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The structural evolution of the Rhenodanubian/Ultrahelvetic thrust wedge in the Attersee to Traunsee region

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Abstract

The structure and the structural development of the Rhenodanubian/Ultrahelvetic Wedge (RUW) in the Attersee to Traunsee region (Upper Austria) have been examined by structural analysis and 2D and 3D structural modelling. The structure is dominated by thin-skinned tectonics mode of deformation of the infilling of the flysch basin, which took place within a wedge at the northern, buttress-type front of the Northern Calcareous Alps. Ultrahelvetic successions that were laid down on a northern continental slope were incorporated into a combined RUW. The structure is dominated by ca. E trending, kilometre-scale kink fold anticlines and synclines, blind thrust faults and splay thrusts. Several major deformation stages can be distinguished. These include: (i) overthrusting of the Ultrahelvetic continental margin sequences by the Rhenodanubian Flysch Zone during Late Eocene (mainly D_2 stage, out-of-sequence thrusts), (ii) subsequent shortening of the combined Ultrahelvetic/Rhenodanubian thrust wedge, likely associated with the emplacement onto the southern margin of the Molasse Zone during Oligocene to Early Neogene, and (iii) disruption of the combined Ultrahelvetic/Rhenodanubian thrust wedge by strike-slip faults during the Neogene.

Introduction

The Rhenodanbian Flysch Zone is exposed along northern margins of the Eastern Alps. It comprises the infilling of a deep-sea basin likely located onto oceanic crust (Decker, 1990). On ideas of the paleogeographic evolution inform Prey (1980), Hesse (1982), Egger (1992), Faupl and Wagreich (1992) and Schnabel (1992). The Rhenodanubian Flysch represents a classical thrust-fold belt. We studied central sectors of the combined Rhenodanubian Flysch/Ultrahelvetic wedge, Eastern Alps, which has been emplaced onto the Molasse zone, the classical peripheral foreland/molasse basin (e.g., Malzer et al., 1994). From the flysch zone detailed modern structural studies are largely lacking although, except scarce structural data (Mattern, 1988), some paleostress data based on evaluation of fault and slickenside data were reported (Meschede and Decker, 1992; Decker et al., 1993). We did choose for our structural study the region between Attersee and Traunsee because of the availability of modern geological maps (Egger, 1996; van Husen, 1989) and because of relatively good exposure compared to western and eastern adjacent regions.

Geological framework

In the study area, southern deformed sectors of the Molasse basin with late Eocene to Miocene clastic successions form the structural base of the combined Rhenodanubian/Ultrahelvetic wedge (RUW). Seismic reflection profiles and some boreholes demonstrate that the molasse sediments and European basement rocks can be traced with a gently south-dipping surface beneath the RUW and the southerly adjacent Northern Calcareous Alps which is part of the Austroalpine nappe complex. The northern boundary of the NCA unit is a steeply south-dipping thrust which result in a wedge shape of RUW in between. Sedimentary sequences of the Molasse basin were deposited on the flexured European lithosphere.

In the study area, the RUW mainly consists of (1) the Rhenodanubian flysch zone with Neocomian to Middle Eocene turbidites intercalated in marls and shales and (2) of the Ultrahelvetic unit with the Cretaceous to Early Late Eocene Buntmergel Formation, which uniformly comprises variegated marls of not more than ca. 100 - 200 metres (structural) thickness. The Ultrahelvetic unit comprises less than five percent of surface exposure and is largely overridden by the Rhenodanubian Flysch unit, and is mainly exposed along northern footwall sectors and within some windows within the Rhenodanubian flysch unit.

The Rhenodanubian flysch unit comprises several formations with variable thickness (Fig. 2). These formations include, stratigraphically upward, the Tristel Formation, Reiselsberg Formation, Seisenburg, Zementmergel and Perneck Formations, which all three are dominated by variegated or grey marls, and the Altlengbach Formation (Egger, 1995, 1996). The latter includes several subformations. No measured sections exist to these formations. Consequently, we estimated the structural thickness for all these formations from available geological maps during the course of our study (Fig. 1). The basement of the Rhenodanubian Flysch Zone is not known in the study area. Decker (1990) described uppermost portions of a Jurassic ophiolite sequence as the stratigraphic base of the Rhenodanubian Flysch Zone. Similarly, the basement of the Ultrahelevetic unit is also unknown.

Structure

The structure of the region was evaluated from available maps and from own field work along sections. Fault and striation data were collected in ca. 60 stations between Traunsee and Attersee in order to evaluate fault kinematics. In many outcrops superimposed, partly complicated sets of faults and striations were found which indicate a polyphase reactivation of faults. Note that along fault traces itself outcrop conditions are poor, and only a few large exposures can be found on individual faults, e.g., the Gmunden quarry (see, e.g., Meschede and Decker, 1993; Decker et al., 1992). We used the GEOSEC 3D©software package for construction, assessment and balancing of the three-dimensional structure.

The structure of the RUW is dominated by a shallow frontal, floor thrust which brought the RUW over the molasse zone and a medium angle to steep roof thrust at the backfront towards the Northern Calcareous (Fig. 1). The gentle dip to the south of the frontal thrust is also documented by well data within the RUW and southerly adjacent NCA, and by seismic reflection profiles. These relationships suggest a wedge-shape form of the RUW which was deformed along the northern front of the NCA.

The internal structure of the RUW between Traunsee and Attersee is complicated. It generally includes E-trending kink-type anticlines and subordinate synclines which are well documented by stratigraphy. These folds are in part overturned towards N. Furthermore, S-dipping thrust surfaces are exposed. Ultrahelvetic Buntmergel Fm. is exposed along thrust

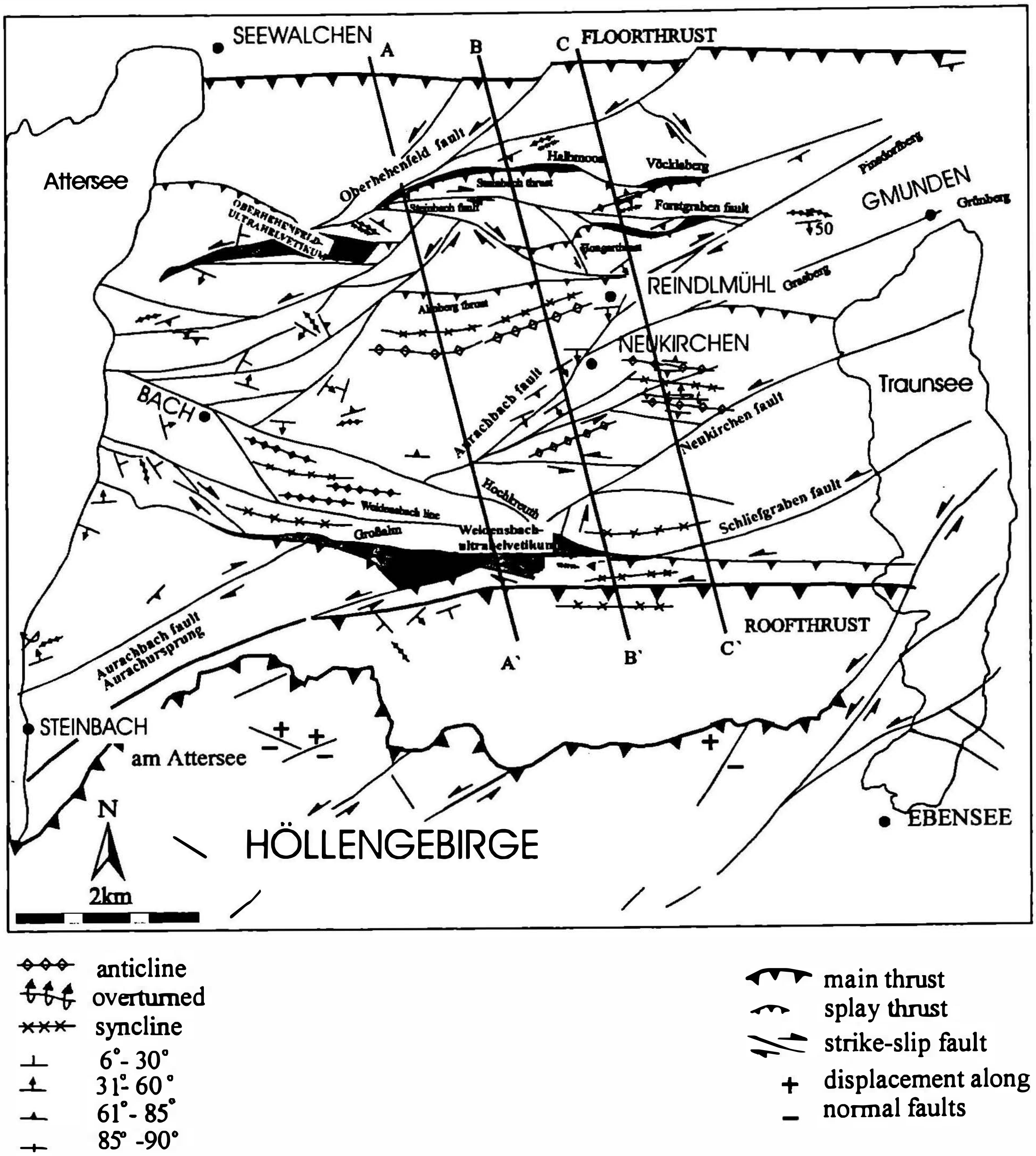

Fig. 1. Simplified structural map of the study area (based on Egger, 1996).

surfaces and partly overrides Rhenodanubian flysch formation in the Oberhehenfeld and Weidensbach windows.

Folds and thrust faults are transected by numerous ENE trending, sinistral strike-slip faults including the Oberhehenfeld, Aurachbach, Neukirchen and Schliefgraben faults (Brandlmayr, 1995; Egger, 1996). These are interpreted to be part of eastern sectors of the supposed ISAM fault system (Egger, 1997). The displacement along these faults varies between several hundred metres to several kilometres. These sinistral faults are transected by the dextral Hochkreuth fault which also cuts the Weidensbach Ultrahelvetic window.

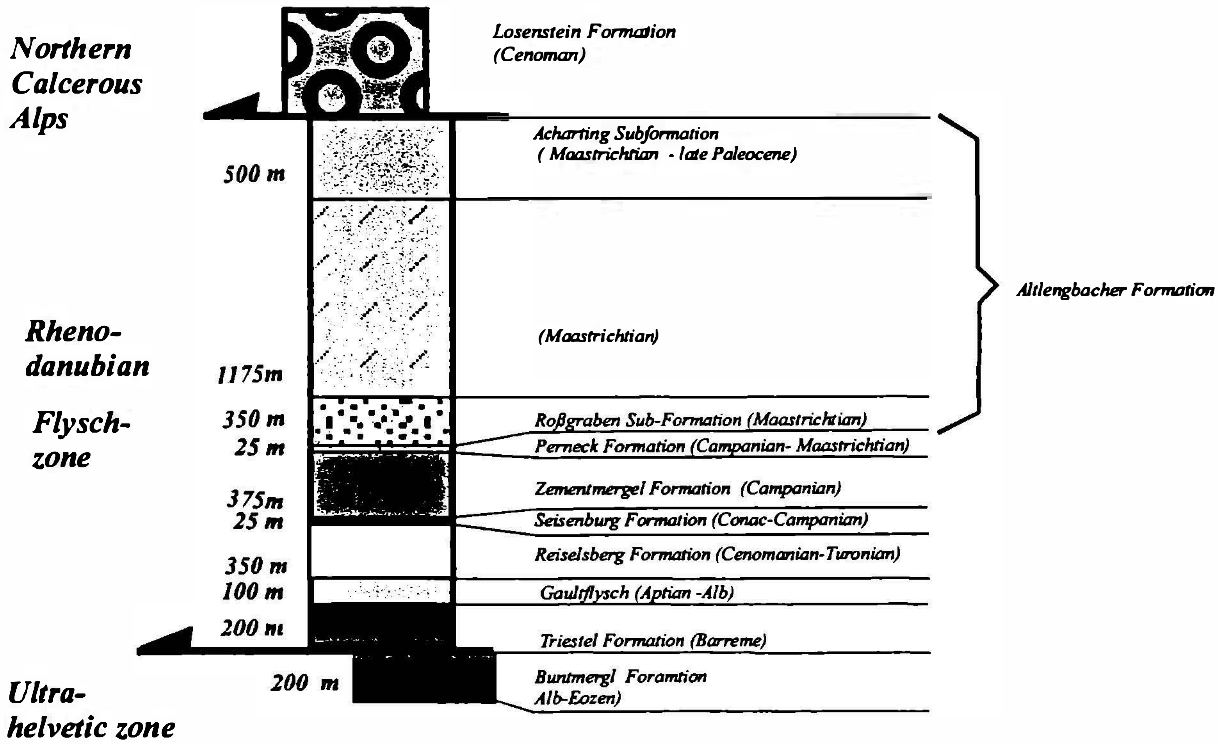

Fig. 2. Lithostratigraphy of individual tectonic units within the study area.

At outcrop scale, a number of detailed structures are observed which include: Ramp anticline and blind thrusts, layer parallel buckling and layer-parallel faults and slickensides. These structures document northward thrusting and shortening of the RUW. Furthermore, faults of all scales are common features documenting together with slickensides complex development and a relative succession of eight deformation stages (see below).

Succession of deformation stages

Several major deformation stages can be distinguished. These include: (i) overthrusting of the Ultrahelvetic continental margin sequences by the Rhenodanubian Flysch Zone during Late Eocene, (ii) subsequent shortening of the combined Ultrahelvetic/Rhenodanubian thrust wedge, likely associated with the emplacement onto the southern margin of the Molasse Zone during Oligocene to Early Neogene, and (iii) disruption of the combined Ultrahelvetic/Rhenodanubian thrust wedge by strike-slip faults during the Neogene which also cut into Neogene succesions of the Molasse Zone. Exposure of Ultrahelvetic units is along D_2 stage, out-of-sequence thrusts. Palaeostress tensors were deduced using fault-slip data (for methods, see Angelier, 1989) from more than fifty stations (Fig. 3-6). A succession of superimposed palaeostress tensors by means of superimposed fault and striae can be deduced as follows: Top-to-NNE nappe stacking led to the compound of RFZ units above the Ultrahelvetic Buntmergelserie. Mainly bedding plane striae yield reduced palaeostress tensors, which have been calculated from separated, homogeneous data sets with the orientations of the principal kinematic axes of D_1 with $\sigma_1 = 217/24$, $\sigma_2 = 122/24$, $\sigma_3 = 9/63$. Subsequent top-to-N

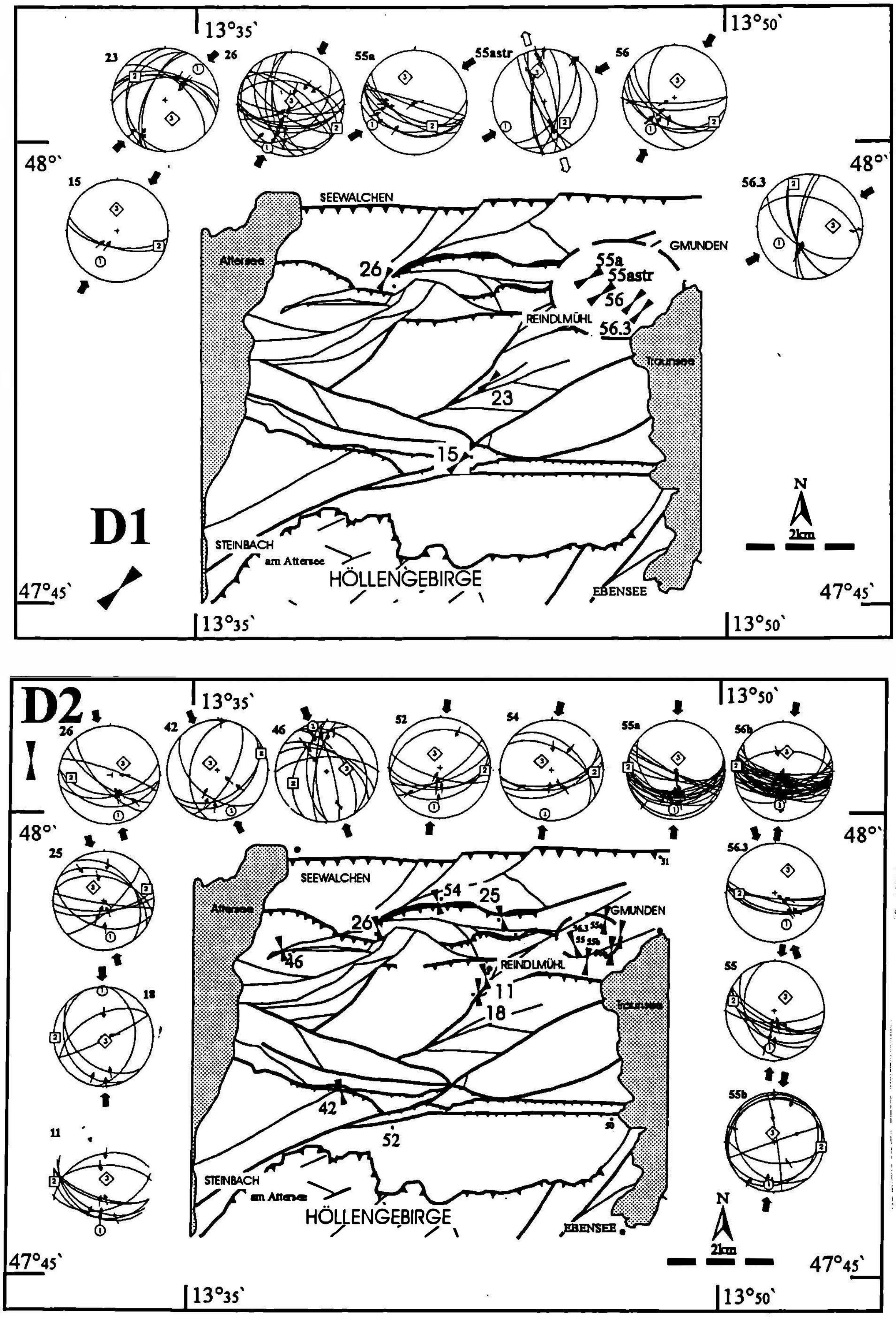

Fig. 3. Paleostress patterns of deformation stages D_1 (above) and D_2(below).

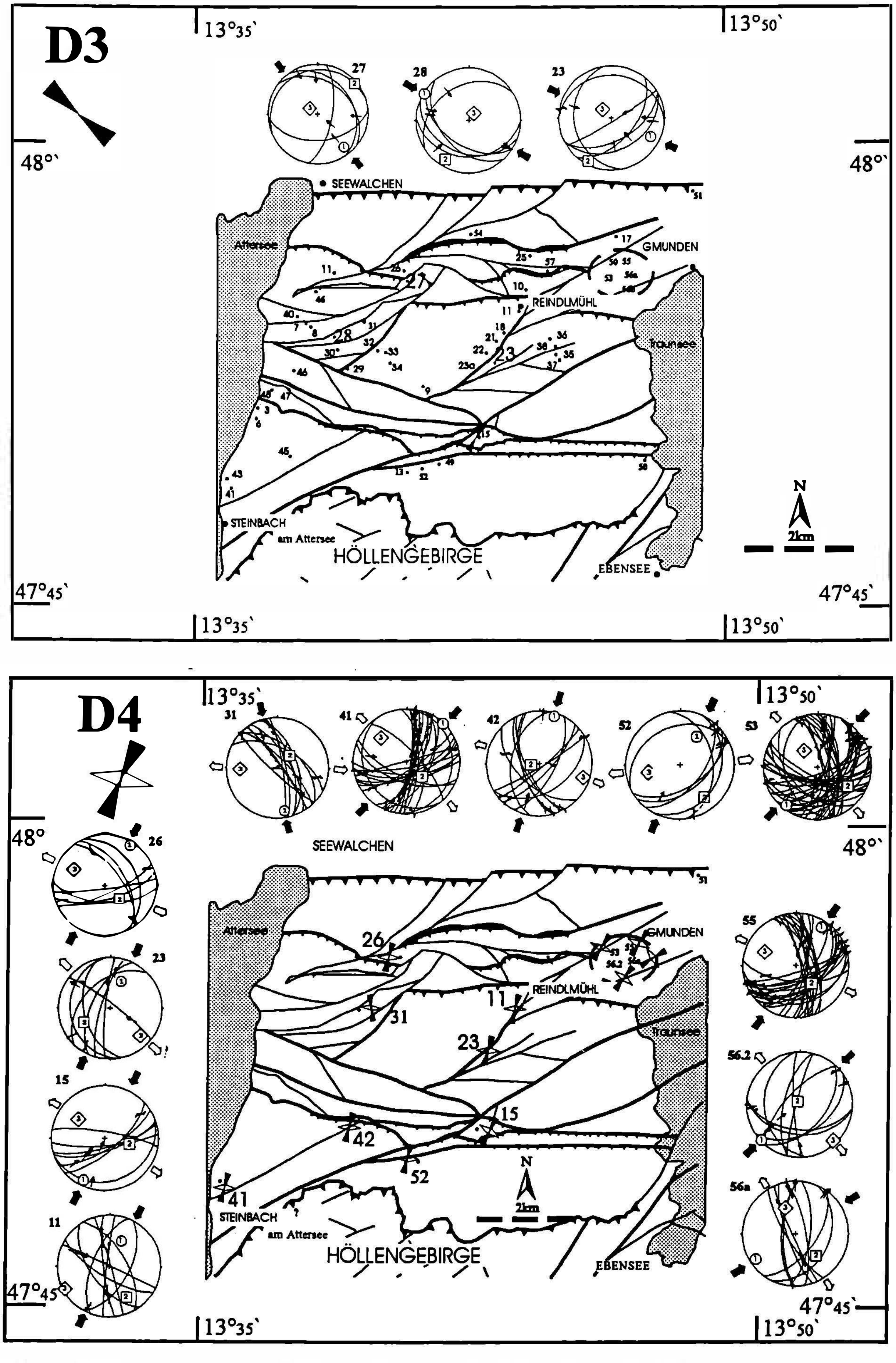

Fig. 4. Paleostress patterns of deformation stage D_3 (above) and D_4 (below).

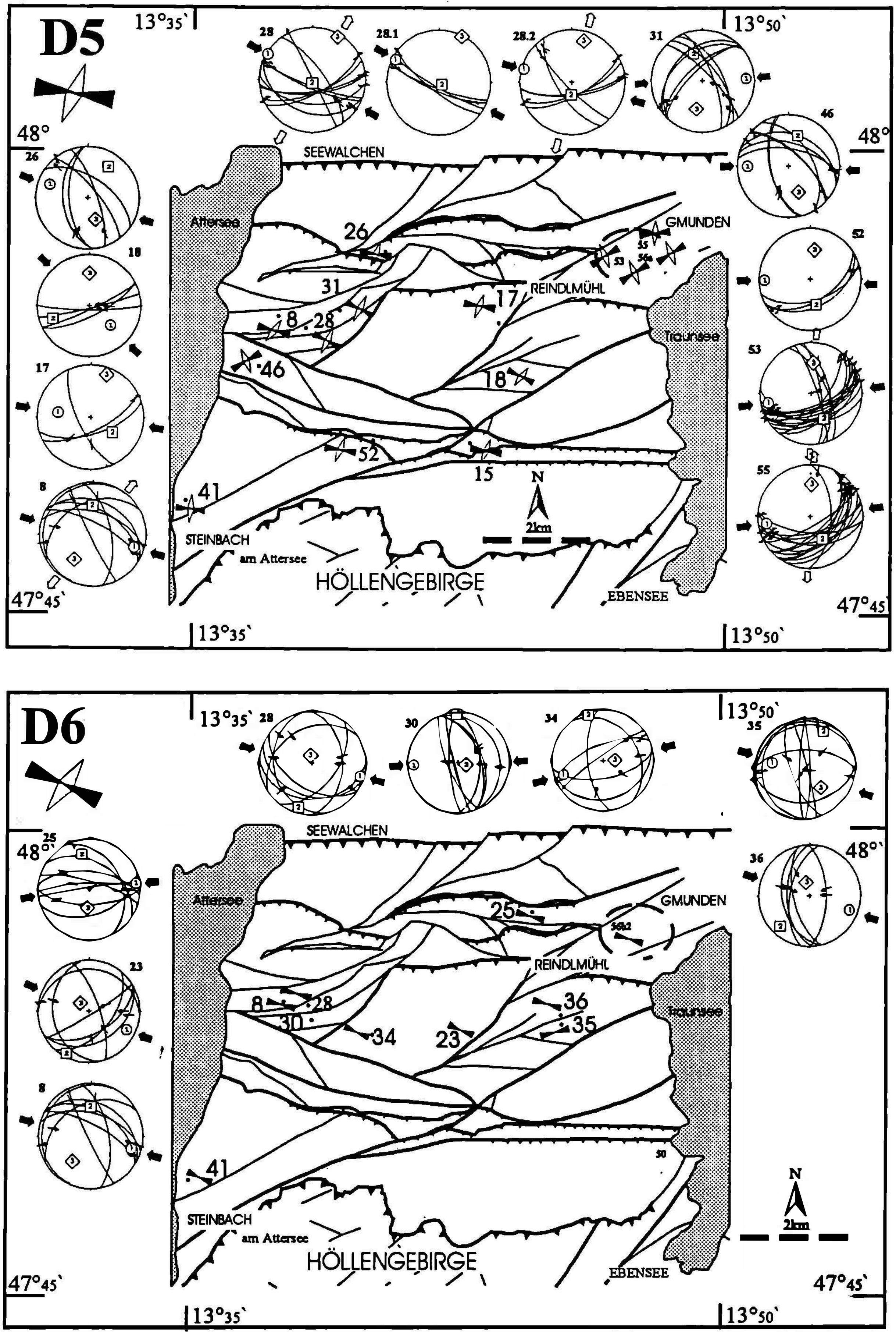

Fig. 5. Paleostress patterns of deformation stage D_5 (above) and D_6 (below).

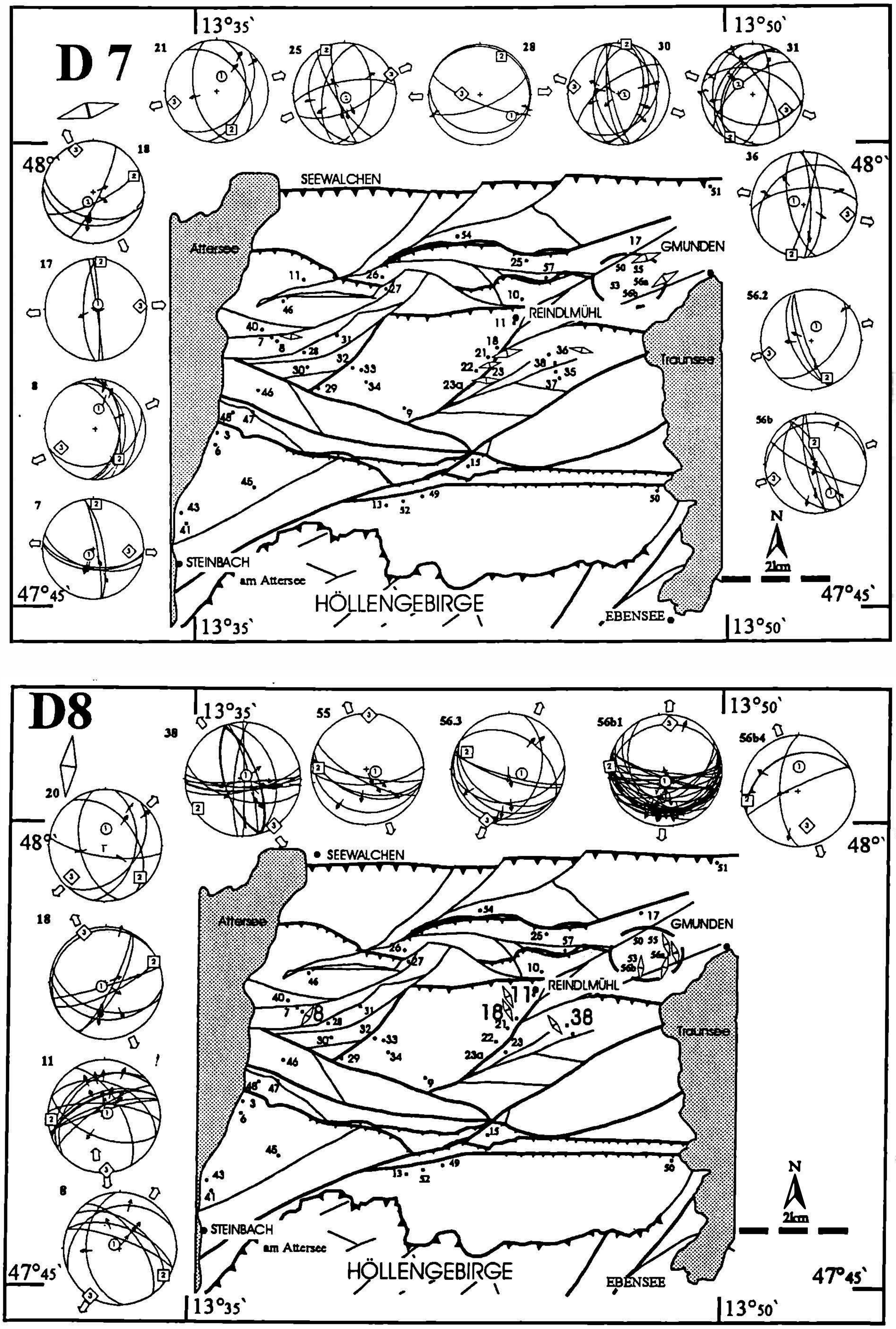

Fig. 6. Paleostress patterns of deformation stages D_7 (above) and D_8 (below).

thrusting is documented tectonically by different styles of splay thrusts, kink folds, and blind thrusts - all detectable on both outcrop- and map-scales. Data separation of bedding plane parallel slickensides and of E-trending faults led to a tensor group D_2 with the orientations of principal stress axes σ_1 = 185/23, σ_2 = 277/32, and σ_3 = 12/57. An anticlockwise rotation of the palaeostress field from N-S shortening D_2 to a final top-to-NW thrusting tensor group finished the architecture of the Rhenodanubian fold and thrust belt. The calculation of bedding plane parallel E-W trending fault results in a palaeostress tensor group D_3 with orientations of the main stress axes σ_1 = 160/31, σ_2 = 268/27, and σ_3 = 30/47.

Conjugate steep strike-slip, NNW- and ENE-trending faults formed due to further, ca. N-S contraction respectively left-lateral wrenching. The orientations of the kinematic axes for this event have been calculated with σ_1 = 153/33, σ_2 = 357/55, and σ_3 = 255/12. Dextral reactivation of D_4 strike-slip fault patterns under transtensional E-W wrenching conditions (D_5: σ_1 = 237/11, σ_2 = 137/42, σ_3 = 338/46). East and westward directed normal faults (D_6), and reactivated D_4/D_5 fault patterns depict E-W stretching of northern sectors of the Alps even in this northern RFZ zone (σ_1 = 241/34, σ_3 = 89/53). Subsequent E-W compression (D_7) due to the geomorphic shape of the basement in this area of the RFZ led to a tensor group with E-W compressional and subvertical extensional directions (σ_1 = 116/18, σ_3 = 314/71). Finally, N-S extension (D_8) is related to final collapse of the RFZ during uplift (σ_1 = 109/69, σ_2 = 293/21, and σ_3 = 202/1).

These data shows a similar but more complicated sequence of deformation stages as reported from regions further to the south (e.g., Ratschbacher et al., 1991; Meschede and Decker, 1992; Decker et al., 1993; Linzer et al., 1997). An important new result is that NNE-SSW motion oblique to the foreland is responsible for the formation of the Rhenodanubian/Ultrahelvetic wedge similar as in central sectors of the Eastern Alps (e.g., Ratschbacher et al., 1991; Neubauer, 1994).

2D- and 3D-modelling

A 2D and 3D structural model of the Rhenodanubian/Ultrahelvetic thrust wedge exposed within the Attersee and Traunsee has been performed by Freimüller (1998). The main idea was to model, based on structural field data and kinematics, the development of the thrust wedge. A restorable 2D model is shown in Fig. 7a. Principal complications for balancing are the presence of major sinistral and dextral strike-slip faults which cut oblique through the thrust-fold wedge. The balancing of these yield the fold-thrust wedge (Fig. 7b, c).

Fig. 7 (color copy after references). Structural model of the Rhenodanubian thrust wedge between Traunsee and Attersee (from Freimüller, 1998). a (upper figure) - 2D structural model (section C-C'in Figure 1); b (middle figure) - 3D model balanced for late-stage strike-slip faults displaying thrusts (yellow) and balanced strike-slip faults. c -(lower figure) - 3D model balanced for late-stage strike-slip faults displaying thrusts (yellow) and various formations but no strike-slip faults.

Conclusions

The following essential conclusions can be reached from the new data of the combined Rhenodanubian/Ultrahelvetic thrust wedge:
(1) The RUW forms a wedge which was deformed during emplacement of these units onto the Molasse zone.
(2) The RUW is dominated by folds and thrust faults which formed during shortening of the RUW thrust wedge.
(3) The Ultrahelvetic windows within the RUW are explained as out-of sequence thrusts.
(4) A polyphase thrusting formed within complicated external paleostress conditions which shifted from initial NE-SW principal stress orientation to later NW-SE maximum principal stress orientations.
(5) The RUW thrust wedge was subsequently dissected by E-W shortening and extension, and major strike-slip fault systems.

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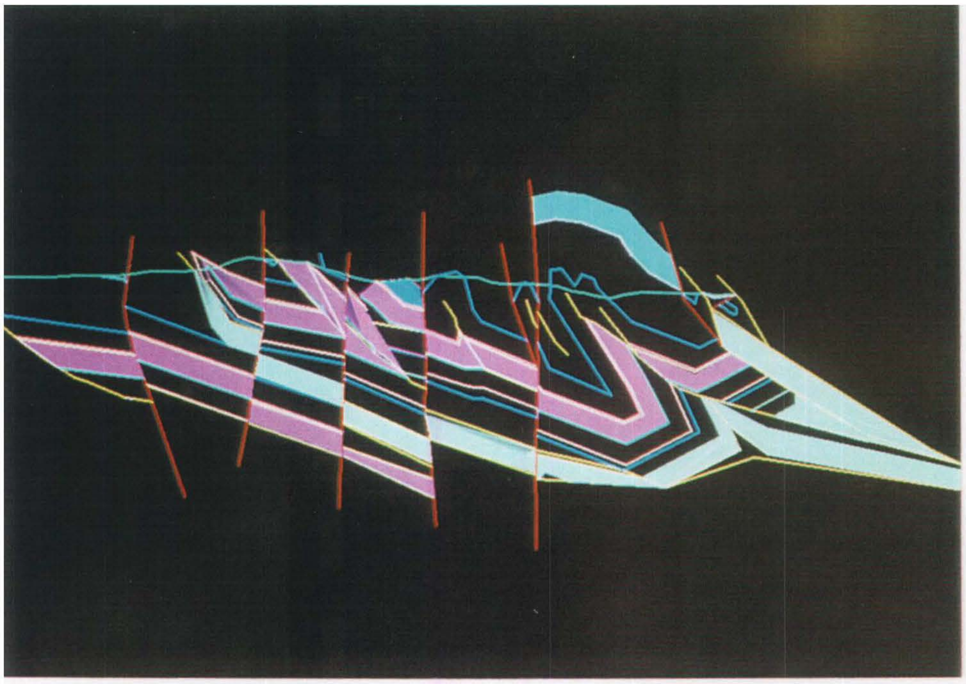

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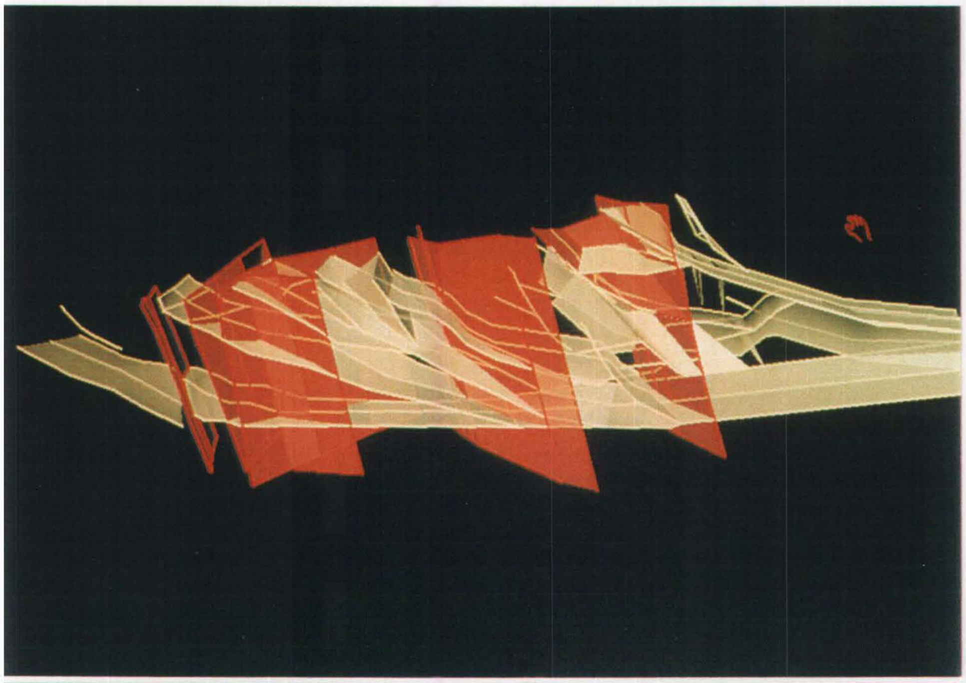

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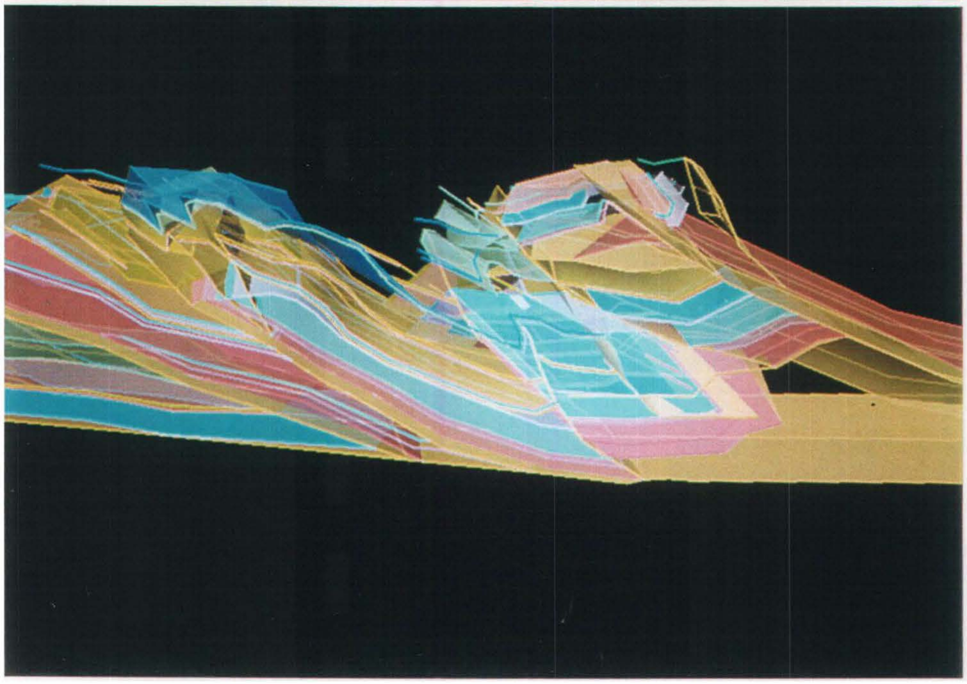

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