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An unusual triangle zone in the external northern Alpine foreland (Switzerland): Structural inheritance, kinematics and implications for the development of the adjacent Jura fold-and-thrust belt

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ABSTRACT

Triangle zones represent typical structural elements of thin-skinned foreland fold-and-thrust belts. Here, we report the results of an in-depth structural analysis of a rather unusual triangle zone at the front of the easternmost Jura fold-and-thrust belt in the otherwise only very mildly deformed Alpine foreland of Northern Switzerland. The investigation is based on the interpretation of recently reprocessed and depth-migrated 2D reflection seismic sections. Classical bed-length and area cross-section balancing methods were used to validate the interpretation and unravel the tectonic evolution of the triangle zone. According to our interpretation the analyzed triangle zone formed along the Baden–Irchel–Herdern-Lineament (BIH-Lineament), a regional Paleozoic normal fault that shows evidence of Cenozoic reactivation. The triangle zone is composed of one major foreland-directed thrust rooting in Triassic evaporites and a back-thrust splaying from it in the Middle Jurassic Opalinus Clay, pointing to the importance of secondary detachments. Steeply dipping secondary reverse faults next to the triangle zone suggest reactivation of pre-existing normal faults. The formation of the thrust triangle is considered to relate to thin-skinned foreland deformation in Late Miocene time. Strain estimations of the thrust triangle along-strike show a laterally very uniform amount of shortening, which is in contrast to the southward adjacent Jura fold-and-thrust belt. We interpret this constant shortening to represent the maximum contractional strain attainable by the specific geometry of the BIH triangle zone. At this point, the complex structure became mechanically ineffective and further shortening led to the formation of new contractional structures in its hinterland. This kinematic hypothesis suggests an early-stage formation of the BIH triangle zone followed by back stepping of the deformation front. As such, it challenges the classical view of a purely forward-breaking sequence for the Jura fold-and-thrust belt in the northwestern foreland of the Alps.

1. Introduction

The structural styles and kinematics of foreland fold-and-thrust belts have been and still are intensively studied, partly due to their important role as hydrocarbon play (Nemcok and Henk, 2006). Thin-skinned fold-and-thrust belts form along a basal décollement horizon typically constituted by mechanically weak lithological units (salt, evaporites and shale). They are found in the forelands of many orogens worldwide, for example the Rocky Mountains (Price, 1981), the Andes (Allmendinger et al., 1983; Baby et al., 1997; Jordan et al., 1993; Roeder, 1988) the Pyrenees (Puigdefabregas et al., 1992; Verges et al., 1992; Williams, 1985) and the Alps (Burkhard, 1990; Laubscher, 1961).

Thin-skinned foreland fold-and-thrust belts are considered to obey the laws of critical wedges (Chapple, 1978). The surface slope and the dip of the basal décollement define the geometry of a critical wedge. Both depend on the basal friction and the material of the wedge, its density and shear strength (Chapple, 1978; Dahlen, 1990; Davis et al., 1983). As a consequence the tectonic evolution and kinematics of thin-skinned fold-and-thrust belts are strongly controlled by the thickness of the sedimentary cover overlying the basal décollement eventually modified by syntectonic erosion or sedimentation, as well as aspects influencing the basal friction of the décollement such as fluid pressure and fracture strength (Hindle, 2008; Kley et al., 1999; Sommaruga, 1997; Uba et al., 2009). In addition to these principal controlling mechanisms, the localization and development of contractional structures in thin-skinned foreland fold-and-thrust belts is known to be commonly influenced by pre-existing structures (cf. Butler et al., 2006; Giambiagi et al., 2003). Deformation events predating thrust-belt initiation affect

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the geometry of the basal décollement horizon and lead to the formation of fractures and faults in the cover series that can act as pre-existing zones of mechanical weakness during thrust-belt formation (Homberg et al., 2002; Laubscher, 1985, 1986, 1987; Madritsch et al., 2008; Ustaszewski and Schmid, 2006).

Triangle zones are typical structural elements of thin-skinned fold-and-thrust belts and are often found at their frontal toe (e.g. Jones, 1982; Price, 1981; Vann et al., 1986). The term "triangle zone" is used in a different manner for structures evolving in truncating thrust systems (Elliott, 1981) or for intracutaneous wedges (for discussion see McClay, 1992). Herein, it will be used for structures, which typically comprise at least two thrust faults, a forward-directed imbricate thrust and a back thrust, which converge at the structure's frontal tip. The localization of such triangle zones is regarded to be mainly influenced by the characteristics of the basal décollement (Sans et al., 1996), while their geometry fundamentally depends on the existence of secondary detachments in the overlying strata (Couzens-Schultz et al., 2003).

In this study we analyze an only recently identified, rather unusual triangle zone located at the front of the Jura Mountains in northern Switzerland, which is considered a type example of a thin-skinned fold-and-thrust belt (Buxtorf, 1907; Laubscher, 1961). Our structural analysis of the triangle zone is based on the interpretation of reflection seismic data, supported by the integration of surface and borehole geological data and geometrical cross-section restorations to illuminate its tectonic development. The results shed new light on the faulting styles of mildly deformed sedimentary cover sequences in orogenic foreland settings and the potentially significant role of structural inheritance in this regard. The investigated triangle zone is also of regional geological relevance as its formation played a crucial role for the localization of the Jura thrust belt front, a matter of long lasting scientific discussions (cf. Amsler, 1915; Buxtorf, 1916).

2. Regional geological setting

The area of investigation is located in the Swiss part of the northern Alpine foreland, where the eastern tip of the arcuate Jura fold-and-thrust belt pinches out into the northern parts of the North Alpine Molasse Basin near Zürich (Fig. 1). The Jura fold-and-thrust belt represents the external deformation front of the Central Alps between Grenoble to the SW and the eastern termination of the Jura fold-and-thrust belt near Zürich and is widely accepted to have formed by "distant push" (Buxtorf, 1916; Laubscher, 1961, 1977, 1987). According to the "distant push" hypothesis shortening in the Central Alps involving the imbrication of Crystalline Massifs was transferred into the foreland along a basal décollement horizon located in Middle to Upper Triassic

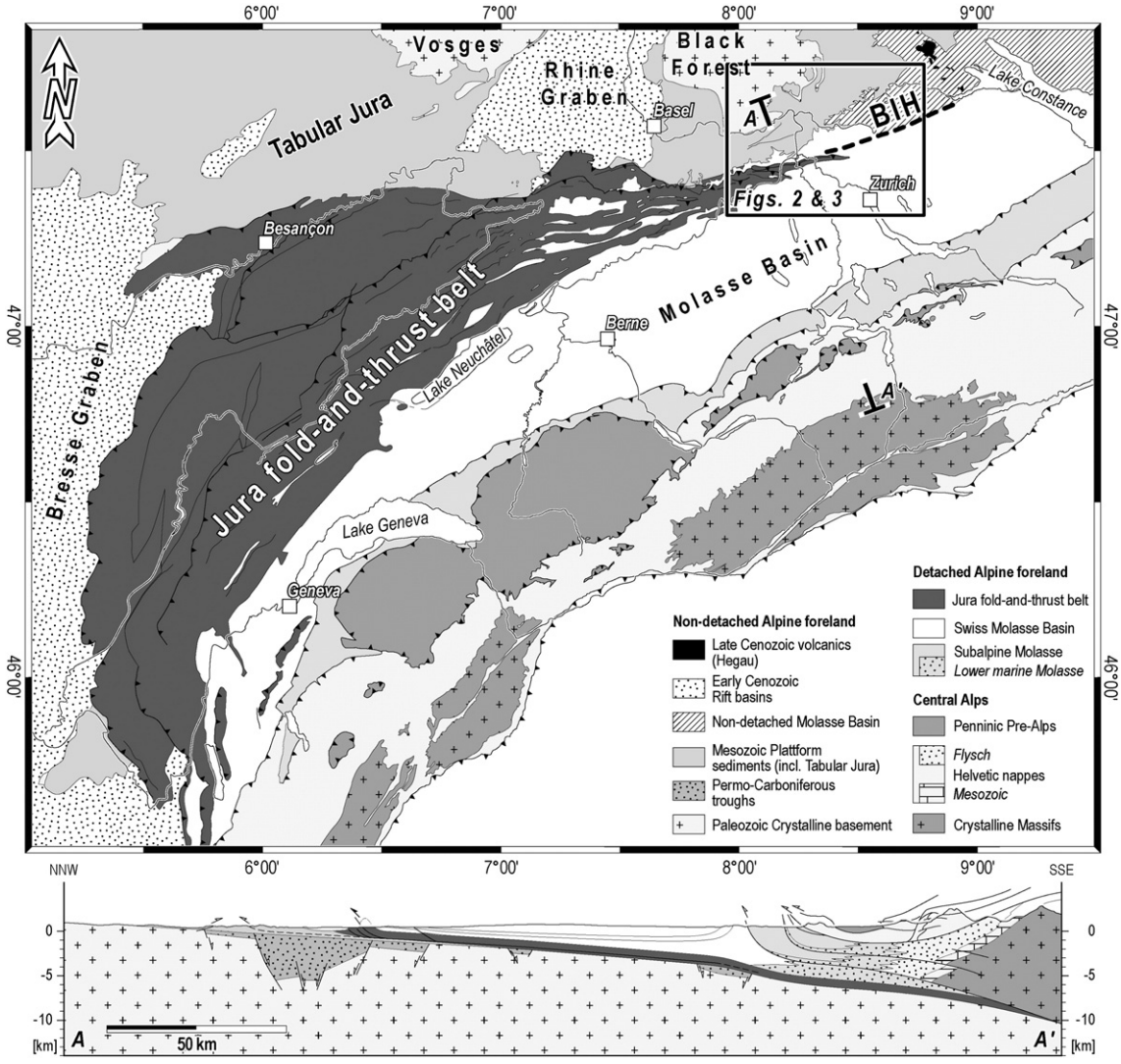

Fig. 1. Simplified tectonic map of the northwestern Alpine foreland and surrounding areas (modified after Bonnet, 2007) showing the setting of the present study at the eastern tip of the Jura fold-and-thrust belt. The black T-shaped marks outline the trace of the shown cross section (modified after Pfiffner, 2010).