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The kinematic evolution of a classical Jura fold: a reinterpretation based on 3-dimensional balancing techniques (Weissenstein Anticline, Jura Mountains, Switzerland)

By Thomas Bitterli[1])

ABSTRACT

Until recently, the southernmost anticline (Weissenstein) of the Jura fold and thrust belt, was interpreted as a narrow, lift-off detachment fold (Jamison 1987). However, modelling its geometry and kinematics in two dimensions (balanced cross sections) and in the third dimension (block mosaic) leads to a completely different interpretation. The huge, lift-off box folds are reinterpreted as fault bend folds and fault-propagation folds. The corresponding thrusts are directed both to the north (general transport direction) and to the south. The south-vergent thrusts form a wedge system that accommodates several kilometers of shortening. The lateral change of areas with south- and north-vergent thrusts occurs along strike-slip faults. Because of their little vertical throw, the only way to estimate the displacement of these faults is to include the third dimension in kinematic modelling.

ZUSAMMENFASSUNG

Die Weissenstein-Antiklinale als südlichste Jurakette wurde bis anhin als enge, hochgepresste Kofferfalte gedeutet, welche sich direkt über dem Abscherhorizont gebildet hat («detachment fold» nach Jamison 1987). Der Versuch, die Geometrie und Kinematik in zwei Dimensionen (balancierte Profile) und in der dritten Dimension (Blockmosaik) zu modellieren, führt zu einer völlig andersgearteten Interpretation. Die riesigen, schlauchartigen Kofferfalten werden durch seichtere Rampenfalten und Falten über Blindüberschiebungen ersetzt. Die zugehörigen Überschiebungsbahnen verlaufen sowohl gegen Norden (allgemeine Schubrichtung) als auch gegen Süden, wobei das Mittelland mehrere Kilometer weit unter die Weissenstein-Antiklinale eingespiesst ist. Der laterale Wechsel von süd- bzw. nordgerichteten Überschiebungen geschieht an Horizontalverschiebungen. Wegen der geringen, vertikalen Verstellungen lässt sich ihre kinematische Bedeutung nur mittels Einbezug der dritten Dimension in der Modellierung abschätzen.

RÉSUMÉ

L'anticlinal du Weissenstein, situé en bordure sud-est du Jura, a été jusqu'à ce jour considéré somme un étroit pli coffré, poussé vers le haut directement à partir du niveau de décollement («detachment fold» d'après Jamison 1987). Un essai de modélisation de la géométrie et de la cinématique en deux dimensions (coupes géologiques équilibrées) puis en trois dimensions (mosaïque de blocs) a conduit à une nouvelle interprétation qui diffère complètement de l'ancienne. Ainsi, les immenses plis coffrés ressemblant à des tuyaux sont remplacés par des plis liés à la présence de rampes et de chevauchements aveugles. Les vergences des chevauchements sont dirigées non seulement vers le nord (direction générale de transfert), mais aussi vers le sud. Cette dernière direction de transport met en évi-

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dence un chevauchement de quelques kilomètres de l'anticlinal du Weissenstein sur le plateau suisse. Les régions où les chevauchements ont une vergence vers le nord sont séparées des régions à vergence sud par des décrochements. Vu le faible rejet vertical de ces derniers, seule l'introduction de la troisième dimension dans la modélisation cinématique permet d'estimer l'importance du rôle des décrochements dans la genèse du pli.

Introduction

In the Jura mountains, geometric and kinematic methods such as the construction of balanced cross sections and three dimensional balancing are helpful instruments to constrain the number of kinematically viable constructions. In the absence of available seismic data, the present study applies these methods to the Weissenstein and Farisberg anticlines. The differences between the classical interpretations and the model presented here are fundamental.

Apart from the poorly known anticlines of the Molasse basin (Nagra 1988), the Weissenstein and the Farisberg anticlines are the southernmost folds of the Jura between Solothurn and Olten (Fig. 1). To the north and to the south they are both bounded by synclines. Due to Tertiary infill, the geometry of the synclines is nearly unknown. However good observation of the structure of the two anticlines is possible in the gorges of Oensingen-Balsthal (Wiedenmayer 1923, Meier 1977, Laubscher & Hauber 1982, Laubscher & Pfirter 1984), of Balsthal-Mümliswil (Meyer 1977) and in the Weissenstein-Tunnel (Buxtorf 1908). The classical interpretations propose a model of box folds that have formed directly above the décollement horizon with some subordinate north-vergent thrusts.

The present work concentrates on a 15 km by 12 km area covering the two anticlines in the Balsthal area (Fig. 1). For sake of simplicity, the results are mainly described for the Weissenstein anticline. The geometries in the Farisberg anticline are quite similar.

After a brief overview of previous studies and following the illustration of the applied methods employed in this study, two balanced cross sections are presented. They show geometries which differ completely from each other. In order to find arguments for one or the other solution, the kinematics are modelled in three dimensions. This leads to a reinterpretation of one section and consequently of the whole structure of the Weissenstein anticline.

Structure of the Weissenstein Anticline: Previous Interpretations

A series of N-S sections several kilometers west of our working area (Fig. 2) are taken from Buxtorf's work on the Weissenstein-Tunnel (Buxtorf 1908) and represent one of his first constructions of Jura sections. The extrapolation of the narrow fold on top of the Weissenstein chain and of the overturned limbs down to the décollement horizon leads to a cylindrical fold core of over 1 km height. The ductile squeezing out in the lower part and the accumulation in the upper part of the fold incorporates not only the evaporitic rocks of Middle Triassic but also large parts of the overlying limestones. In the easternmost section the fold core is even displaced southwards of at least 1 km by a backthrust. The eastward continuation of this Günsberg-backthrust is very uncertain.

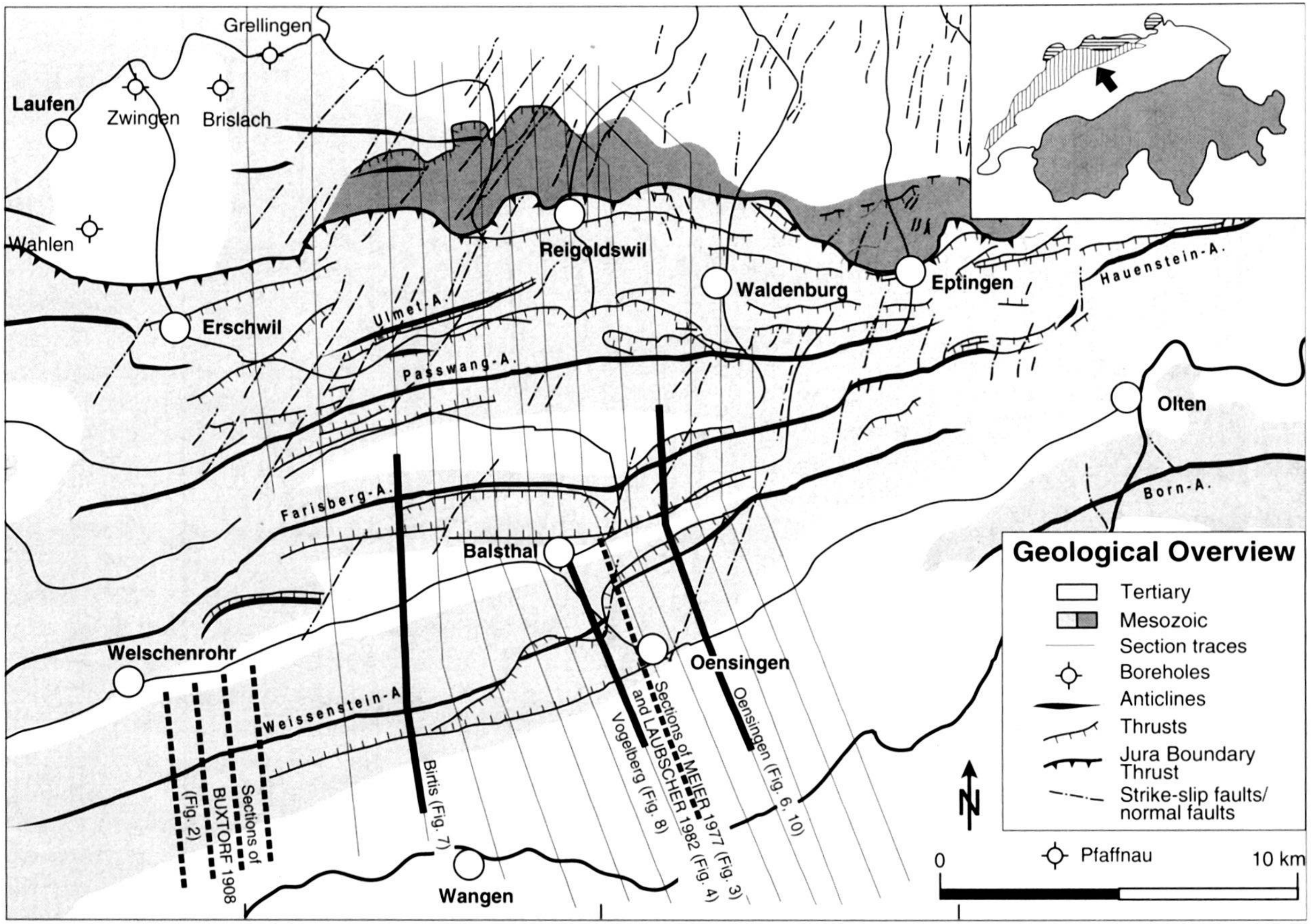


Fig. 1. Geological overview of the Folded Jura between Solothurn and Olten. The studied area contains the Weissenstein and Farisberg anticlines as well as the syncline of Balsthal (in white). The thin lines are the sections traces used for the kinematic analysis; the sections presented in this study are drawn as thick lines.

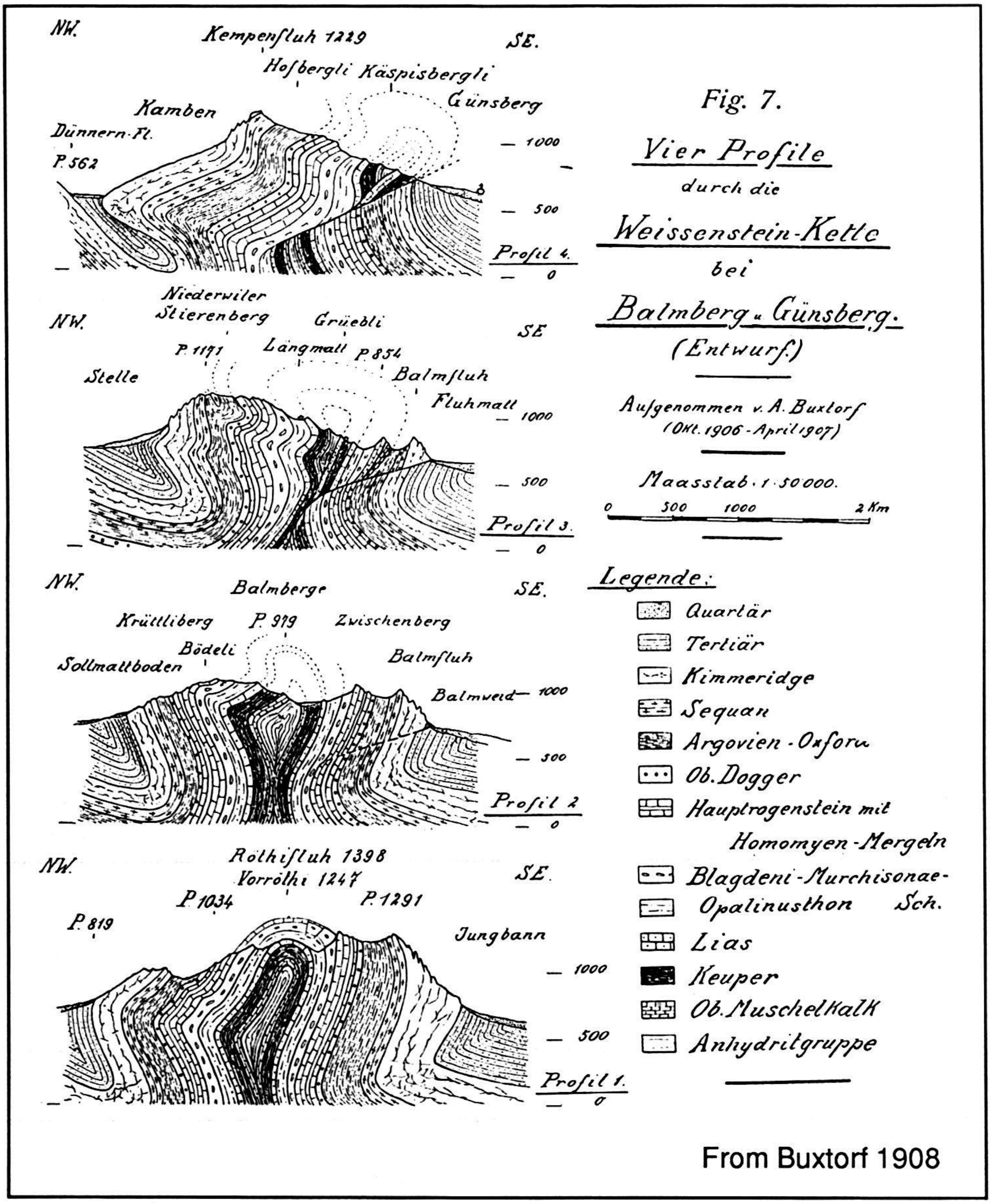


Fig. 2. Some sections of Buxtorf (1908) through the Weissenstein anticline west of the studied area. The cylindrical, squeezed-out fold core results from projecting the overturned limbs down to the décollement horizon (not shown on the sections). Note the Günsberg-backthrust in the eastern sections (upper part), interpreted as accommodating movement out of the intensively deformed fold core.

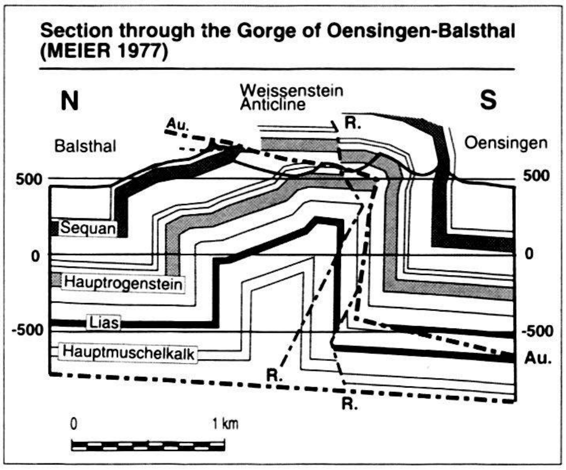


Fig. 3. Section through the Weissenstein anticline between Oensingen and Balsthal (MEIER 1977). Interpretation as typical detachment box fold by projecting down the steep southern limb and by assuming a vertical northern limb (not observed in the field). The folded Ausserberg-thrust (Au) corresponds to an older generation of thrusting. It displaces some Oligocene extensional faults (R).

The other constraint on the structure of the anticline comes from the gorge of Oensingen-Balsthal. However, WIEDENMAYER (1923) did not try to extrapolate the structure to depth. This was first attempted by MEIER (1977). His solution (Fig. 3) is a typical box fold with a steep and narrow core, but without any squeezing.

An important feature of this section is the Ausserberg-thrust with about 1 km of displacement, which is folded by the big Weissenstein box fold. This thrust strikes slightly oblique to the fold axis. To the west it disappears in the rockslide masses of the south limb before reaching the sections of Buxtorf. Its eastern termination within the north limb is not yet fully understood.

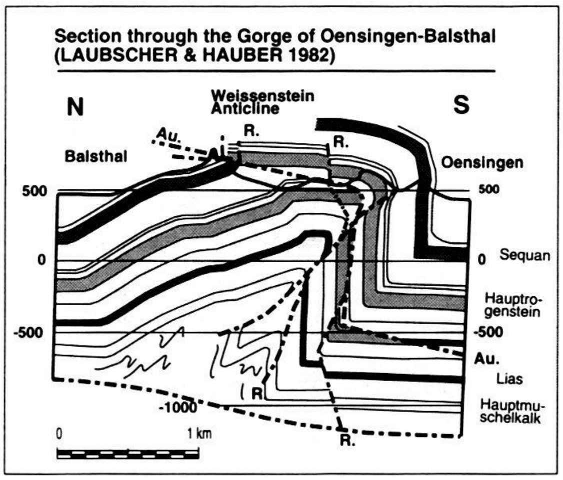


Fig. 4. Section through the Weissenstein anticline between Oensingen and Balsthal by LAUBSCHER & HAUBER (1982), who proposed a south-vergent fold above a blind backthrust.

Further proposals about the structure of the Weissenstein anticline were made by Laubscher & Hauber (1982) and Laubscher & Pfirter (1984). To explain the south-vergent fold geometry, these authors replaced the box fold by a combination of backfolds and blind backthrusts (Fig. 4).

Methods

a) Construction of balanced cross sections:

To begin with, a series of parallel cross sections spaced 1 km apart were constructed. The extrapolation proceeds not only from the surface downwards but also from the regionally estimated décollement horizon (Middle Muschelkalk evaporites, Middle Triassic) upwards. The base of the deep synclines is taken to be horizontal and to represent directly the geometry of the décollement horizon. The stratigraphic thicknesses are derived from specially constructed isopach maps of the Eastern Jura, using the available data from boreholes and stratigraphic profiles (for a summary of the stratigraphic column see the well log of Pfaffnau, Buechi et al. 1965). Except for the Upper Jurassic formations (Gygi 1969, Gygi & Persoz 1986), the lithologic units show little variation in thickness. The variations are taken into account for the balanced construction.

The deformation is commonly brittle. Except for local phenomena like pressure solution and internal shearing (e.g. in narrow fold hinges), tectonic changes in bed thicknesses can be neglected in most of the stratigraphic horizons, whereas ductile deformation is restricted to gypsum and anhydrite rocks of the Middle and Upper Triassic. The kink method (Suppe 1985) was used to facilitate the construction.

Since the bed thicknesses remain almost unchanged during deformation, balancing of sections can be based on the assumption that the bed lengths of all layers are conserved during deformation (line-length method of Mitra & Namson 1989). The restoration takes into account that at least two generations of Jura thrusting are distinguishable. Unfortunately, the Jura fold and thrust belt contains many strike-slip faults and oblique ramps whose geometries are poorly known. Sections through such zones cannot be balanced because of the lateral material transport along these structures (out of the section and into the section, respectively).

Balancing was performed with the help of the software GEOSEC-20™ (Geologic Systems, Inc.). It must be emphasized that while the methods of balancing cannot prove a certain geometry to be correct, they do yield a plausible model which is consistent with the law of material balance in two dimensions. Often several geometries exist which fulfill these conditions. The only way to confirm or reject a solution is by modelling the kinematic evolution in three dimensions.

b) Three dimensional kinematic modelling (Block mosaic)

Instead of working in the vertical section plane, modelling is performed within a horizontal plane. A selected layer, subdivided by thrusts and faults into a pattern of slightly deformed blocks, is projected onto a horizontal plane. Preliminary constructed and balanced sections are very helpful for this projection. In the case of thrust-domi-

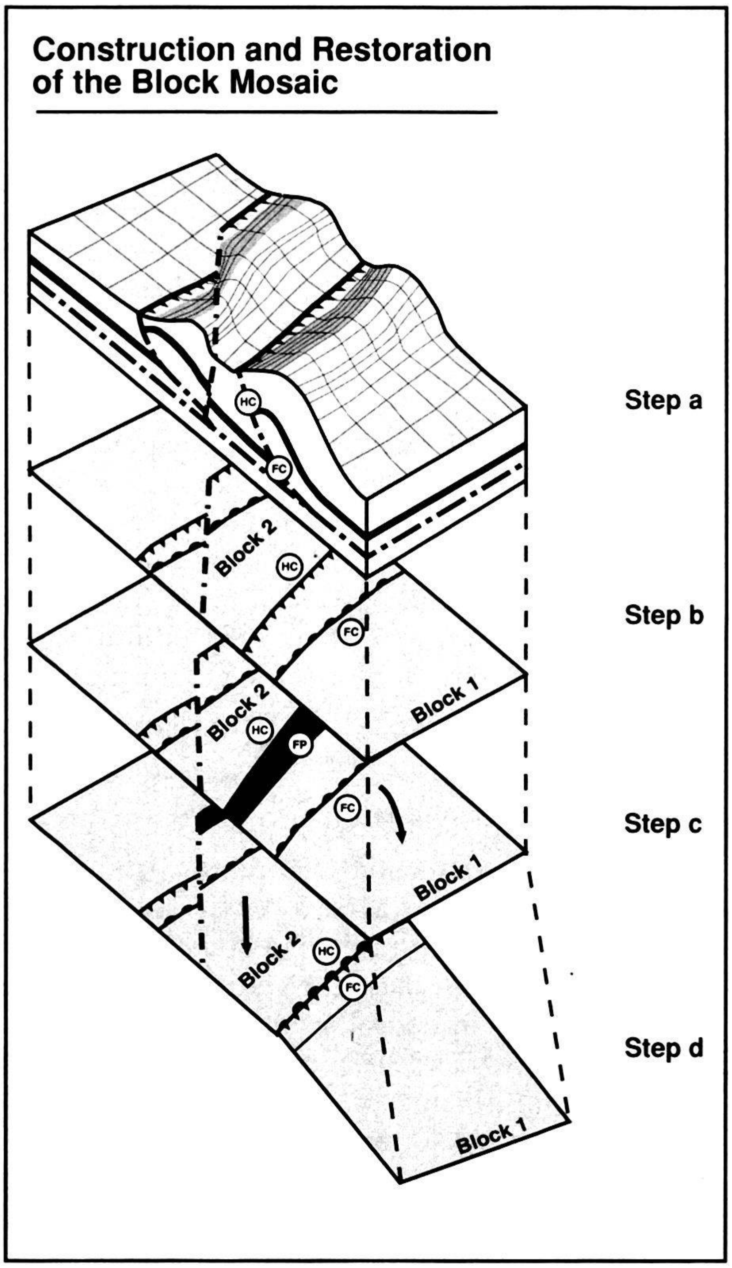


Fig. 5. Material balancing within a horizontal plane – schematic procedure.

Step a: Block diagram illustrating the basic input: surface data and preliminary constructions of cross sections. Surface data are simplified to a pattern of little deformed tectonic units. The selected layer is shown in the section part with the hangingwall cut-off line (HC) and the footwall cut-off line (FC), representing the intersections between the selected layer and the thrust surfaces (see also inset of Fig. 9a).

Step b: Extrapolation of the tectonic units onto the selected layer with the help of cross sections and projection onto a horizontal plane. The result is a mosaic of partly superimposed blocks (e.g. block 1 over block 2).

Step c: Addition of the internal deformation (in the section difference between the length of the selected layer and the length of the projection) to the first block, using the available information on the sequence of deformations and movements (shown here as block 1). FP: Folded part.

Step d: Restoration of the movement of block 1, using the data on transport directions. The HC of block 1 must fit together with the FC of the underlying block (here block 2), requiring a rotational movement in this example. If this condition ist not fulfilled the basic input (geometry of blocks, succession of movements and deformations, transport directions, kinematical concepts...) has to be changed. Addition of the internal deformation (step c) and restoration of the movement (step d) of the following blocks (in this example block 2)...

nated tectonics, this results in a mosaic of partly superimposed blocks (Fig. 5, upper part).

The restoration of the block mosaic to the original tectonic configuration must take into account the transport directions of each block and the sequence of deformation and movement. In each block, the internal deformation (folds, kinks, flexures) must be added to the block and then the movement of the block must be reversed, so that the hangingwall cut-off line of the moved block fits together with the footwall cut-off line of the underlying block (Fig. 5, lower part). During the restoration of the movement along strike-slip faults, no gaps between and no superposition of neighbouring blocks should occur. Depending on the restored tectonic phase, the final product is a mosaic, whose blocks are perfectly compatible.

The method is based on trial-and-error. It is a very helpful way to delimit the geometry of blocks, to estimate the magnitudes of displacement on faults and thrusts, to discern rotational movements and to detect unknown duplexes. The detection of unknown strike-slip zones and the estimation of their displacement is probably the most interesting side-effect of the method.

To my knowledge, only Laubscher (1965, 1981, 1987) has ever applied this method. For a more detailed description of the method, the reader is referred to Bitterli (1988).

The two cross sections Oensingen and Birtis

Fig. 6 shows the balanced cross section Oensingen slightly east of the gorges of Oensingen-Balsthal, near the section of Meier 1977 (Fig. 3). This trace was chosen because there is less need of laterally projected field data. In a first attempt, the concept of a box fold was maintained. Because the vertical north limb cannot be seen in the field, there is some freedom in adjusting the geometry of the fold so that the requirement of two dimensional mass balance can be fulfilled. The only changes needed compared with the constructions of Meier (1977) concern the width of the box fold, which must be narrower and closely resemble the lift-off folds of Buxtorf (Fig. 2). Mitra & Namson (1989) describe silimilar, even tighter box folds in the Taiwan fold and thrust belt. However, the question as to how beds can be moved through such narrow hinges without being totally fractured remains unanswered.

The Birtis-section (Fig. 7) is situated between the Oensingen-section and the sections of Buxtorf (1908). It is quite different from the classical model of Jura folds. The well documented, homogeneously north-dipping limb of the Weissenstein anticline is much longer than in the Oensingen-section. An interpretation as a boxfold cannot be maintained because the filling of the broad core requires enormous masses of Middle Triassic rock. Together with the narrow, south-vergent fold on top of the Weissenstein chain and the minor horizontal distance from the southernmost Mesozoic outcrops to the Tertiary formations of the Molasse basin, these are indications for a large-scale backthrust. Since the thrusts were north-directed, the footwall was wedged under the backthrust, lifting the hangingwall and producing a fault-propagation fold at its frontal part.

Comparison with the sections of Buxtorf a few kilometers to the west (Fig. 2) reveals that this backthrust correlates with the Günsberg-backthrust. However, in

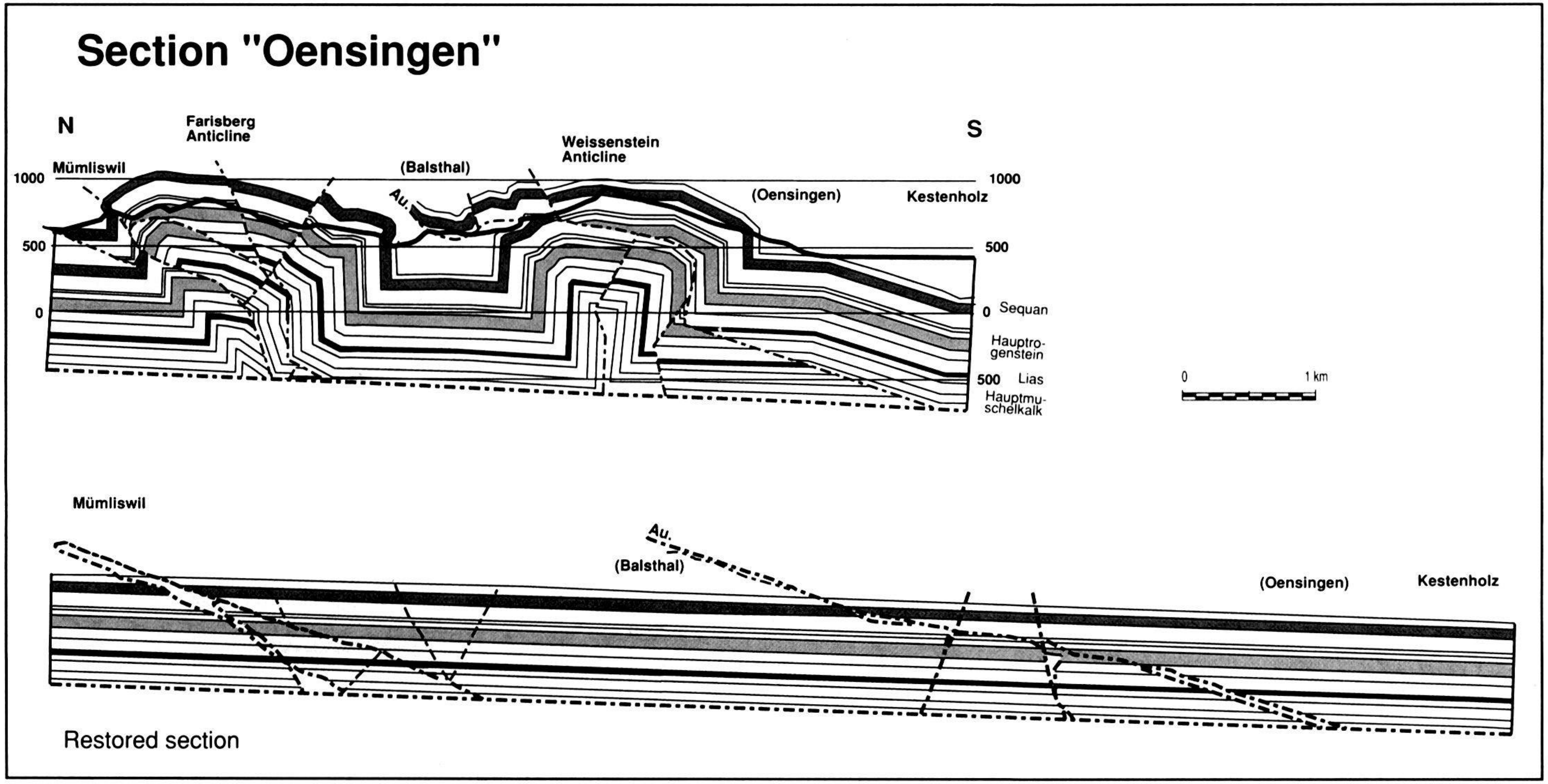
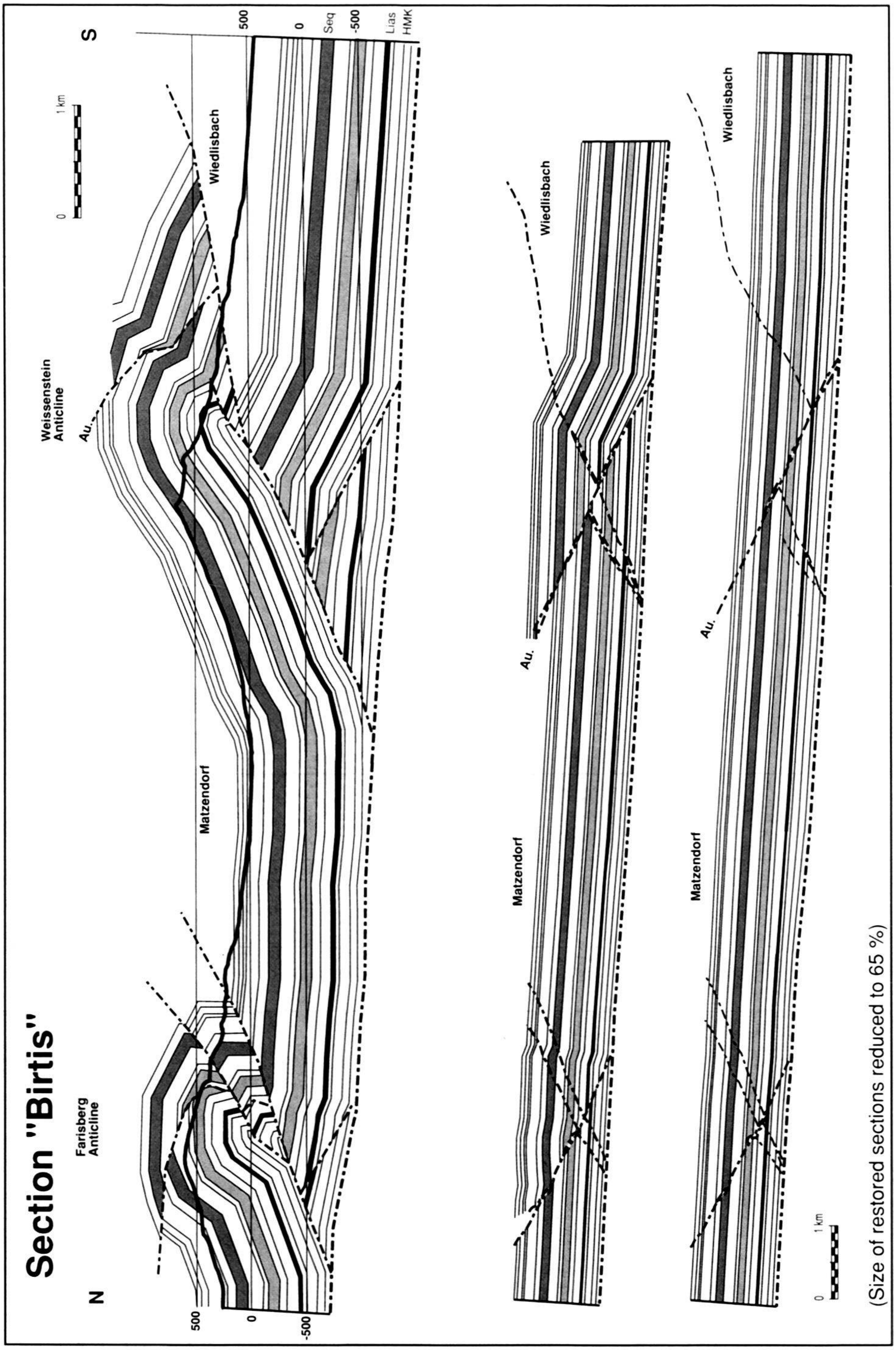


Fig. 6. Balanced Oensingen-cross section slightly eastward of the sections through the gorge of Oensingen-Balsthal (Figs. 3 and 4, traces see Fig. 1) based on the box fold concept of Meier (1977). The vertical southern limb of the Weissenstein anticline is extrapolated from the west. The position and steepness of the northern limb is a result of balancing the section and cannot be confirmed for lack of outcrops.


Section "Birtis"
N
S
Farisberg Anticline
Weissenstein Anticline
Matzendorf
Wiedlisbach
Au.
500
0
-500
Seq
Lias
HMK
0
1 km
(Size of restored sections reduced to 65 %)

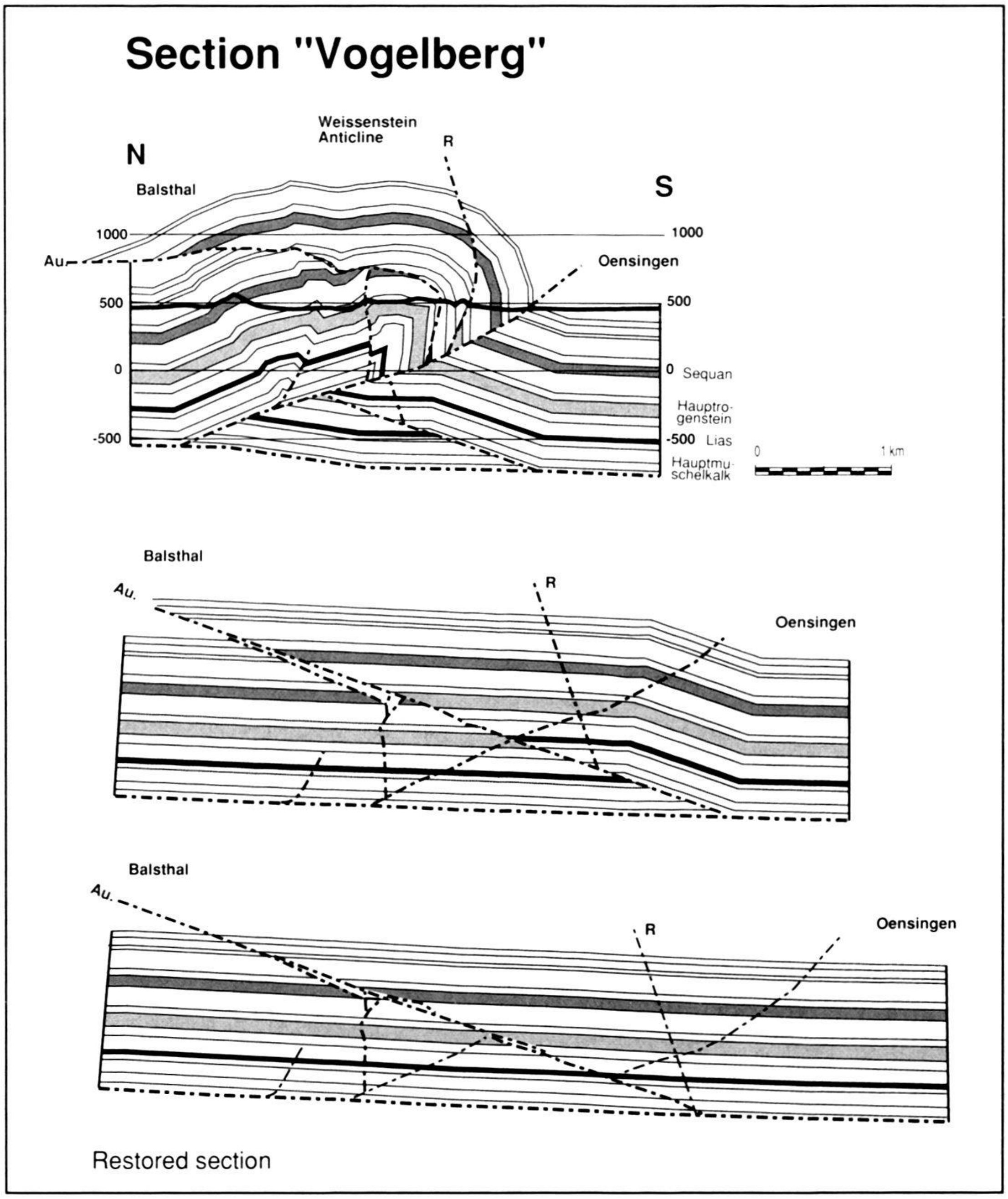


Fig. 8. Balanced Vogelberg-cross sections between the Birtis- and Oensingen-sections (slightly west of the gorge of Oensingen-Balsthal, traces see Fig. 1). The structure of the Weissenstein anticline is very similar to the one in Birtis-section and contains as well two, geometrically distinguishable tectonic generations. It is apparent from the decreasing height of the Weissenstein anticline from west to east the shortening of the wedge system also decreases, whereas the amount of the Ausserberg-thrust (Au) shows no change.

Fig. 7. Balanced Birtis-cross section in the western part of the studied area (traces see Fig. 1). The long, homogeneously north dipping northern limb of the Weissenstein anticline is not compatible with a box fold. However, it indicates a south-vergent ramp system with a narrow fault propagation fold on top. The moving mechanism is not real backthrusting but wedging of the Molasse basin under the thrust and consequent lifting of the hangingwall. Note the folded and disconnected Ausserberg-thrust (Au) indicating an older tectonic event. Consequently balancing of the section is performed in two steps corresponding to the wedging (younger generation) and to the Ausserberg-thrust (older generation).

analogy to the Birtis-section, it does not displace a cylindrical core but separates a completely different geometry in the footwall from the thrust-related, narrow fold in the hangingwall. Thus, the south-vergent "back"-thrust is not interpreted as local structure, that accommodates movement out of an intensely deformed fold core, but as a major tectonic element of the décollement-thrust system.

Kinematic modelling in three dimensions

The comparison of the Birtis-geometry (Fig. 7) to the totally different box fold geometry of the Oensingen-section (Fig. 6) causes some problems which cannot be solved by merely using series of balanced cross sections. Even the viability of a boxfold geometry has to be questioned for the Oensingen-section.

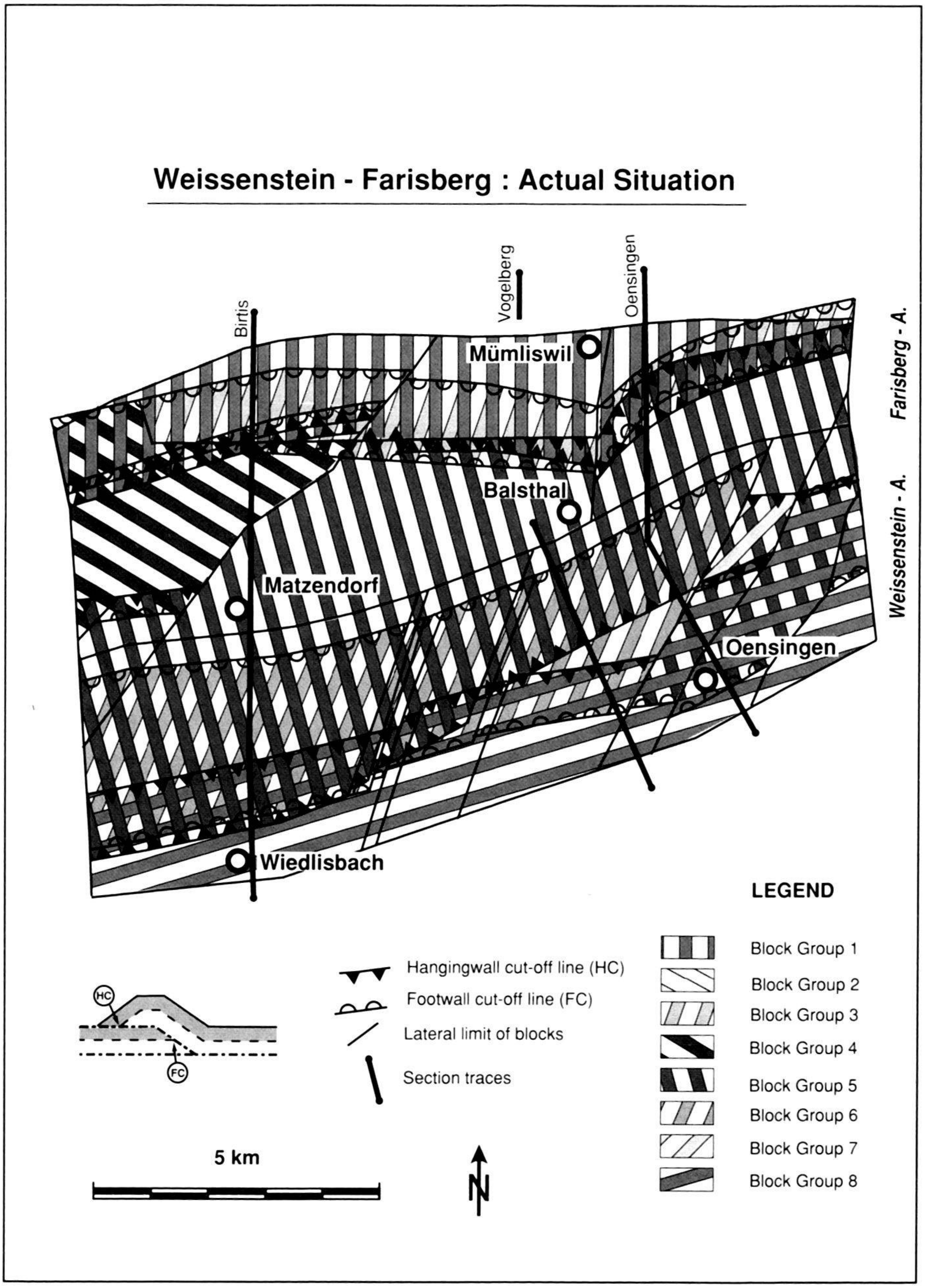
In the trial-and-error process of modelling the block mosaic (Fig. 9 a–c), the top of the Middle Muschelkalk was used as reference layer. It represents the bottom of a brittly deformed, calcareous formation, only 40–60 m above the décollement horizon. Starting from the Birtis-section (Fig. 7) its main structures (about 25–30° dipping north limb, narrow fault-propagation fold as south limb) were followed to the east. This was possible at least up to the gorge of Oensingen-Balsthal without any important change in the structure of the fold. Fig. 8 shows the balanced Vogelberg-section just west of the gorge, whose geometry is similar to the section Birtis. As the surface data of the Vogelberg-section are comparable to those of the nearby Oensingen-section, the latter is interpretated in the same manner, too. This can easily be done by removing the hypothetical vertical northern limb of the original box fold.

East of Oensingen, the vergence of the Weissenstein anticline turns to the north, thus indicating mainly north-vergent thrusts. The change of geometry occurs within a few hundred meters. Although this transitional zone separates two completely different geometries and tectonic patterns, the few strike-slip faults recognized at the surface show only insignificant vertical throw.

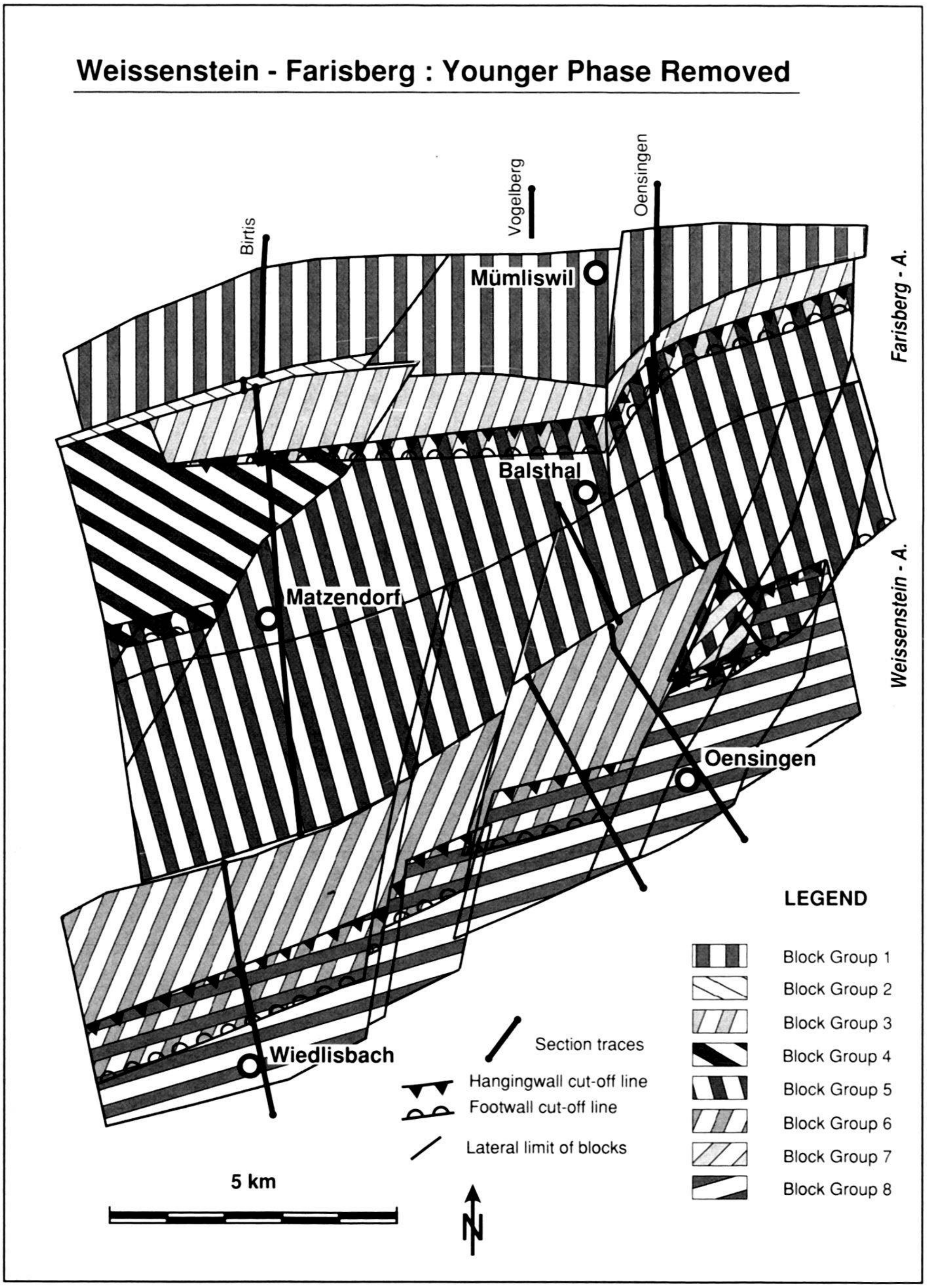
The hitherto unknown strike-slip zone passes right through the Oensingen-section (Fig. 6) and causes important lateral material transport (see the disconnected traces of the section in Fig. 9c). Because the fundamental assumptions of balancing are not fulfilled, a two dimensional restoration of the Oensingen-section has no geological meaning at all. Consequently, the revised version of Oensingen-section (Fig. 10) shows the tectonic situation of the western area on the left side of the strike-slip fault (as illustrated in the Birtis and Vogelberg-sections, Fig. 7 and 8). The eastern structures (north-vergent thrusts) are represented on the right side. The two parts are regarded as fragments of two independent sections, cut and brought together by the strike-slip fault during thrusting. The two versions of the Oensingen-section (Fig. 6 and 10) are based on the same surface data, except for the vertical south limb of the Weissenstein anticline. This exists only on the west side of the strike-slip fault and cannot be extrapolated to the east as in the older construction (Fig. 6).

Structure of the Weissenstein Anticline: New Interpretation

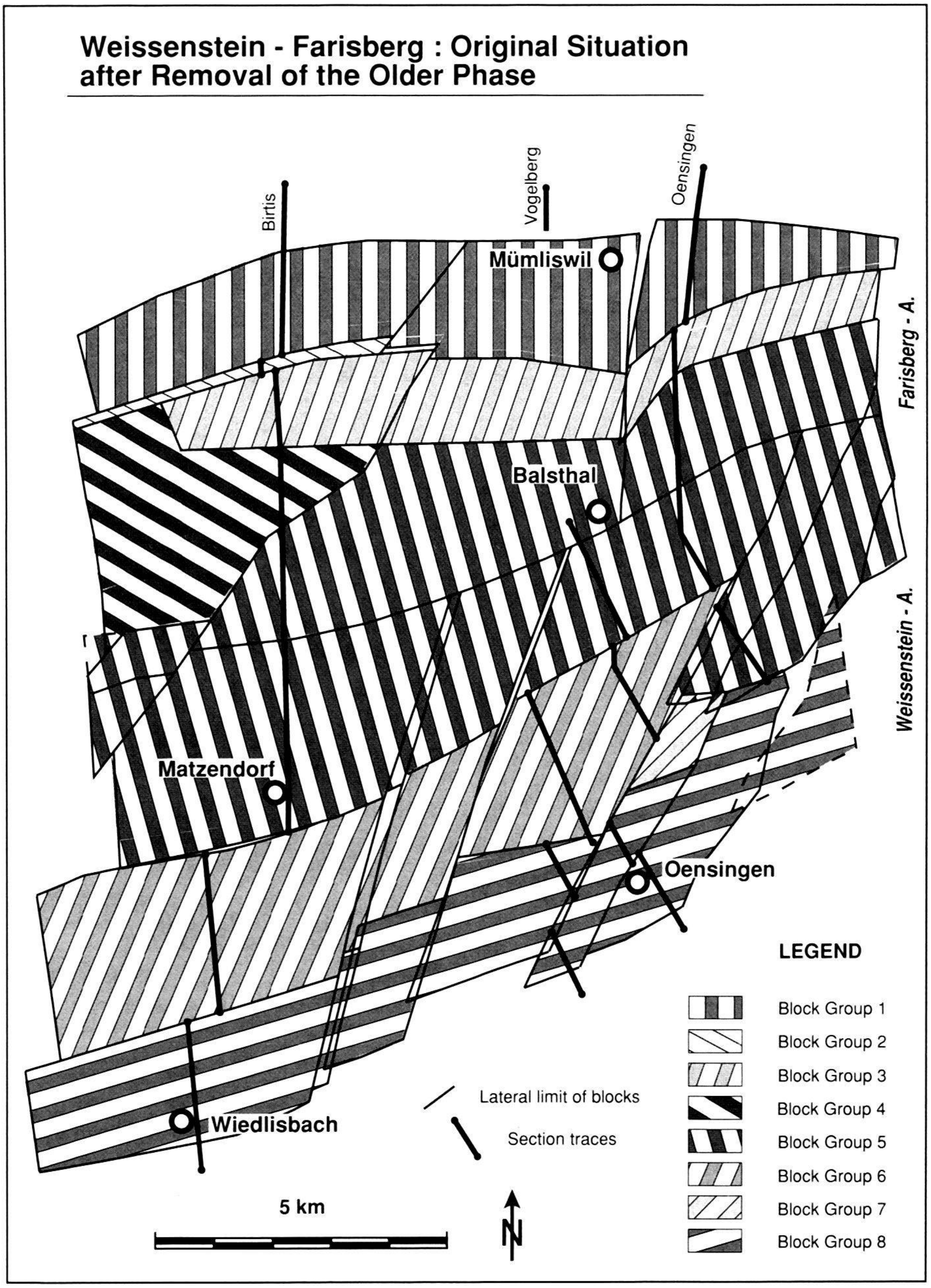
The Weissenstein anticline and the geometrically similar Farisberg anticline, both result from two thrust-related folding phases, as already recognized in the gorge of



Figs. 9a-c. Restoration of the block mosaic in the two tectonic phases described with the balanced cross sections. Fig. 9a represents the present location of the tectonic units, extrapolated onto the top of the Middle Muschelkalk, projected onto a horizontal plane and completed by the folding component of the total shortening (procedure see Fig. 5). Fig. 9b corresponds to the situation before the (younger) wedging and Fig. 9c before the movement of the



(older) Ausserberg-thrust. Note the roughly disconnected traces of Oensingen-section precluding two dimensional balancing of this section. The notation of hangingwall cut-off line (HC) and footwall cut-off line (FC) as an intersection of the selected layer with the thrust surfaces is shown in the inset of Fig. 9a. Overlying blocks are shown with through-going patterns, overlain blocks with disconnected patterns.


Weissenstein - Farisberg : Original Situation after Removal of the Older Phase
Birtis
Vogelberg
Oensingen
Mümliswil
Farisberg - A.
Balsthal
Weissenstein - A.
Matzendorf
Oensingen
Wiedlisbach
LEGEND
Block Group 1
Block Group 2
Block Group 3
Block Group 4
Block Group 5
Block Group 6
Block Group 7
Block Group 8
Lateral limit of blocks
Section traces
5 km
N

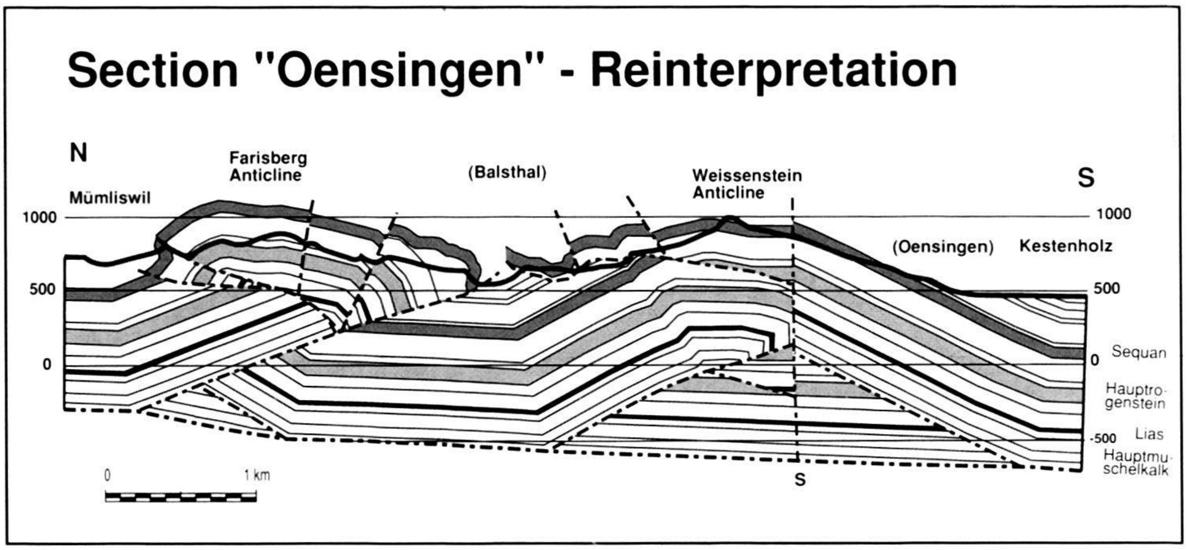


Fig. 10. Reinterpreted cross Oensingen-section, taking into account the results of other balanced sections and restoration of the block mosaic. The strike-slip fault (S) separates two completely independent geometries in the NW (south-vergent thrust, wedges of Birtis- and Vogelberg-sections, Figs. 7 and 8) and in the SE (mainly north-vergent thrusts, not shown). The steep southern limb of the Weissenstein anticline shown in Fig. 6 exists only on the west side of the strike-slip zone and should not be extrapolated to the section plane. Two dimensional balancing across the strike-slip zone has no geological meaning at all.

Oensingen-Balsthal (WIEDENMAYER 1923) and of Balsthal-Mümliswil (MEYER 1977). The two phases are easily distinguished geometrically with the Ausserberg-thrust (first generation) which was folded by the second phase.

The first generation (Fig. 11, upper part) is characterized by "classical" north-vergent thrusts which form a single ramp from the décollement (Middle Triassic) horizon up to Tertiary rocks. The displacement amounts to about 1 km. Laterally, the ramp, actually folded, is split up into many fragments and displaced along discrete tear faults (NNE-SSW) with displacement ranging from several hundred meters to several kilometers. These tear faults usually terminate at the ramps, a fact which causes some difficulties in pursuing the trace of the thrust system. Regionally the strike of the thrust system is oblique to the Weissenstein anticline. In the western part, it is not traceable any further to the west because the upper part of the ramp is eroded and the lower part is displaced and hidden by the backthrust of the second generation.

The second generation (Fig. 11, lower part) reveals a much more important component of shortening, increasing from the east (about 2 km) to the west (3 km). In the eastern part, the thrust system uses the same north-vergent ramp as the first generation. The geometry of this thrust system changes completely along a NNE-SSW striking, reactivated tear fault. On the western side, we find the previously described, south-vergent backthrust-wedge system which extends at least 15 km to the west. Contrary to the first generation, the ramps are probably not displaced by tear faults but are curved. This inferred geometry which is unusual for the Jura fold and thrust belt is reinforced by the steepness of the ramp (30–35°) and the fault-propagation fold, whose footwall is wedged several kilometers to the north underneath the Weissenstein anticline and whose hangingwall is lifted and folded.

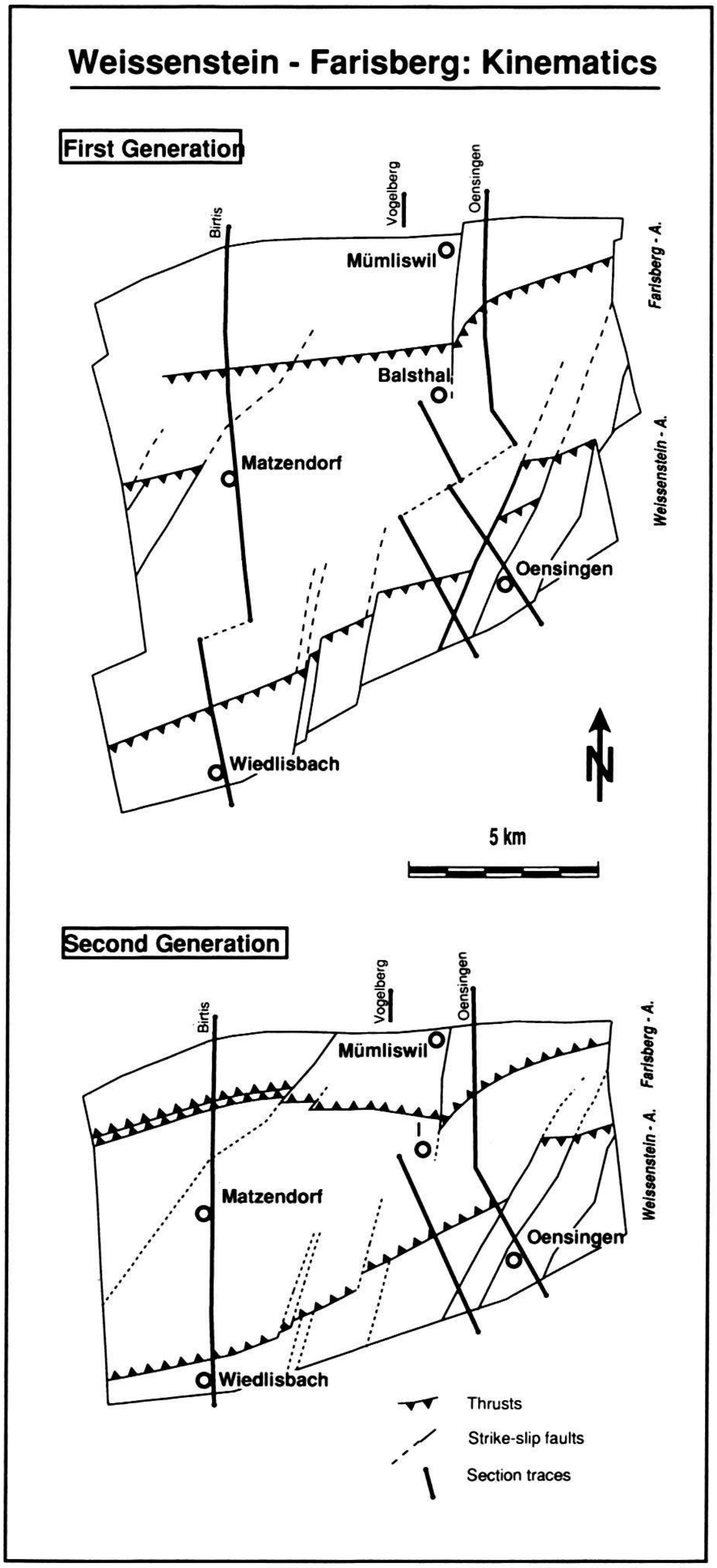


Fig. 11. Simplified model of tectonic phases of Jura thrusting. The upper part represents the first generation (Ausserberg-thrust) *after* performed movement and deformation. The section traces are still disconnected by the second generation (lower part) consisting mainly of a backthrust-wedge system. To the east, this system changes to a north directed thrust system.

Probably the NNE-SSW directed tear faults correspond to Oligocene normal faults related to the extensional fault system of the Rhine Graben and its southern continuation (e.g. MEIER 1977). At present, it is not known whether these normal faults acted as guides for the moving blocks, thus causing a transport direction to the NNE (oblique to the fold axes), or whether they were detached from the basement and transported in a N to NNW-direction. The kinematic restoration of the block mosaic (Figs. 9 and 11) shows only the relative movements between the blocks but does not include the superposed movement of the whole block mosaic relative to the basement. Therefore these directions cannot be taken as the regional transport direction.

Conclusions

Three dimensional kinematic modelling of a classical Jura fold involved balanced section construction and restoration of the tectonic units on a horizontal plane. Contrary to older concepts of lift-off box folds formed directly above the décollement horizon, the model presented here leads to a kinematic interpretation of at least two thrusting generations, best illustrated in the Birtis-section (Fig. 7).

The first thrust generation is dominated by a system of north-vergent thrusts (Ausserberg-thrust) and strike-slip zones. These thrusts strike slightly oblique to the fold axes of the big anticlines formed during the second generation.

The second, much more important generation shows a rather unusual geometry, rarely described in the Jura fold and thrust belt so far. It mainly consists of a large-scale south-vergent thrust (Günsberg-backthrust of Buxtorf) with associated fault bend folds and fault propagation folds. As the overall transport direction is still to the north, this thrust is not a backthrust in the strict sense but corresponds to a wedge of the Molasse basin pushed to the north beneath the Weissenstein anticline.

Three dimensional balancing reveals an important change of the geometry to the east. Along a narrow strike-slip zone the wedging system of the second generation is replaced by a classical, north-directed thrust system. The main function of this strike-slip zone is not really the accommodation of differential shortening but mainly the separation of different geometries. Therefore the Oensingen-section (Figs. 6 and 10) transsecting this zone of lateral material transport should not be balanced.

Acknowledgments

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