Critical taper analysis of the North Alpine Thrust Wedge, SE Germany

Influence of fluid overpressure on fault strength in a subaerial orogenic wedge

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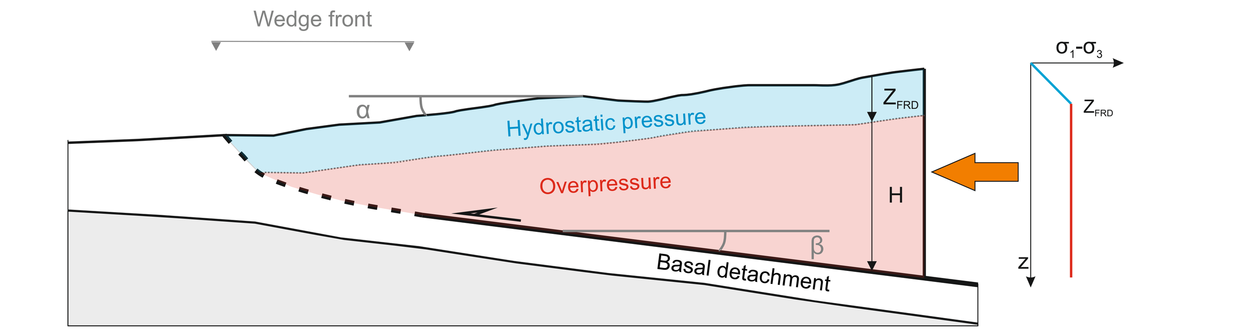
Critical taper theory

Weak detachments below active thrust fronts of subaerial orogenic wedges are mostly controlled by wedge taper geometry. A common method to investigate wedge properties is critical taper analysis. According to critical taper theory fault strength in a mechanically homogeneous wedge can be constrained from surface slope angle α and the angle of inclination of the basal detachment β [1]. However, the influence of fluid overpressure on fault strength is often underestimated. Here, we present a simplified 3D wedge taper model of the North Alpine Thrust Wedge (SE Germany) between Lake Constance and the Inn Valley which is used for critical taper analysis. Different scenarios with varying input parameters are considered, with special emphasis on fluid overpressure ratios.



$$F = \alpha + (\alpha + \beta)W \quad (1)$$

$$\alpha + \beta = \frac{\beta + \mu f\left(\frac{ZFRD}{H}\right)}{1 + kC\left(\frac{ZFRD}{H}\right)} \quad (2)$$

Fig. 1: Simplified critical taper model of a subaerial thrust wedge [modified from 3]. Dimensionless detachment strength F is a function of surface angle α, dip of detachment β and a dimensionless factor W (1), which describes the internal wedge strength (usually ± 1, see [3]). In case the wedge is at least partly overpressured, total height of the overpressured section needs to be taken into account (2)[3].
Z_{FRD} = fluid retention depth, μ_f = fault friction, k_c = internal friction (compression). Taper angles are given in radians.

Study area and tectonic framework

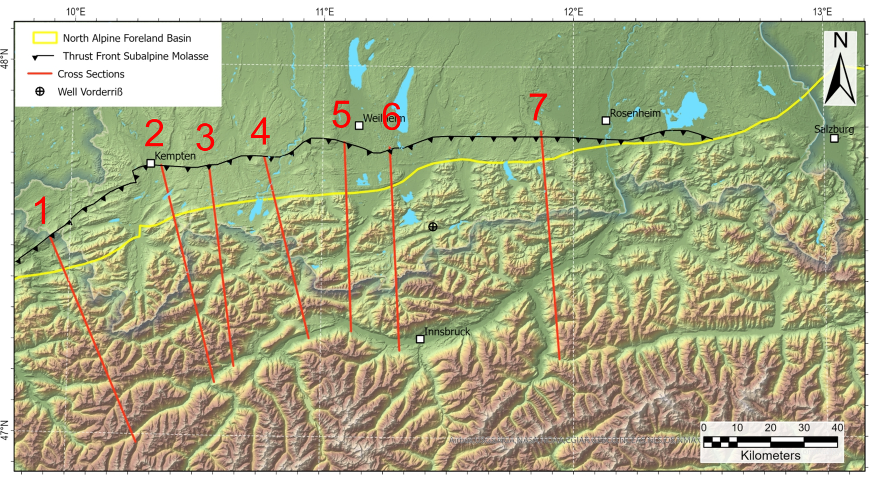


Fig. 2a: Shaded relief map of the study area with locations of cross sections and wellbores used for interpolation of the basal detachment. Sections 1 to 6 are based on [4], data on section 7 is taken from [4] and [5].

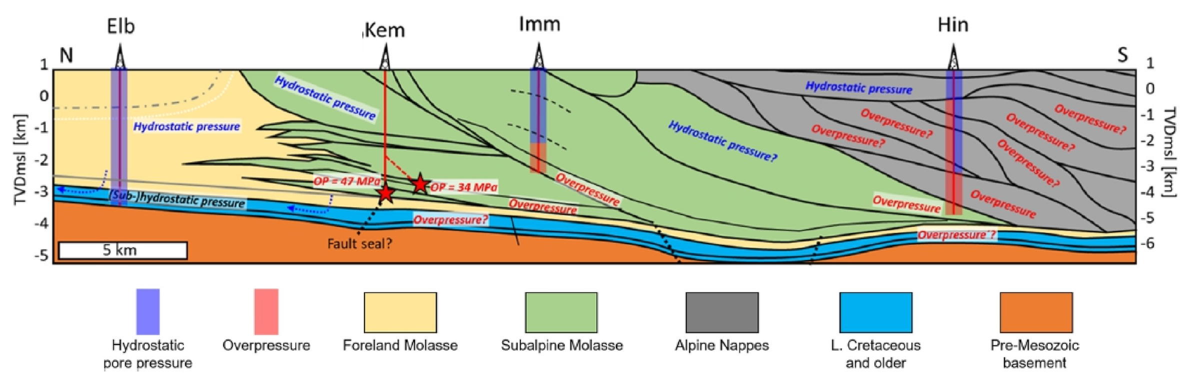


Fig. 2b: Cross section 2 exemplifies fluid overpressure distribution within the western part of the North Alpine Thrust Wedge (from [10]). Overpressured cells can be observed within the Subalpine Molasse and Alpine nappes. The Foreland Molasse, however, is hydrostatically pressured in this area.

3D Model - Wedge geometry

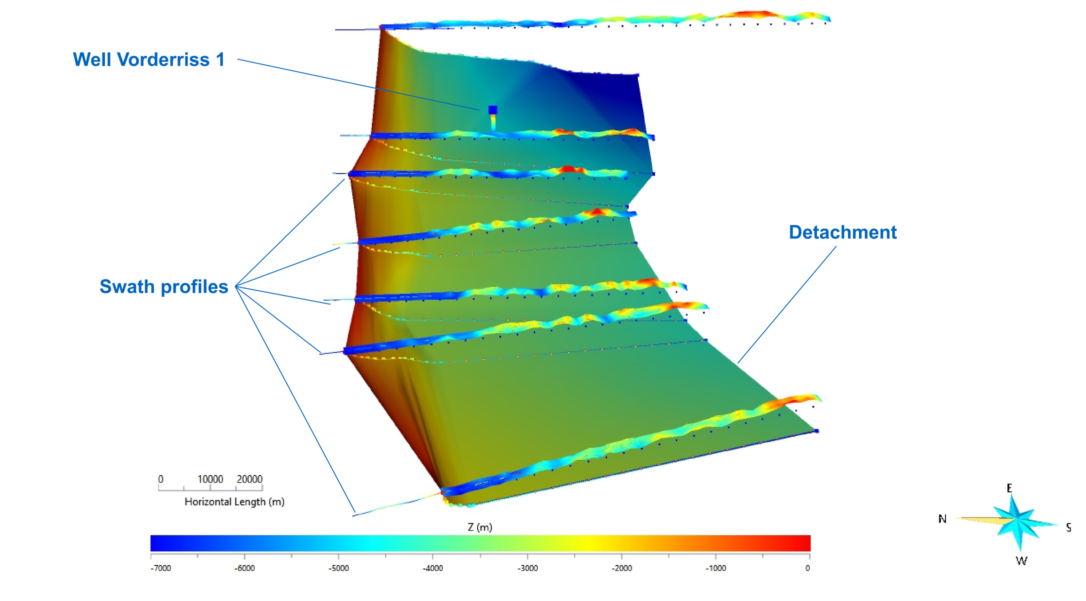


Fig. 3a: 3D model of the study area. The basal detachment is interpolated from seven cross sections and one borehole, according swath profiles are based on LIDAR data. Colors indicate elevation and depth, respectively.

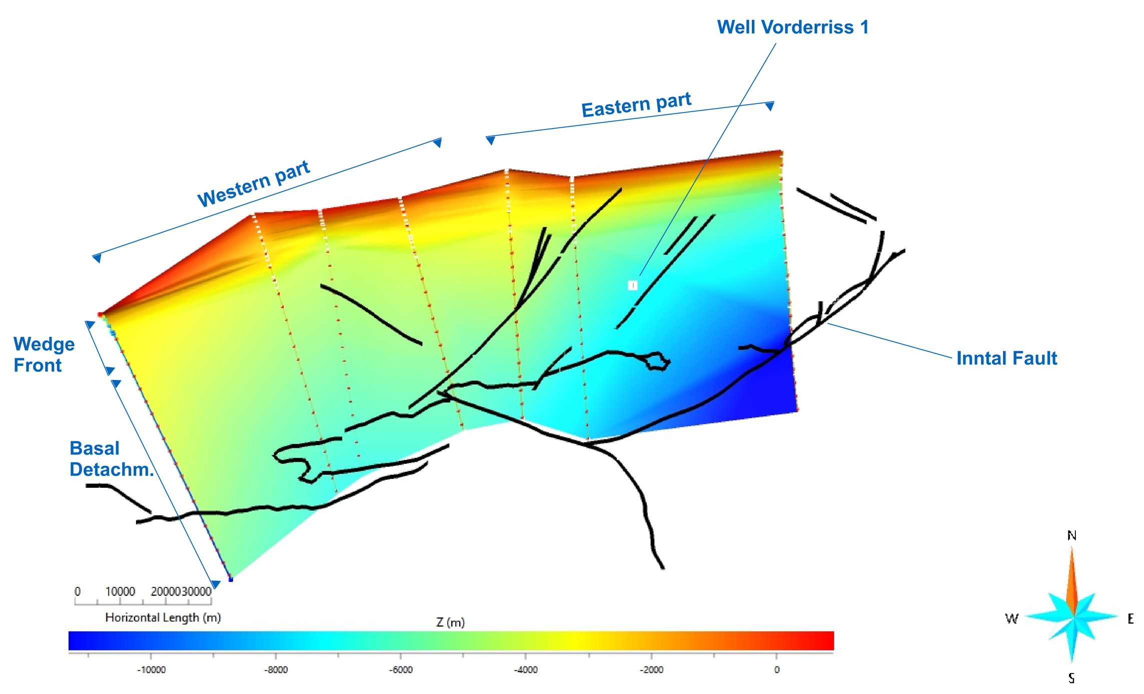


Fig. 3b: The study area can be divided into a western and an eastern part, respectively. Based on published data on pore fluid overpressure in the thrust wedge [10] the western part is assumed to be locally overpressured, whereas in the eastern part evidence for significant overpressure is missing. Black lines represent major fault systems.

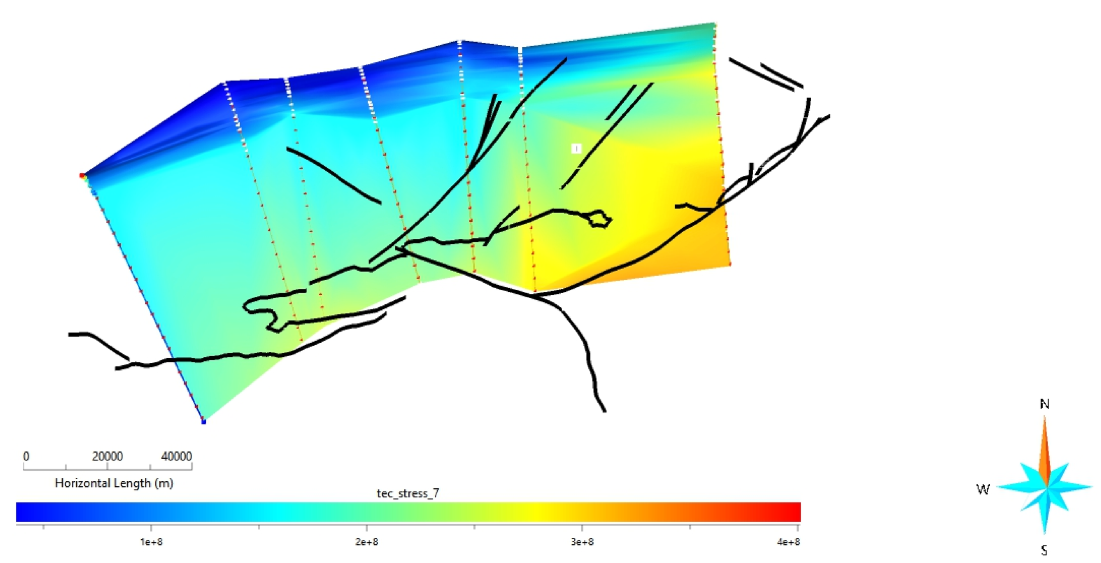


Fig. 3c: Interpolated detachment shear strength for scenario 7. According to our results shear strength increases towards the eastern part even when sigificant fluid overpressure is assumed.

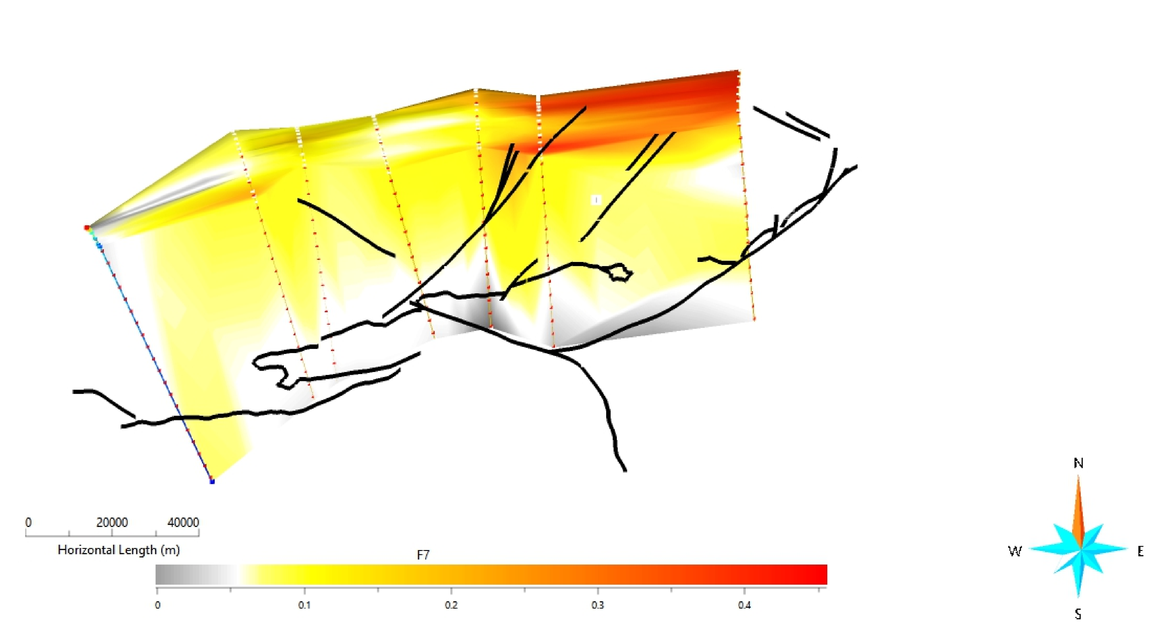


Fig. 3d: Spatial distribution of detachment strength F (scenario 7) with comparatively high pore fluid overpressure (see **Tab. 1** for values).

Pore fluid pressure and Fault strength

- Various scenarios on fluid pressure distribution within the detachment and the frontal wedge are considered for fault strength calculation.
- Data on measured overpressure and fluid retention depth (z_{FRD}) in the frontal part of the wedge are taken from [10].

Tab. 1: Compiled fluid pressure properties used for critical taper analysis.

Scenario	Structural element	Cross section 1	2	3	4	5	6	7
1	Wedge Front λ	0.4	0.4	0.4	0.4	0.4	0.4	0.4
	Detachment λ	0.4	0.4	0.4	0.4	0.4	0.4	0.4
2	Wedge Front λ	0.4	z_{FRD}	z_{FRD}	0.4	z_{FRD}	z_{FRD}	0.4
	Detachment λ	0.4	z_{FRD}	0.4	0.4	0.4	0.4	0.4
3	Wedge Front λ	0.9	0.9	0.9	0.9	0.9	0.9	0.9
	Detachment λ	0.4	0.4	0.4	0.4	0.4	0.4	0.4
4	Wedge Front λ	0.9	0.9	0.9	0.9	0.6	0.6	0.6
	Detachment λ	0.4	0.4	0.4	0.4	0.4	0.4	0.4
5	Wedge Front λ	0.9	0.9	0.9	0.9	0.7	0.7	0.7
	Detachment λ	0.4	0.4	0.4	0.4	0.4	0.4	0.4
6	Wedge Front λ	0.9	0.9	0.9	0.9	0.7	0.7	0.7
	Detachment λ	0.4	0.4	0.4	0.4	0.4	0.4	0.4
	Detachment φ	35°	35°	35°	35°	35°	35°	35°
7	Wedge Front λ	0.9	0.9	0.9	0.9	0.7	0.7	0.7
	Detachment λ	0.8	0.8	0.8	0.8	0.8	0.8	0.8
8	Wedge Front λ	0.9	0.9	0.9	0.9	0.7	0.7	0.7
	Detachment λ	0.4	0.4	0.4	0.4	0.4	0.4	0.4
	Taper α	2.81°	2.68°	2.96°	3.25°	2.72°	3.43°	2.31°

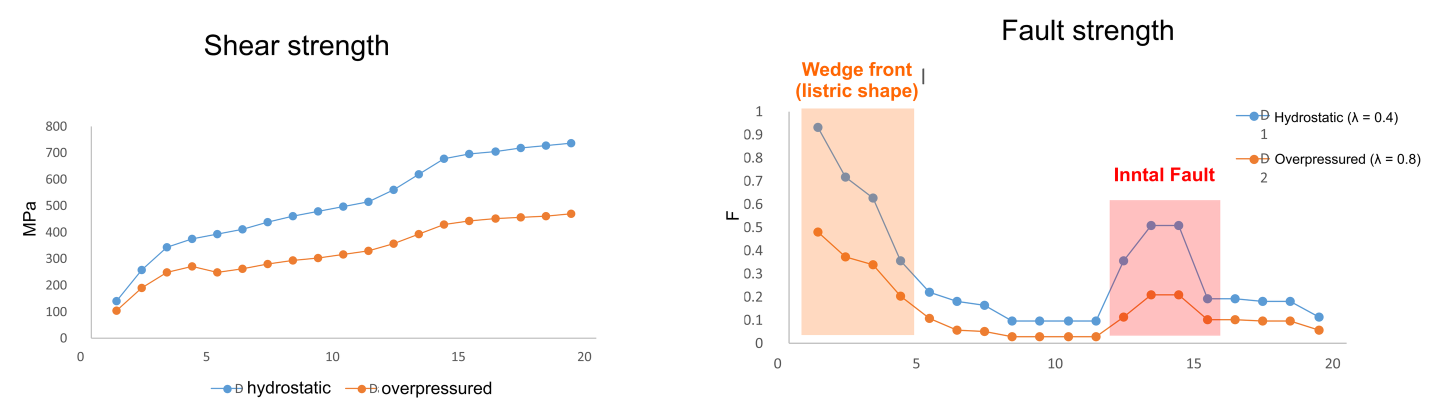


Fig. 4: Comparison of critical shear strength (left) and detachment strength F (right) for cross section 7 with respect to hydrostatic (λ = 0.4) and overpressured (λ = 0.9) conditions. X-axis shows data points along cross sections. Note how fluid overpressure impacts especially where detachment geometry is changing abruptly.

Methodology

- Surface slope angle α inferred from swath profiles along seven sections of interest using a digital elevation model (ArcGIS Pro/ESRI)
- Angle of detachment β derived from published interpretations of respective seismic sections, deep wells and structural models of the Northern Limestone Alps (frontal part of the wedge after [4], section 7 based on TRANSALP profile [5], structural models from [6, 7], deep well Vorderriss 1: [8])
- Interpolation of constructed cross sections and subsequent development of a 3D model of the basal detachment using SKUA (Paradigm) (compare [2])
- Angles α & β determined along the profiles in 3 km intervals. Angle measurement and detachment strength calculation was done automatically using a specially developed Python script [9].

Preliminary results and Conclusions

- **Fluid pressure:** Significant impact on detachment strength → F locally reduced by ca. 60% (λ 0.4 ↔ 0.8)
- **Geometry:** Especially faults that cause local steepening in the basal detachment result in a drastic increase in fault strength (e.g. Inntal Fault / section 7)
- **Western part:** Depth of basal detachment roughly coincides with seismogenic zone [13]. Overpressure in this area likely close to lithostatic conditions [see 10]
- **Eastern part:** Fault development (→ Inntal Fault) likely responsible for (a) reduced thrusting and associated uplift in the Mangfall Mountain area and (b) simultaneous uplift and exhumation of the Tauern Window complex along the Tauern ramp [compare 11,12]

Open questions and Outlook

- **Slab theory:** Influence of slab break-off on geometry of the detachment and wedge evolution [see 12]?
- **Role of fault zones and overpressure cells within wedge** → wedge strength may be locally reduced
- **Refine model** of the basal detachment in order to better understand role of geometry
- **Sensitivity analysis:** Compare impact of geometry vs. pore fluid pressure on detachment strength

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Related research

Mahmoodpour, S., Drews, M., and Duschl, F.: Geomechanical forward modeling of the stress field, pore pressure and compaction in the North Alpine Thrust Front, SE Germany, EGU General Assembly 2023, Vienna, Austria, 24–28 Apr 2023, EGU23-7038.

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