NEHRP Final Technical Report

USGS Award Number: G12AP20063

Title of award: **Testing models of thin-skinned vs. basement-involved faulting in the Yakima Fold and Thrust Belt, Washington**

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Award Period: March 2012-March 2013

Abstract

The Yakima Fold and Thrust Belt in the Columbia Basin of central Washington shows abundant evidence for geologically recent deformation and earthquakes. The Olympic-Wallowa Lineament (OWL) appears to connect these active folds across the Cascade Range to active faults in the Puget Lowland. The size and depth of the faults that underlie the Yakima Folds is not known. The depth of faulting is a first order problem in evaluating seismic hazard, modeling long-term growth of the folds, and understanding regional tectonics and seismogenesis. We report on bedrock mapping and characterization of the surface expression of western Umtanum Ridge, a significant structure at the center of the Fold Belt and within the OWL, and describe initial findings that constrain the geometry and kinematics of the underlying fault or faults. Results include: a new bedrock geologic map of the western Umtanum Ridge at Yakima River Canyon and exploration of the range of fault geometries consistent with western Umtanum as a fault propagation fold. These results are consistent with interpretation of shallow "thin skinned" faulting responsible for the structural relief produced by the folds, but do not rule out other interpretations that permit "thick skinned" deformation.

Introduction and geologic setting

The Yakima Fold and Thrust Belt (YFB) is a central structural feature of the Columbia Basin, east of the Cascade Range in Washington. The fold array comprises a dozen east-west or southeast-northwest trending anticlines that deform flows and associated sedimentary units of the late-Miocene Columbia River Basalt Group (*e.g.* Reidel et al. 1989a). Paleoseismic investigations reveal late Quaternary faulting associated with many folds (USGS 2006; Campbell & Bentley 1981; West et al. 1996; Blakley et al. 2011), commonly attributed to flexural slip during fold growth. Uplifted late Quaternary deposits also attest to active growth of the folds (Reidel, 1984; Ladinski et al. 2010). Geodetic and geologic observations suggest that the folds accommodate north-south shortening at present rates of about 3 mm/yr (McCaffrey et al. 2007, 2013; Wells et al. 2009), with deformation rates declining to the east (McCaffrey et al. 2013). Background seismicity is abundant and diffuse (Gomberg et al. 2011) with weak spatial correlation to mapped structures across the region; Finnegan and Montgomery (2003) associate planar clusters of relocated earthquakes with specific folds. Published earthquake focal mechanisms are generally consistent with thrust faulting, and a significant fraction of the events show strike-slip mechanisms (compilation in McCaffrey et al. 2007).

The subsurface structure of the folds is not well known, and remains a critical concern for seismic hazard evaluation (e.g. Chamness et al. 2012). The basic stratigraphy of the region includes pre-Tertiary crystalline basement overlain by Tertiary sedimentary rocks (Catchings and Mooney 1988, Campbell 1989). These, in turn, are covered by up to several kilometers of Columbia River Basalt Group (CRBG) and topped by Quaternary deposits (Campbell 1989; Riedel et al. 1989; Baker et al. 1991). Most previous published structural interpretations of the Yakima folds has presumed that the deformation is "thin-skinned," that is, constrained to the basalt and detached from the basement on horizon(s) above or within the Tertiary sediments (*e.g.* Bruhn 1981; Campbell & Bentley 1981; Watters 1988; Riedel et al. 1989). This interpretation restricts the height of faults coring the folds and thus the magnitude of potential earthquakes. An alternative hypothesis, informed in part by potential field studies, is that the Yakima folds are the surface expression of basement-involved faulting (*e.g.* Bentley 1977; Blakely et al. 2011). Gravity data, in particular, seem to require significant relief on the top of pre-Tertiary basement (Saltus 1993), as do some seismic reflection data (Jarchow et al. 1991). A basement-fault origin for the folds does not restrict the height of the faults, and therefore would permit larger magnitude earthquakes.

The YFB sits astride a larger, enigmatic tectonic element, the Olympic-Wallowa Lineament (OWL). First recognized on geomorphic maps by Raisz (1945), the OWL strikes northwest across the state of Washington, from the Olympic Peninsula, across the Cascade Range, through the Columbia Basin, and into northeast Oregon. The nature of the OWL has been elusive, but it is posited to represent a major crustal structure accommodating contraction (McCaffrey et al. 2007, Blakely et al. 2011) and/or dextral shear (*e.g.* Wise 1963; Hooper and Conrey 1989; Pratt 2012). Recent work traces the OWL as it connects the active faults in the Puget Lowland across the Cascades to the YFB (Blakely et al. 2011). Unraveling the role of the OWL in regional tectonics is key to evaluating and advancing models of active crustal deformation, such as the influence of forearc migration east of the Cascades (Wells et al. 1998; Wells et al. 2009). These models, in turn, provide the framework for understanding and anticipating regional earthquake distributions. Structural characterization of the YFB provides critical information that can constrain the long-term kinematics of the OWL and inform broader regional understanding of seismogenesis.

Research approach

Here, we report on high-resolution bedrock mapping and structural study of western Umtanum Ridge, a key structure in the central YFB and within the OWL. Rigorous structural interpretation of western Umtanum Ridge may serve as a case study for evaluating the structural style (shallow vs. deep faulting) of other folds in the region and will contribute to understanding the tectonic role of the OWL. Well-established geometric analyses are used to evaluate geometry of faulting in at western Umtanum Ridge.

A number of different hypotheses for the sub-surface structure of folds in the YFB have been proposed, explicitly or implicitly, by previous workers, schematically illustrated in Figure 2. These range from fully-detached buckle folds in which faults are minor secondary features (Watters 1988; 1989), to deeply-rooted basement-involved faulting (Bentley 1977; Blakely et al. 2011) and include folds driven by shallowly-rooted blind or emergent faults (Riedel 1984; Finnegan & Montgomery 2003) with kink-style (Price and Watkinson 1989) or trishear deformation, and fault-bend folding (Bruhn 1981). It is possible also to consider a hybrid model involving both basement and shallow faults. This last arrangement of faults honors the mechanical constraints on basement thrusting beneath layered rocks (Schultz 2000; Lin & Stein 2004) and is similar to geometric interpretations of the Seattle Fault zone (Brocher et al. 2004, Kelsey et al. 2008). Each of these model hypotheses predicts specific relationships among the geometry and displacement of fault(s) in the subsurface and the structure of the fold at the surface. For example, a fault-propagation fold produces a tighter, higher amplitude fold with a steeper forelimb than a fault bend fold with the same underlying fault geometry. Detailed mapping provides key data with which to test various hypotheses for fault geometry.

Two advances permit examination of the bedrock structure in the YFB in a new light.

1. New lidar datasets (Earthscope, 2010; Puget Sound Lidar Consortium, 2010; Army Yakima Training Center provided by Brian Sherrod, written comm.) provide high resolution topography from which the geologic structure was interpreted (Fig. 1). The images clearly show mappable contacts between flow surfaces. The attitude of these surfaces is determined in a geographic information system, yielding strike and dip data. Thus it is possible to remotely acquire bedding/flow attitudes over a wide area. Lidar provides a perspective unattainable in the field and a spatial precision unmatched by aerial photography, greatly enhancing our ability to produce an accurate structural interpretation. Lidar interpretation complemented field efforts and compilation of prior mapping.
2. Modern, cross-section development software facilitates generation and testing of multiple alternative scenarios. Midland Valley Exploration's *Move* suite of software was used to construct two-dimensional cross sections representing the alternative hypotheses presented above.

Results

Our new geologic map of western Umtanum Ridge (Fig. 1) synthesizes new field observations, new interpretation of LiDAR DEMs and existing published (Bentley and Campbell 1983; Bentley et al. 1993) and unpublished (Jack Powell, written comm.) geologic maps. Compared to prior published maps, the density of structural observations is significantly increased and the position of unit contacts and faults is confirmed or refined.

Bedrock map units are as follows:

> Quaternary undifferentiated (Qu): Includes modern alluvium and alluvial fans found in and adjacent to the Yakima River and its tributaries. Note that this does not include numerous Quarternary landslides which were not mapped for this study.
>
> Upper flows of Columbia River Basalt Group (CRBu): Includes the Pomona Member of the Saddle Mountains Basalt, Priest Rapids and Roza Members, both of the Wanapum Basalt, as well as the intercalated sedimentary rocks of the Ellensburg Formation. We grouped these members to aid in the structural analysis because they are very thin (10s of meters each) compared to lower units. All these members are older than 12 Ma (Reidel et al. 1989b).
>
> Frenchman Springs Member, Wanapum Basalt (FS): Includes at least two flows in this area the youngest of which is dated to 15.3 Ma (Reidel et al. 1989b). The underlying Vantage Sandstone of the Ellensburg Formation is also included. The Frenchman springs Member has a maximum thickness of 100 m in the map area.
>
> Upper flows of normal polarity, Grande Ronde Basalt (GRn2): Youngest flows date to 15.6 Ma (Reidel et al. 1989b). This unit has a minimum thickness of 300 m based on the YM 1-33 borehole located adjacent to the Yakima River in the core of the southern anticline in the map area.
>
> Upper flows of reversed polarity, Grande Ronde Basalt (GRr2): Comprised of the uppermost reversely magnetized Grande Ronde Basalt flows. Unit has a minimum thickness of 750 m based on the YM 1-33 borehole.

The geologic map and structural data were used to constrain the geometry of the western Umtanum anticline. Umtanum anticline is a southeast plunging, north verging, asymmetric fold, which deforms at least the entire Columbia River Basalt section. At its eastern end, the anticline plunges beneath Quaternary deposits near the Hanford Nuclear Reservation. At its western end the fold loses definition at the edge of the Columbia River Basalt and rocks of the Cascade Range. In the map area, the Yakima River cuts its canyon through the Umtanum anticline, offering exposure with which to characterize its geometry.

The geometry of the anticline, in turn, constrains the range of possible fold-related faults in the subsurface. We have evaluated the parameter space of possible fault geometries, assuming the Umtanum anticline is a fault propagation fold. Mitra (1990) defines the geometric relationships among the hinge to limb angles γ and $\gamma*$ of the hanging-wall anticline for both blind and emergent cases, respectively, and the fault cutoff angle θ, assuming, plane strain, conservation of volume, and an anticlinal geometry composed of 2 or 3 dip domains. Following these conventions, the western Umtanum fold geometry can be reproduced by either a blind fault (Figure 2)or an emergent fault (Figure 3). The three solutions presented for the blind case (Figure 2) represent both the mean and extremes in the hinge to limb angle γ (and hence the fault cutoff angle θ), representing the range of fold-limb dips permissible by the flow-top attitudes presented on the map within 1 km of the line of section. The positions of the intersections of geologic contacts and the line of section (specifically the top surface of map unit GRr2) constrain the position of the fault cutoff and the amount of slip, which we determined iteratively using Midland Valley Exploration *Move*.

Figure 2 shows the solutions presented for the case of a blind fault. (A), (B), and (C) show mean, maximum, and minimum values, respectively, for the hinge to limb angle and the fault cutoff angle or dip. This results in a mean fault dip of 31° with maximum and minimum values of 35° and 28°, respectively. In each case the depth to detachment varies but is generally near the base of the CRB as inferred from the YM 1-33 borehole. The amount of slip (propagation) from the detachment ranges from 760 m (A and B) to 910 m (C). The slip has occurred post-emplacement of unit GRr2 because the slip and position of the fault are required to match the observed contact positions of the top of unit GRr2. The fault trace mapped at the surface, then, represents a small fault to accommodate synclinal folding, with a maximum of 150 m slip. One apparent problem with the models is that the other unit contacts do not line up with their mapped positions. This arises because the modeling software requires a stratigraphy which does not vary in thickness. It has been documented that the basalt flows thin over the anticlines and thicken in the synclines (Reidel 1989a). The stratigraphy recorded in borehole YM 1-33 forms the basis for the model stratigraphy therefore representing a minimum thickness, as YM 1-33 drilled the core of the southern anticline.

Figure 3 presents a model of W Umtanum Ridge as an emergent fault propagation fold. In this case two dip domains define the structure of the anticline. This assumption approximates the observed geometry based on measured flow-top attitudes poorly. Nonetheless, we present a model with the mean orientations of the two limbs calculated from forelimb and backlimb flow-top attitude measurements. We omitted the maximum and minimum cases because the emergent fault geometry fit the data poorly. The mean case results in a fault dip of 31° and 1750 m of slip. In contrast to the blind case, the emergent case requires a relatively shallow detachment depth, well within the CRB.

Discussion

The Umtanum Anticline can be plausibly produced by fault propagation folding with geometric constraints as specified by Mitra (1990). Other interpretations are also possible, including “trishear” models (Erslev 1991; Regalla et al. 2010). Quantitative inversion of the fold geometry for fault slip using trishear kinematics is planned.

The kinematic solutions presented here yield a shallowly-rooted fault, consistent with prior interpretation of the eastern end of Umtanum Ridge (Price and Watkison 1989) and with the structural interpretations of the Saddle Mountains Anticline (Reidel 1984; Casale and Pratt, in prep. 2013). A steep fault, deeply routed structure or basement coupling is not required by the fold geometry; but work to date does not preclude the involvement of deeper structures or "thick skinned" deformation. Further work, integrating surface observations with constraints on the geometry of subsurface structures may help resolve questions regarding the degree of coupling or correspondence between faults that deform the surface and the extent and geometry of faulting at depth (e.g. Chamness et al. 2012).

Publications resulting from the work

Miller, B A, J G Crider, 2012, Testing thick-skinned vs thin-skinned faulting in the Yakima fold and thrust belt, Washington: kinematic modeling based on new geologic mapping, AGU Fall Meeting T23E-2731.

Acknowledgements

We are grateful for LiDAR data from the National Center for Airborne Laser Mapping (NCALM), the Puget Sound LiDAR Consortium, and US Army Yakima Training Center LiDAR care of Brian Sherrod. Midland Valley Exporation generously provided *Move* software on an academic license. Field efforts benefitted by assistance from John Lasher and Barb Brim. Jack Powell, Washington Department of Natural Resources, shared unpublished geologic maps of Umtanum Ridge at Yakima Canyon. The research efforts benefitted by conversations with Tom Pratt, Brian Sherrod, Harvey Kelsey, Gabe Casale, and Darrel Cowan.

Figure captions

Fig. 1. Bedrock Geologic Map of the Yakima River Canyon, Kittitas and Yakima Counties, Washington

Fig 2. Cross sections through Umtanum Ridge west of Yakima Canyon (see map for location). Fine black line is topographic profile, small red tics show dip of surface units projected to section line from within 1 km. Units are labeled with map symbols at the right edge of (A), with on the lower CRBG units (pre GRr2) shown in red. Three alternative interpretations are presented, with (A), (B), and (C) illustrating mean, maximum, and minimum values, respectively, for the interlimb angle (γ) in the case where the master fault has not propagated to the surface. See text for discussion. Vertical units are meters above sea level. Horizontal units are meters northeast of cross section origin. Figures produced using Midland Valley's Move software.

Fig 3. Same line of section from figure 2 but for the case where the fault has propagated to the surface. See text for discussion.

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Legend

Unit Contact

- Map boundary
- Line of section
- Contact--identity or existence questionable, location inferred
- Contact--identity or existence questionable, location approximate
- Contact--identity or existence questionable, location accurate
- Contact--identity and existence certain, location inferred
- Contact--identity and existence certain, location approximate
- Contact--identiy and existence certain, location accurate
- Thrust fault--identity and existance certain, location approximate
- Thrust fault--identity and existence certain, location concealed

upright attitude

- field measured, horizonal
- lidar measured
- field measured

overturned attitude

- lidar measured
- field measured

Unit

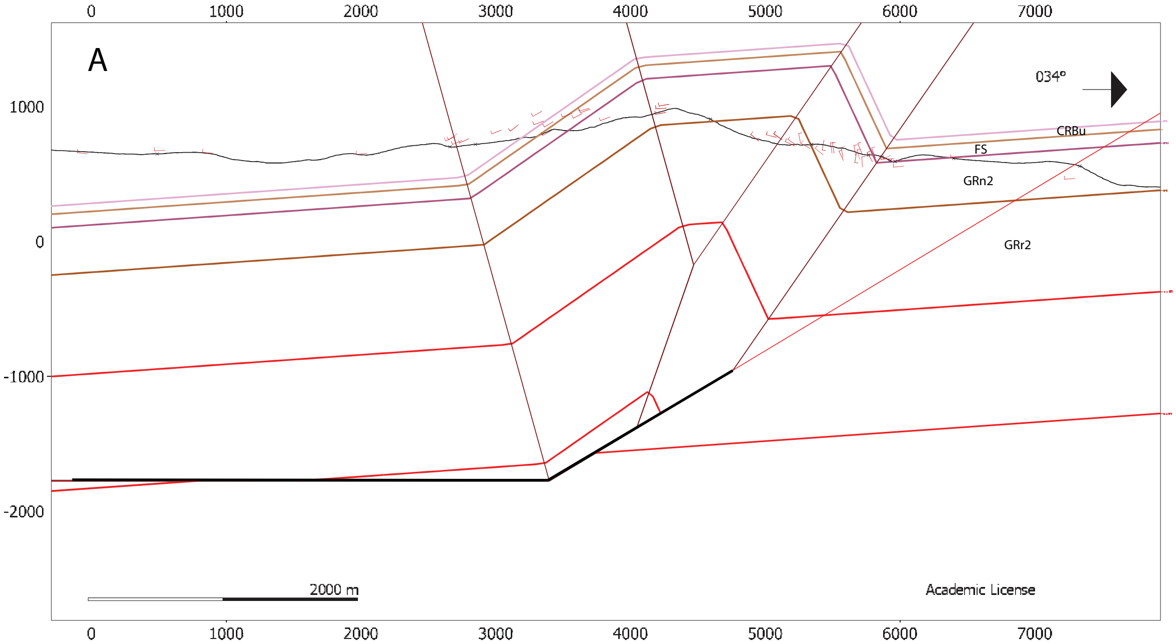
- Qu--Quaternary undifferentiated
- CRBu--Upper flows of Columbia River Basalt Group (see text)
- FS--Frenchman Springs Member, Wanapum Basalt
- GRn2--Upper flows of normal polarity, Grande Ronde Basalt
- GRr2--Upper flows of reversed polarity, Grande Ronde Basalt

Bedrock Geologic Map of the Yakima River Canyon, Kittitas and Yakima Counties, Washington

By
Brendan A Miller

June 2013
compiled from original field mapping, interpretation of LiDAR DEMs,
unpublished maps by Jack Powell WA DNR, and
published maps of Bentley and Campbell 1983 and Bently et al. 1993.
Please see accompanying NEHRP report (Crider and Miller 2013).

Figure 2



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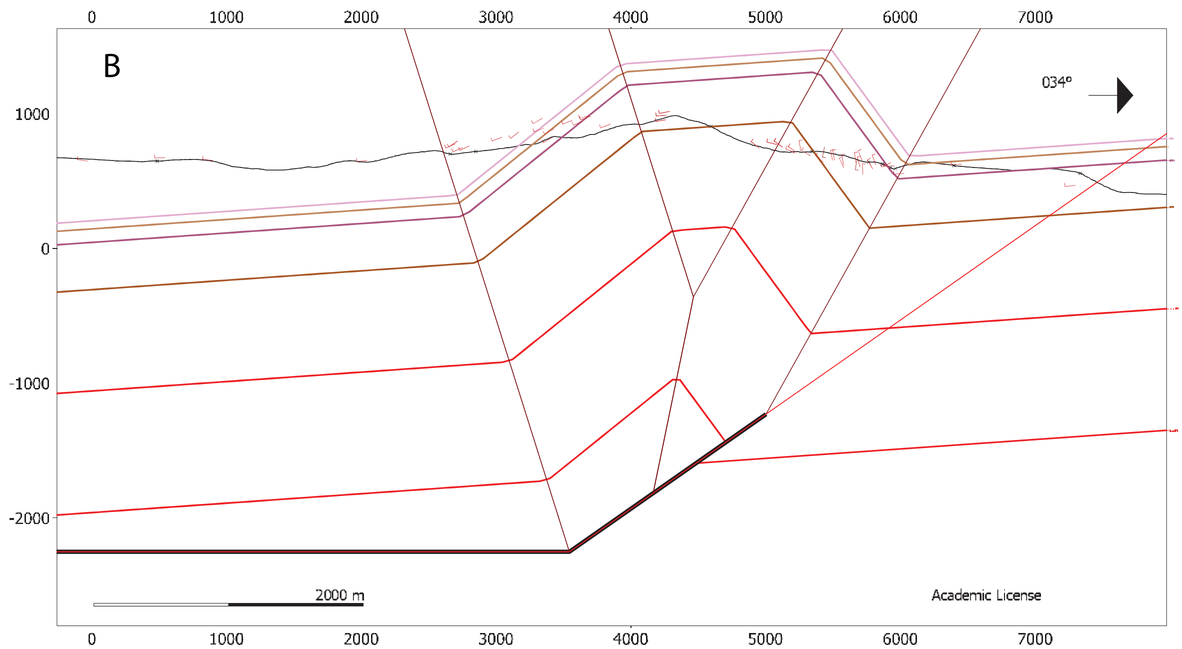

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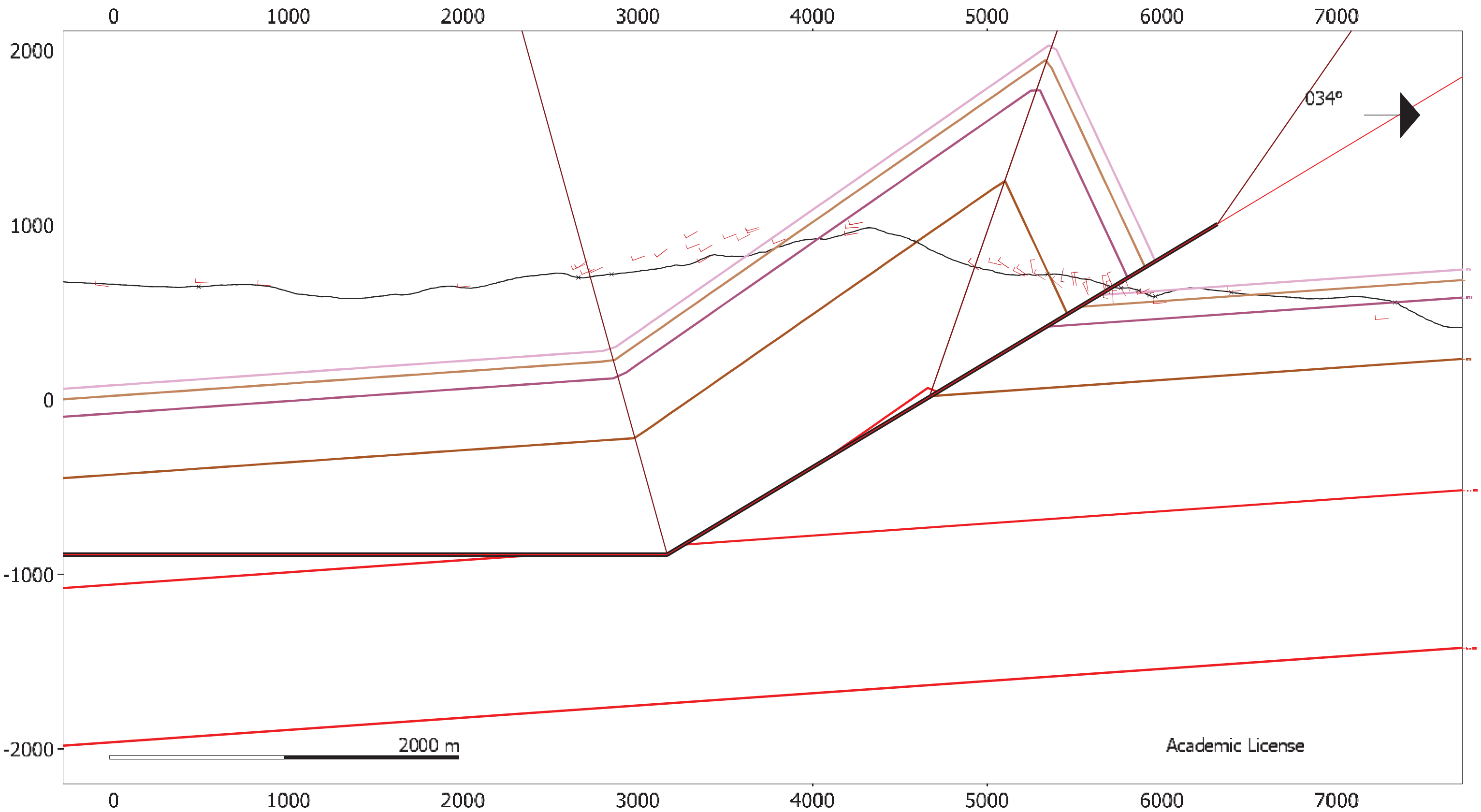
Figure 3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