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In-Sequence /Out-Of-Sequence Thrusting - Governing Processes and Implications: an Example from the Subalpine Molasse Basin

V. Schuller and U. Herzog
OMV Exploration&Production, Austria (volker.schuller@omv.com)

This work aims to reconstruct the dynamics and unravel compressive tectonic structures in order to understand the processes which led to the present day subsurface and surface constellations within the German Subalpine Molasse Basin.
Recent oil and gas exploration focused on the deeper subsurface of the German Subalpine Molasse Basin in Bavaria. Approximately 500 km of 2D and 220 km2 3D seismic data was acquired within the last decade which was entirely available for this study. Interpretation on seismic lines in conjunction with surface geology data were used to perform section balancing on several cross section lines. Geometrical reconstruction and modelling was done with aid of the 2DMove software package by MVE. The results of the restoration of major thrusts reflects that at least two stages of thrusting sequences occurred: (1) in-sequence thrusting generated foreland-/north verging duplex thrusts with formation of triangles and (2) out-of-sequence thrusting with north-verging emergent thrusts. The governing process for this development is proposed to be the progressively increased erosion towards the hinterland levels of the elevated taper of the Molasse deposits.
The Oligocene to Upper Neogene northern Alpine Molasse Basin formed during the final phase of the Alpine orogeny. Sediments were deposited in the accommodation space generated by the down-bending European plate. They underwent several syn-sedimentary and post-sedimentary tectonic deformation stages. The German part of the Molasse Basin has been separated into an undisturbed (autochthonous) and disturbed (allochthonous) unit, in some areas with a transition zone – the par-autochthonous. Triangles are visible in the par-autochthonous unit and have to be inferred for the allochthonous units too. Early formed duplex structures were dissected by the later out-of-sequence thrusting. A number of duplexes were modelled in order to obtain the structures which are required prior to out-of-sequence thrusting. Out-of-sequence thrusting can be proven on seismic: e.g. fault-bend-folding present in the foot-wall of a thrust is not visible in the hanging-wall.
With regards to the sequence of tectonic events the following picture can be drawn: initially detachments occurred along the base of the Molasse sediments. Flat-ramp-flat structures generated several duplexes and triangle zones. Thrusting occurred in-sequence from south to north. Early Molasse sediments only are incorporated into this thrusting stage. The subsequent phase is marked by thrusts reaching shallower sections and surface levels. Restoration showed that these thrusts occurred successively out-of-sequence from north to south.
The steering process for the out-of-sequence thrusting is proposed to be the movement of the critical wedge from north to south. Establishing of a stable surface drainage system led to increased erosion in the southern part of the basin. Flattening of the critical wedge resulted in relaxation in the overburden. In order to keep its predefined angle, the critical wedge now had to move south, towards the hinterland. Thrusting was able to develop again in the area towards the hinterland.