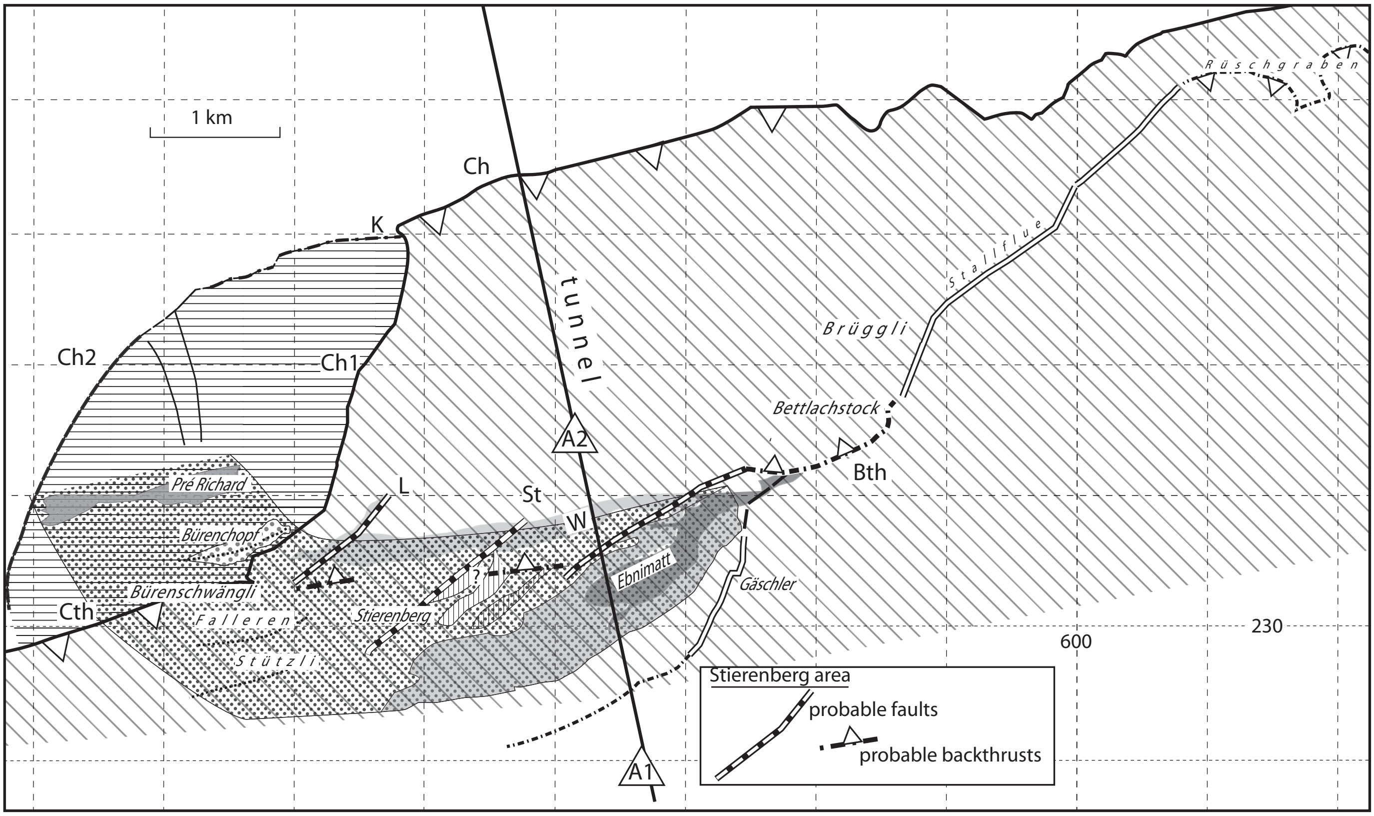


Fig. 12. Map view of Chasseral stage sinistral transfer boundaries (the main Chasseral unit is obliquely ruled), the probably Chasseral stage Stallflue transpression and of Montoz stage Ebnimatt-Pré Richard wrinkles (dotted). Dark gray: Effingen beds of the Ebnimatt and Pré Richard brachyanticlines; light gray: lower "Sequanian" of the Ebnimatt wrinkle and the south limb (W) of the emerging Weissenstein fold; L = Längschwang fault; St = Stierenberg fault -the faults and backthrusts of the Stierenberg area are not in Antenen et al. (2004), but revisions by Aufranc and inspection by Aufranc and the author revealed that the area is a complex of faults and folded backthrusts; Ch = Chaluet thrust; Ch1 = main sinistral boundary fault of the Chasseral thrust (Cth), taking off at "K"; Ch2 = possible subsidiary sinistral boundary fault of the Chasseral thrust; Bth = Bettlachstock backthrust; double line = sinistral transfer fault Bettlachstock-Rüschgraben.

A second approach to the problem of Grenchenberg kinematics attempts to utilize the concept of fold collision already applied to the Pierre Pertuis problem. This approach promises some further insights because, as shown in Fig. 9, the Chasseral unit overrode the domain of the future Montoz unit – a clear case for collision. According to the schematic Fig. 7 it ought to be closely connected with an anchor in the Montoz stucture that locally held up propagation of décollement (A2 in Fig. 10). Are there symptoms of that, comparable to those of the Pierre Pertuis collision? The author thinks there are. The narrow Ebnimatt fold (Fig. 10), so conspicuous in Buxtorf's tunnel profile (Fig. 9), in map view (Fig. 8) is clearly associated with the area of collision. Moreover, there is a tale-telling belt of, generally, dextrally arranged wrinkles (Fig. 12), that connects it with the Bürenschwängli-Pré Richard area. Would the tentative assumption of an anchor at A2 in Fig. 10 and Fig. 12 help solve some of the problems of Grenchenberg kinematics? The author thinks it would indeed: In these figures, the Ebnimatt fold is found to be in a backfold position with respect to A2. The belt of brachyanticlines may be equated, according to Fig. 5, with the dextrally transpressive western flank of the anchor domain. From E to W it traverses the Chasseral fold, passing into the emerging Montoz fold. In Fig. 10, A2 is located at the décollement horizon, where asperities ought to be found, although displaced into an allochthonous position; it is contained within the Montoz domain. It would appear, therefore, that it is a feature of the Montoz stage. Although issuing from the Montoz domain, it also affected the overriding Chasseral thrust mass, adding to its area in Fig. 11. In that figure it may be seen, that it apparently transferred mass from the axially plunging Montoz to the axially rising Weissenstein unit. Fig. 14 is a highly simplified schematic of this mass transfer in map view.

A third approach to Grenchenberg kinematics is that of linked sinistral transfer faults resulting in an inflation structure (Fig. 15; compare Laubscher 2008b). The published maps contain a number of small cross faults, but more significant ones may be interpreted and postulated on the basis of the maps as shown in Fig. 8, Fig. 12 and Fig. 15. There is a noticeable similarity beetween the inflation structures, associated with linked strike-slip faults, and the simple experiment by

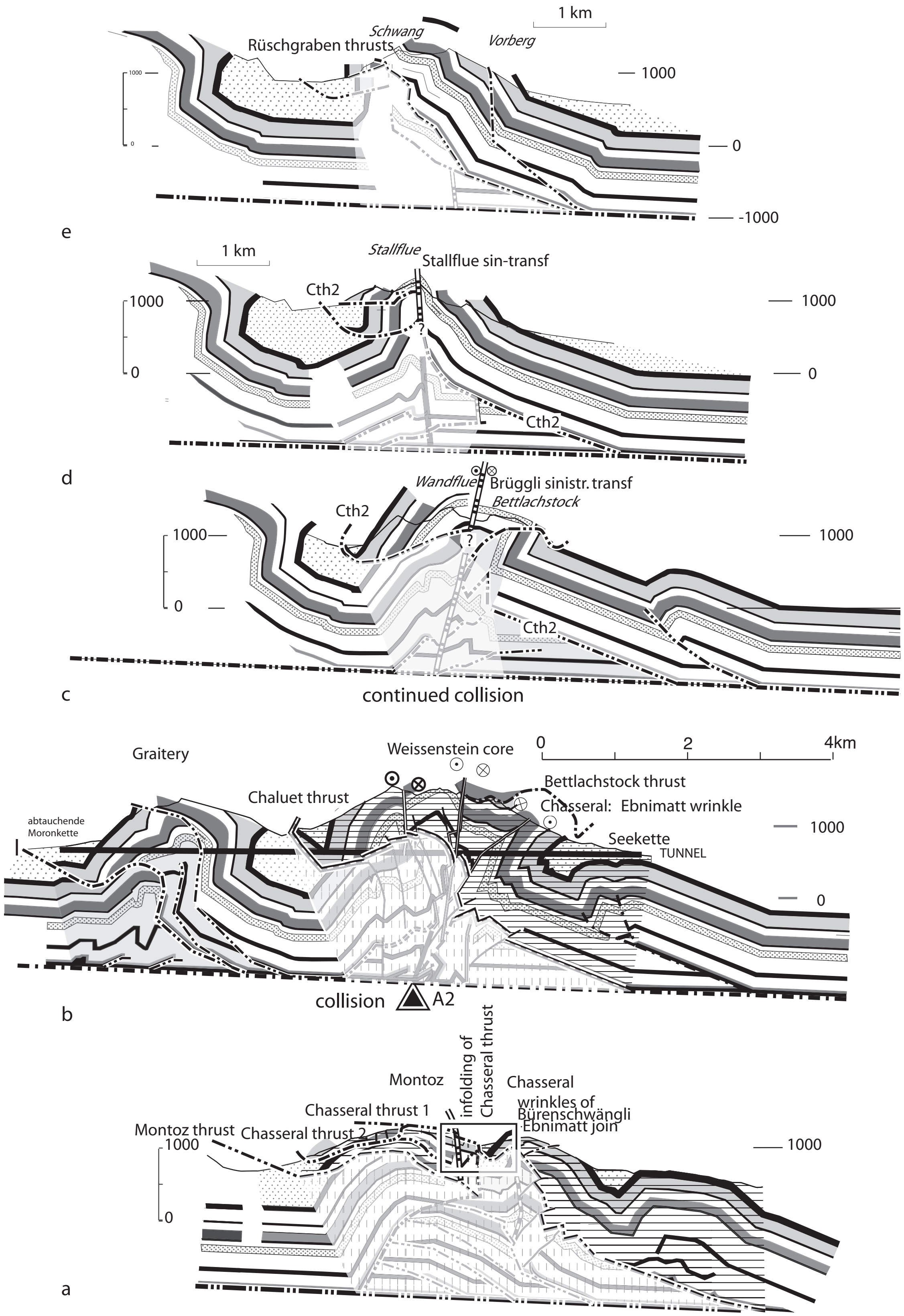


Fig. 13. Profile series from Bürenschwängli to Rüschgraben. Tracks in Fig. 8. In Profile (a) an altogether different core structure is shown, illustrating the conclusions of Laubscher (2003b) that the core can only be area balanced as an entity, the details being rather arbitrary. Explanations in the text.

Richard et al. (1995), which features a single pair of linked and sinistrally moved strike-slip faults (for instance, compare the Envelier inflation structure (E in Fig. 1), discussed in Laubscher (2008b), although there several linked transpressive faults were at work). In the Grenchenberg inflated domain too a number of linked strike-slip faults were probably active, but two of them seem to be of particular importance (Fig. 12). The preeminent one is the Brüggli-Stallflue fault in the southeast, which unfortunately is not shown in the published maps but may be postulated on strong grounds as discussed before; the northwestern one is near the western margin of the Chasseral thrust Ch1 (Fig 12), or perhaps at the Längschwang cross-trend ("L" in Fig. 12, Fig. 15). The inflation structure includes the Chaluet and Bettlachstock thrusts (Fig. 16) – both Chasseral features-, and is therefore considered a Chasseral stage structure. The linked transpressive faults would have to issue from the décollement layer and would only in parts reach the surface, particularly a deeply hidden possible thrust at the link- a situation not unlike the one shown by Richard et al. (1995). It goes without saying that this extremely simplified model is only an approximation to that partial aspect of Grenchenberg kinematics.

This complex overlap of modes of deformation occurs on the allochthonous Schwarzwald line (SL1 in Figs. 1 and 2) and there seems to issue from a cluster of asperities such as those illustrated in Fig. 6.

From map-view kinematics back to cross sections

The interpretation of the mapping results should be kinematically compatible in 3D. The above discussion aims at that goal. In the author's view, the pro tempore insights may be summed up as follows (cross-sections in Fig. 16; for the map view consult Fig. 12). The Grenchenberg is a collisional structure. The early Chasseral thrust was held up by an anchor or anchors (symbolized by "A1") that triggered sinistral transfer faults leading to a major displacement of the thrust and to inflation due to linking of transpressional features. Other, more northerly anchors (symbolized by "A2") held up the propagation of décollement during the subsequent Montoz stage, resulting in collision of the Chasseral and Montoz structures. This collision was most severe in the Grenchenberg area, but to a minor degree persisted to the west all along the Péry syncline. Around A2 the typical flank deformations developed, particularly a belt of wrinkles in its western flank. They issued from the décollement layer in the Montoz domain but also affected the hanging wall of the Chasseral thrust. Very late additions to the Grenchenberg entity affected all the above units, e.g. the kink band in the south limb responsible for the overturned south limb of the Ebnimatt part of the Grenchenberg complex; it resulted in the infolding of the Bettlachstock backthrust and unforeseeable contortions in the core. Likewise, the late kinkband in the south limb of the Graitery fold, which followed the Montoz stage, produced the synclinal infolding of the Chaluet part of the Chasseral thrust.

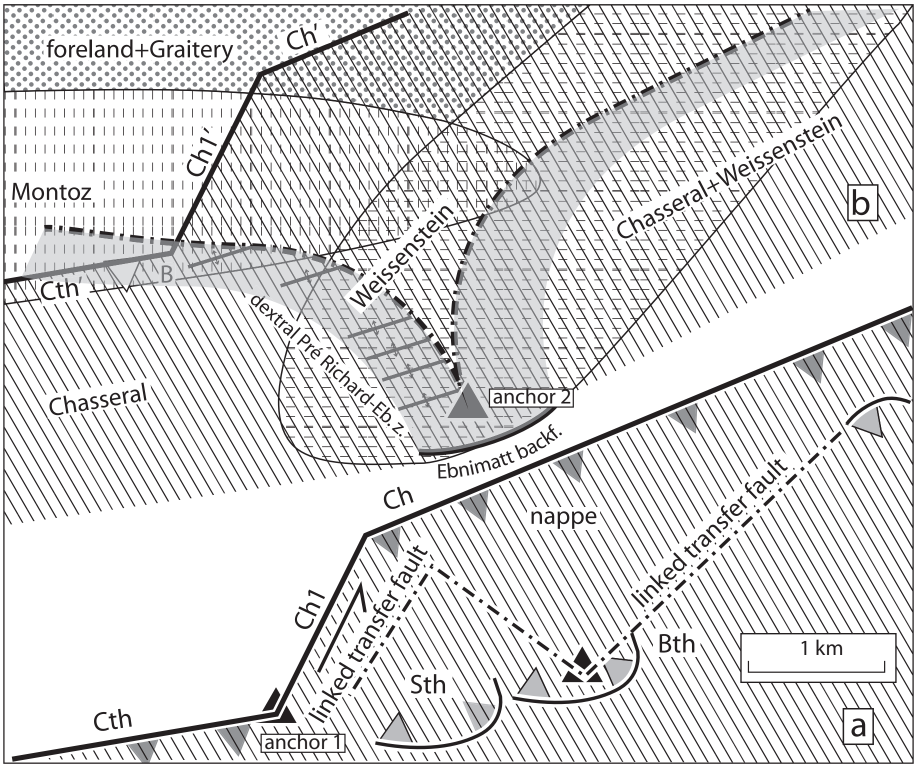


Fig. 14. Schematic of the Grenchenberg collision. (a) Chasseral stage. Abbreviations as in Fig. 12, except Sth = Stierenberg backthrusts, Bth = Bettlachstock backthrust. (b) Montoz stage. The primes refer to the displaced Chasseral thrust system. The highly simplified elements are: The Montoz fold (vertical dashes), plunging to the east; the Weissenstein fold (horizontal dashes), plunging to the west; they are linked by the Pré Richard-Ebniflue zone of dextral transfer (suggested by en échelon brachyanticlines, shaded); the Chasseral fold, highly deformed by these elements. In particular the front of the Chasseral thrust is infolded in the west (Cth') by the south limb of the Montoz fold, in the center (Ch1') by the main part of the Montoz fold, and in the north (Ch') by the south limb of the Graitery fold.

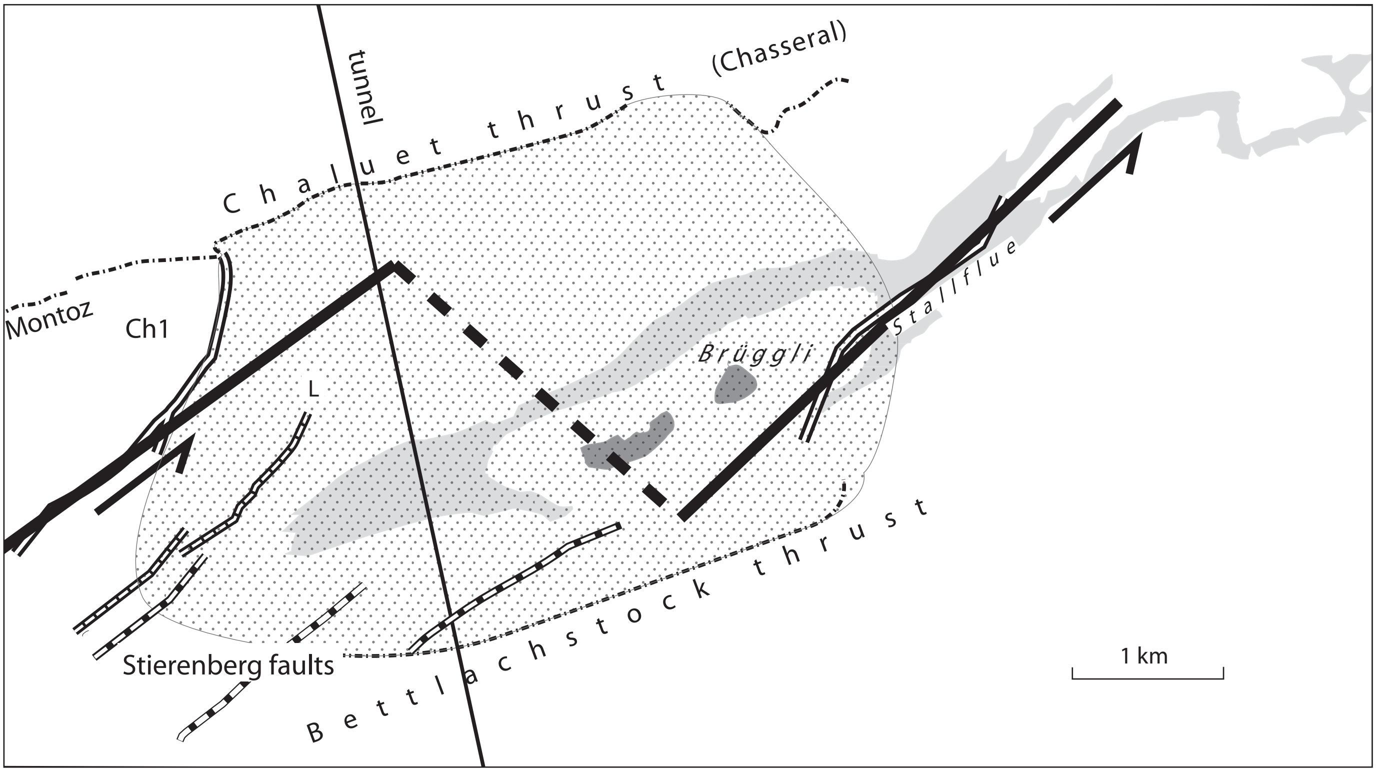


Fig. 15. The Grenchenberg collision, Chasseral stage: superposition of putative linked sinistral transpression. Bold: The simplest model of linked sinistral transpression (the dashed link would not reach the surface as a thrust); double lines: Faults with a probable sinistral transfer function; light gray: Hauptrogenstein; dark gray: Lower Liassic; stippled: Main area affected by linked transfer faults. Explanations in the text.

This succession of deformations is shown in the cross-sections of Fig. 16 (see caption). Of particular interest is Fig. 16e, where the dotted area signifies the addition by dextral transfer of material from the axially plunging Montoz structure (Fig. 11) to the axially rising Weissenstein structure (compare Fig. 8). This process, abounding in the Jura, had been known as "Kernaustausch", meaning the gradual passage from one fold in an anticlinorium into another fold of the anticlinorium. So far as the author can see, the above explanation as a transfer of material by a dextral zone of brachyanticlines, based on actual observation, is new. Obviously, the wrinkles involved in the process have often been underestimated. In the particular case of the joining of three major anticlines in the Grenchenberg structure it may explain why at this triple junction the Weissenstein fold grows at the expense of the Montoz and Chasseral folds which disappear.

Grenchenberg kinematics and the tunnel profile (Buxtorf 1916)

Fig. 9 is an attempt at constructing a cross-section that respects map-view kinematics. As the Grenchenberg tunnel passes through this area, Buxtorf's (1916) 2D kinematics need to be adapted to the 3D requirements, and this adaptation too is applied to the cross-section Fig. 9. Although one may be inclined to accept Buxtorf's picture as factual, it ought to be borne in mind that it represents a data set filtered to accommodate 2D kinematics. This becomes rather obvious when attention is focussed on the weaker points of his cross section, as done in Fig. 9a (see figure caption). While accepting all the formation contacts observed in the tunnel but attributing drastic variations in formation thickness to brittle (faulting) rather than to ductile deformation, adjustment to the 3D requirements is feasible (Fig. 9b).

Fig. 9a, preoccupied only with two dimensions, looks admittedly more elegant than Fig. 9b, which attempts to incorporate the more complex or even somewhat chaotic and therefore less elegant 3D collisional kinematics. Where would Buxtorf's profile have to be modified to conform to the latter? A series of points numbered in Fig. 9a have been singled out for discussion.

Beginning in the north with point 1 at the synclinal axis of the Chaluet thrust, we notice that there is a problem with the coordination of folding in the hanging and the footwall of the thrust. While the Chaluet syncline in the hanging wall is bottomed by a thrust that was folded simultaneously with the footwall, the latter is not shown as folded harmoniously, its synclinal hinge being offset some distance to the north, to the very bottom hinge of the south limb of the Graitery fold. As a

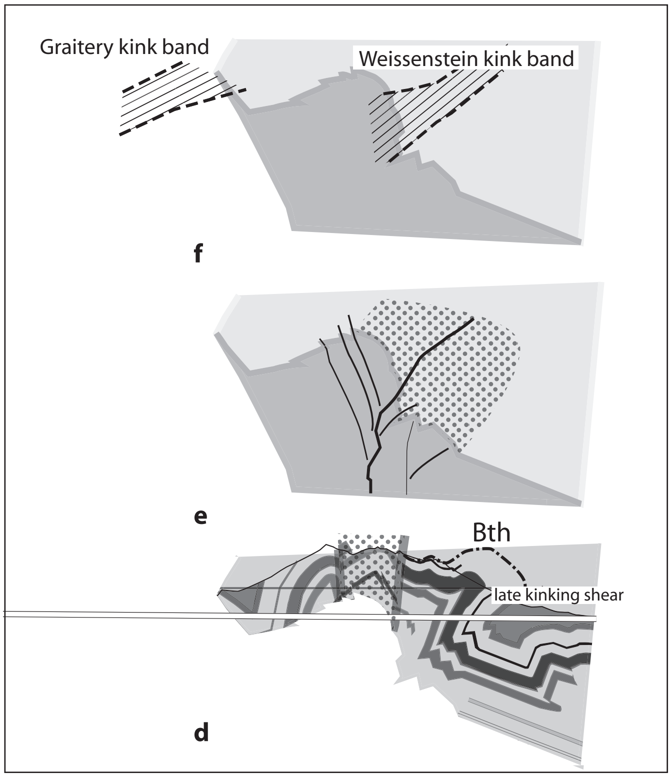
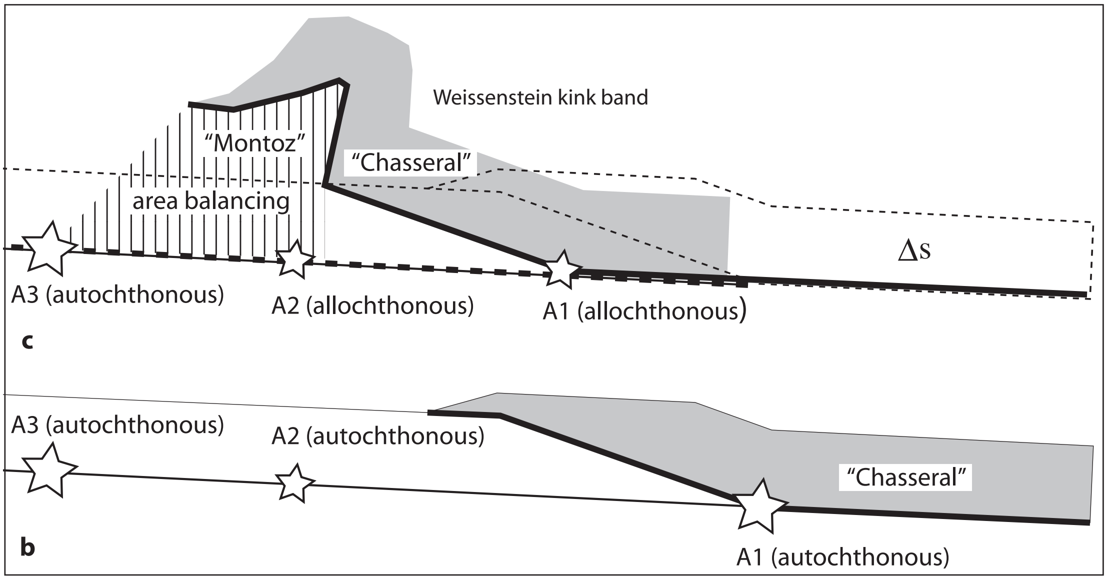
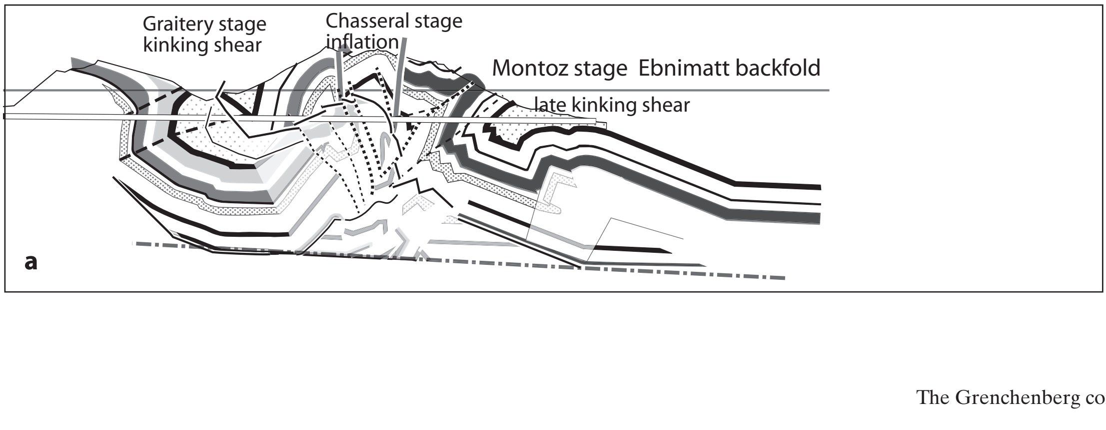


Fig. 16. Collisional stages at the Grenchenberg (tunnel profile). (a) The revised tunnel profile; matted: uncertain core structure. (b), (c): Schematic of the development with the proposed asperities (asterisks) converted to anchor points: A1 = Chasseral; A2 = Montoz; A3 = Graitery. (b) The initial thrust and ramp fold of the "Chasseral" structure; schematic model after Laubscher (2003b); Δs = Montoz" stage contraction. Quotation marks signify that the schematic profiles are copied from a cross-section several km farther east. (c) Development of the Montoz structure (ruled) at A2. The Chasseral thrust is folded by the Montoz structure (not shown is the 3D material transfer by the Pré Richard-Ebnimatt belt shown in Fig. 16e and discussed in the text); schematic model after Laubscher (2003b). (d) to (f): Special features acquired in the course of the fold buildup, shown in present tectonic environment. (d) Chasseral stage: linked sinistral transfer faults and the inflation of the Grenchenberg core (dotted). (e) The brachyanticlines of the western flank of A2. The branches of the flower structures, though originating in the Montoz core, penetrate into the Chasseral domain, deforming it and transferring mass into it (dotted). (f) Addition of the late kink bands (ruled in the direction of bedding plane shearing), further deforming the Grenchenberg structure. The south-limb of the Graitery fold causes the Chaluet thrust to be synclinally folded.





consequence, the Jurassic of the footwall south of the Chaluet hinge is represented as paralleling the thrust, while in the hanging wall it is cut off obliquely by the thrust as expected. All of this is not contained in the tunnel data but is the result of a rather doubtful extrapolation. Indeed, as has been pointed out above, the synclinal infolding of the Chaluet thrust is the result of folding during the Graitery stage and should conform to the latter. May it be noted in passing that Buxtorf believed that the Graitery fold had existed before the Grenchenberg sructure (out of sequence) and that it had been this obstacle that effected the deformation of the thrust; however, this construction does neither conform with regional kinematics nor does it produce acceptable results.

The really important questions, however, turn up in the core of the fold (points 2 and 3). Buxtorf obviously weighed the observations in favor of folding, e.g. by plastic thinning in the overturned top of the north limb of the footwall. Clearly, at such points there is room for faulting – considering the cold near-surface brittle conditions for deformation – favored by the 3D kinematics outlined in this article. In the profile Fig. 9b this consideration enters the picture. In particular, the Ebnimatt brachyanticline is treated as a sort of flower structure, similar to the brachyanticlines of the Pierre Pertuis anchor (Fig. 4). As the map evidence favors a late, Montoz stage origin, it is shown as distorting and even chopping up the Chasseral thrust.

Between points 3 and 4 in Fig. 9a Buxtorf extrapolated the overturned south limb down to the very décollement horizon, although this is not a very probable solution on two counts. Firstly, the accumulation of Triassic evaporites at point 5 and their elimination at point 4, though appealing to intuition, looks arbitrarily exaggerated when weighed against the data from localities where the Triassic evaporites are exposed, e.g. the Hauenstein base tunnel (Buxtorf 1916) and the "Muschelkalk Schuppenzone" surrounding it (e.g. Mühlberg 1914a, 1915; Hauber 1960; Laubscher 2005); and secondly, because the superimposition of the overall Grenchenberg fold on the initial ramp fold required a splitting of the nappe motion between continued thrusting on the initial fault and simultaneous folding of the footwall, which is hardly conceivable for the amount of overturning shown. This issue has been discussed in great detail by Laubscher (2003b), and the computer-assisted forward kinematics have been inserted as cross-sctions (b) and (c) in Fig. 16.

Fig. 9b instead prefers a solution that reduces the overturned south limb to a mere kink band (default structure), leaving the basal part of the thrust in its original form. In doing this, one follows the rule that default structures should be preferred wherever there is not compelling evidence to the contrary. On the other hand, the early component of linked strike-slip (in extreme simplification represented by the Richard model), which helped the uplift of the core of the Weissenstein fold, should be respected at least schematically. This may be achieved by inserting two steep faults in the Chasseral domain that frame the core (Fig. 16d), although they may end blindly before reaching the surface in the Effingen beds.

Finally, upon collision (Fig. 16e, f), the belt of brachyanticlinal wrinkles (Fig. 12), which developed around anchor 2 in the Montoz domain but also affected the Chasseral domain, somehow ought to be included. This mainly concerns the most important of these brachyanticlines, the Ebnimatt one, which is represented schematically as a flower structure; with its branch faults it severely dissects the Chasseral thrust. The same effect is also attributed to minor faults of the same belt.

Finally (Fig. 16c, f), the customary late kink bands add other severe deformations, first the one in the south limb of the Chasseral fold, and thereafter the one in the south limb of the Graitery fold, which folded the Chaluet thrust synclinally.

The above critical review of Buxtorf's 2D tunnel profile brought to the fore the difficulty of incorporating in a cross-section the kinematics as tentatively organized in map view. Some remaining rather tantalizing questions turn around the problem where faults are hidden that originate at the basal décollement and make it to the surface only outside the cross-section. Although these issues resist accurate analysis, they do not require modifications of the fundamental default assumptions.

To sum up, the observational data in the tunnel may be reconciled with the current map data and the inferred 3D kinematics. The difference between profiles (a) and (b) in Fig. 9 are an illustration for the history of tectonics- how a fundamental idea was updated in a number of steps. The original décollement model of Buxtorf (1907) is still valid, although concepts concerning its details have changed in the intervening 100 years, influencing the view of how the Jura came into being.

The origin of the Pierre Pertuis and Grenchenberg asperities (Fig. 2)

The Pierre Pertuis anchor (PP) is connected through a series of striking anomalies in various ranges with the Vicques Line (ViL1, allochthonous position) of Liniger (1925) (compare Pfirter et al. 1996), an Eocene-Oligocene structure emanating from the Rhine Graben. Even more striking are the anomalies which tie the Grenchenberg anchor domain (Gre) to the Rheintal Flexure at the eastern border of the Rhine Graben, the Schwarzwald Line (SL1, allochthonous position) of Steinmann (1892). The amount of allochthony may be estimated by using the kinematic model of Laubscher (1965) as outlined in Laubscher (2008b), which, as mentioned above, still proves useful. The resulting autochthonous positions of these lines in the basement (ViL, SL) have a plausible, rather straight NNE strike. The amount of allochthony in the southern ranges is remarkable, exceeding 10 km.

The nature of the Vicques and Schwarzwald lines may be inferred from a number of data. The "Schwarzwald line" is both in its northern part ("Rheintal Flexure") and, where it enters the folded Jura ("Schäll Flexure"), a rather complex Eocene-Oligocene extensional feature, including both normal faults and flexures, that was reactivated in the Early Miocene by sinistral transpression (Laubscher 2003a). Some data reveal that, particularly where intersecting with other paleolines, complex

3D structures developed, e.g. where the Rheintal flexure intersects the Adlerhof and the Landskron trend (Fig. 2 and Koch et al. 1936, Bitterli-Brunner et al. 1984; Laubscher 1998, 2003a). One would surmise that preferentially at similarly preformed structures extended anchor domains such as the Grenchenberg anchor domain would evolve, whereas along other segments of the lines rather individual anchor points would turn up (e.g. Laubscher 2008a). What these lines really are at depth can only be conjectured from their current allochthonous and badly deformed appearance. One such conjecture would be that the Grenchenberg domain originated where the Schwarzwald line for one reason or another split up into short segments of faults or flexures in a sinistrally transpressional arrangement. As to the Pierre Pertuis anchor we note that further to the Vicques line there is a northwest striking dextral line that transcends the Montoz fold, heading into the western border (Orange brachyanticline) of the Tavannes and the Bellelay synclines (Fig. 3).

The Weissenstein fold east of the Grenchenberg

As shown in Fig. 14, the Weissenstein fold originates in the Grenchenberg complex, incorporating in its south limb Chasseral elements and in its core Montoz elements. However, what happens to the Chaluet thrust? Fig. 8 reveals that in the area of Schwelliboden, where the inflation of the Grenchenberg core ends, severe disturbances in the north limb take place. The eastward projection of the Chaluet thrust does not seem to exist beyond this point. Rather. as may be gathered from Pfirter et al. (1994), a new NNE-striking fault zone enters the south limb of the Graitery range and initiates the Crémines inflation in that range (“Cr” in Fig. 2). Apparently, the early Chaluet thrust here followed the Schwarzwald line (“Ch3” in Fig. 8 and “SL1” in Fig. 2). This may be taken as an indication that east of Schwelliboden a new thrust developed in the Weissenstein range (Cth2). Unfortunately, it is not clear, what role the Bettlachstock-Rüschgraben transfer fault played in this new configuration, particularly as regards the Weissenstein core. However, this and the Crémines inflation structure are issues to be treated in another analysis and synthesis.

Conclusion

The Grenchenberg problem, even within the analysis of simplified, semi-quantitative kinematics attempted in this paper, turns out to be extremely hard to solve; it is a true conundrum. On the other hand, the reexamination of the Chasseral-Montoz-Grenchenberg-Weissenstein complex is apt to demonstrate that the décollement nappe model, upgraded with empirically inferred logical conceptions, may be able to cope with rather intractable problems. The conceptions used in this paper are: Décollement proceeded in sequence from south to north; staircase thrusts and attending ramp-folds were initial structures that were deformed by subsequent folding; asperities in the décollement layer functioned as anchor points, temporarily holding up the progression of décollement; collision of folds developed at some anchor points; structures were locally inflated, particularly where several anchor points form an anchor domain; transpressive structures are often the site of linked strike-slip and transpressional faults. These are default conceptions in the sense that they should be applied automatically unless the data require a different solution. Applying them to Grenchenberg kinematics results in a comprehensive 3D model that demands modification of Buxtorf’s classical 2D tunnel profile although remaining firmly within the frame of the original décollement model of Buxtorf (1907). In this view, the Grenchenberg complex is the domain where the Chasseral and the Montoz folds collided, and where in this collision dextral transfer of material from the Montoz to the Chasseral fold resulted in the disappearance of the former and the transition of the latter into the emerging Weissenstein fold.

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