Editor's Note:
Click to view *outstanding* slides of oral presentation.

Structural Modelling in the Kirthar Fold Belt of Pakistan: From Seismic to Regional Scale*

Ralph Hinsch[1], Chloé Asmar[1], Peter Hagedorn[1], Muhammad Nasim[2], Muhammad Aamir Rasheed[2], Noah Stevens[1], Bernhard Bretis[1], and James M. Kiely[1]

Search and Discovery Article #30546 (2018)**
Posted February 5, 2018

*Adapted from extended abstract prepared for oral presentation and the presentation at AAPG/SEG International Conference and Exhibition, London, UK, October 15-18, 2017.

[1]OMV E&P, Upstream, Vienna, Austria (ralph.hinsch@omv.com)
[2]OMV (PAKISTAN) Exploration GmbH, Islamabad, Pakistan

Introduction

The Kirthar Fold Belt is part of the lateral mountain belts in Pakistan linking the Himalayan orogeny with the Makran accretionary wedge. This region is deforming very obliquely, nearly parallel to the regional plate motion vector (Figure 1, Mohadjer et al., 2010). The Chaman fault (Figure 1A), a large-scale strike-slip fault, is considered to represent the lithospheric plate boundary (transform fault) in this lateral collision zone (Bannert et al., 1992). East of the plate boundary, a 150-200-km-wide deformation zone is present (Bannert et al., 1992; Szeliga et al., 2009). Due to the highly oblique orientation to the plate vector, strain partitioning is ongoing in this lateral deformation zone (i.e., dividing overall displacement into components of shortening and strike-slip deformation, cf. Szeliga et al., 2009, and references therein). For the frontal part of this deformation belt neither the deep structural architecture nor many aspects of the complex deformation are well understood.

Existing structural concepts for the area were developed for the northern Kirthar Fold Belt and the Sulaiman Fold Thrust Belt. These early concepts proposed a passive roof duplex model (Bank and Warburton, 1986; Jadoon et al., 1992). For the southern Kirthar Fold Belt a model of basement inversion with folds in the sedimentary cover had been put forward (Fowler et al., 2004). However, detailed kinematics on how thick-skinned and thin-skinned structures link are not obvious.

The objective of the present study is to clarify the structural architecture in the frontal structures of the central Kirthar Fold Belt for exploration purposes.

Stratigraphy and Mechanical Stratigraphy

The stratigraphic succession of the study area is displayed in Figure 2. This succession is the result of the deposition on the northeastern margin of the Indo-Pakistani plate which developed as part of the northern margin of Gondwana until Triassic/Early Jurassic (Kadri, 1995, and references therein). The study area is approximately situated on the long lived hinge area from the stable shelf to the more extended margin (e.g., Smewing et al., 2002). The oldest rocks outcropping in the wider study area are from the Jurassic and the deepest drilled strata is the Triassic Wulgai Formation. Rocks older than Triassic are only known from distant wells and outcrops. From a mechanical point of view there are several weak horizons observed in the field that display potential detachment horizons, as marked in Figure 2. Additionally, detachment horizons are inferred from seismic interpretation and geometrical analysis, also marked in Figure 2.

Methods and Available Data

Between 2014 and 2016 two new 2D seismic surveys have been acquired (240 km) and processed to PreSDM level. The PreSDM processing benefited from initial structural interpretations incorporated into the velocity modelling.

Surface geology data is obtained from our own field work, as well as from field work of contactors in the area (Tectostrat, 2001; University of . Peshawar, 2014). Furthermore, the interpretation of deformation styles was conducted by analyzing and mapping observable features using Google Earth, which shows very high-resolution image data in the wider study area. Additional bedding dip and strike measurements extracted, using remote sensing techniques, were incorporated into section constructions. Stratigraphic thickness templates were compiled by integrating well data and stratigraphic sections from outcrop observations.

All the data was then integrated for the construction of the cross sections. In order to better constrain the deeper structural architecture of the section, it was necessary to understand the regional to local deformation. To achieve this, regional sections, kinematical forward models and simple analogue modelling experiments were conducted.

Interpretation and Results

Regional to Local Observations

There is a rise in regional elevation of all stratigraphic units towards the west; it exceeds the rise one could expect from thrusting a wedge-shaped body. There is no significant deformation east of the main structures imaged in the 2D seismic. The surface geology does not show any major thrust in the area with old on young stratigraphic contacts (Figure 1C). Instead, the map shows a complex pattern of large- and small-scale folds, as well as areas with relative structural highs and lows numbered in Figure 1C:

1) Relative structural highs are represented by the outcropping Jurassic rocks west of the Kirthar escarpment (Figure 1C). The Kirthar escarpment itself also represents a structural high. There, Kirthar limestones are several thousand meters above the regional level observed in the seismic in the undeformed foreland (cf. Figures 3A and 4A).

2) Relative structural lows are represented by the areas with Miocene to Oligocene rocks outcropping west of the Kirthar escarpment as well as the synclines (Figure 1C).

3) Large scale anticlines with several km of wavelength dominate the map pattern. Most of the anticlines are double plunging and strike in roughly N-S direction, although other directions are present as well (Figure 1C).

4) Small scale anticlines with wavelength much smaller than those of point 3. These folds often fringe the limbs of the large-scale anticlines. The higher frequency of folding indicates that the detachment is relatively shallow compared to the large anticlines.

Seismic Sections Interpretations

Northern Section (Figure 3A)

The northern sector is folding-dominated. No major thrust faults are observed at the surface. The depth to detachment analysis of the main fold on the section indicate a decollement at approximately 9 km below sea level. However, the anticline shows an uplift of regional elevation towards the west, as strata in the syncline west of the anticline is at higher elevation than in the foreland. This uplift is associated with an inverting fault underneath. Towards the deformation front a small triangle zone is present; it is cut by a subsequent thrust fault with a fault-propagation fold on top. The relative timing is constrained by growth strata. The detachment level of the thrust fault is clearly below Jurassic rocks, as these have been drilled in the hanging wall of the fault-propagation fold.

Southern Section (Figure 4A)

The southern section features a frontal structure similar to the northern sector (small triangle structure cut by a subsequent thrust with a fault-propagation fold). The syncline west of the fault-propagation fold is much broader than in the north and indicates a shallower detachment level with a thrust flat (in Jurassic or just below Jurassic). The amount of structural shortening in the frontal anticline from structural modelling is on the order of 5000m.

West of the syncline the regional elevation of the strata packages rises in the order of 6500m towards the Kirthar Escarpment (Figure 4A). This massive amount of regional elevation rise cannot be explained by just 5000m of shortening, which is observed in the frontal structures. The additional shortening required to explain this large uplift is accommodated by some duplexes below the very weak Eocene Ghazij shales, which act as passive roof back-thrust. The duplexes originate from an inverting normal fault, partly shortcutting into the footwall.

Regional to Local Deformation Model

Strain partitioning is present along the lateral margin of India. Strike-slip deformation dominates the rear of the mountain belt, whereas dip-slip faulting dominates the deformation front. Some of these faults show angles between 45 and 50°, based on focal mechanisms. These steep reverse faults indicate fault reactivation rather than newly generated thrust faults. The best model to explain all the observations in the region is an inversion model (Figure 5). With systematic analogue models Yamada and McClay (2004) have shown that the geometry of a half graben controls the geometry of the anticline while the system is inverted (Figure 5 A, B). If we consider that the inverting fault is not breaking to the surface through the post-rift sediments but is rather linking with a detachment horizon, we can get a large-scale anticline with a plunging axis (from the inverting normal fault) and higher frequency folding on the shallow detachment in front of it (Figure 5C). A more complex system of normal faults/half grabens including relay ramps and other complex fault configurations of rift systems (Figure 5D) in the subsurface can be potentially expected to be responsible for generating the observed complex map pattern after inversion (Figure 1C). Consequently, folding and faulting, as observed in the sections, are linked to inverting normal faults. In the southern section deformation seems to be related to one large normal fault, as the observed massive regional elevation uplift occurs along a single structure. The northern section shows a more gradual regional elevation gain; hence several smaller inverting normal faults at depth can be assumed.

Conclusions

The structure of the frontal part of the Central Kirthar Fold Belt is controlled by inversion with linked thin-skinned deformation (duplex/thrusting and folding). The shortening on different balanced sections in the study area is 8.5 – 10 km (around 19-24% depending on pin positions, Figures 3B and 4B). The northern sector shows large- scale detachment folding, uplifted by inverting faults. The southern sector is dominated by a large-scale single structure, indicating one major inverting fault in the subsurface. Detachment depths of the coupled frontal thin-skinned structures is deeper in the northern sector (likely Triassic) than in the southern sector (likely Jurassic). Laterally changing mechanical properties of the decollement horizons as well as different spacing of inverting normal faults seem the most likely explanation for the observed differences.

The study results are in line with the results from southern Kirthar Fold Belt, where some basement-involved/inversion style of deformation was considered by Fowler et al. (2004). Nevertheless, duplexes, in part, are present in our study area, but they are smaller and accommodate less shortening than those anticipated by Banks and Warburton (1986). Duplexes in the southern sector of this study form as a result of the imbrication above an inverting normal fault (including footwall shortcuts) in combination with a suitable decollement horizon for the roof thrust.

Acknowledgments

Several colleagues at OMV Pakistan contributed input in the course of the study (i.e., Waqas Ahmed, Shaista Sultan, Muhamad Ibrahim, Muhammad Asif Abbas). Also additional colleagues at OMV in Vienna where involved or contributed through discussions (e.g., Klaus Pelz, Wolfgang Thöny, Maziar Haghighi). The Mehar EL Joint Venture (OMV, OPL, ZPCL, GHPL) is thanked for the permission and opportunity to present and publish the study. Analogue modelling was performed at the University of Vienna.

Selected References

Banks, C.J., and J. Warburton, 1986, 'Passive-roof' duplex geometry in the frontal structures of the Kirthar and Sulaiman mountain belt, Pakistan: Journal of Structural Geology, v. 8, p. 229-237.

Bannert, D., A.Cheema, A. Ahmed, and U. Schafer, 1992, The structural development of the western fold belt. Pakistan: Geologisches Jahrbuch Reihe B, v. 80, p. 3-60, including 3 maps 1:500000.

Dewey, J.E., R.E. Holdsworth, and R.A. Strachan, 1998. Transpression and transtension zones, *in* R.E. Holdsworth, R.A. Strachan, and J.E. Dewey, editors, Continental Transpressional and Transtensional Tectonics: Geological Society, London, Special Publications, no. 135, p. 1-14. Website accessed January 17, 2018, http://sp.lyellcollection.org/content/specpubgsl/135/1/1.full.pdf.

Fowler, J.N., R. Graham, W. Sassi, J.D. Smewing, and J. Warburton, 2004, Two-dimensional kinematic modeling of the southern Kirthar fold belt, Pakistan, *in* R. Swennen, F. Roure, and J.W. Granath, editors, Deformation, Fluid Flow, and Reservoir Appraisal in Foreland Fold and Thrust Belts: AAPG Hedberg Series, no. 1, p. 117–131.

Haq, S.S.B. and D.M. Davis, Oblique convergence and the lobate mountain ranges of western Pakistan: Geology, v. 25, p. 23-26.

Hughes, A.N. and J.H. Shaw, 2014, Fault displacement-distance relationships as indicators of contractional fault-related folding style: AAPG Bulletin, v. 98, p. 227-251.

Jadoon, I.A. K., R.D. Lawrence, and R.J. Lillie, 1992,. Balanced and retrodeformed geological cross-section from the frontal Sulaiman Lobe, Pakistan: Duplex development in thick strata along the western margin of the Indian plate, *in* K.R. McClay, editor, Thrust Tectonics: Chapman & Hall, London, p. 343-356.

Kadri, I.B., 1995. Petroleum Geology of Pakistan: Pakistan Petroleum Limited, 275p.

Mohadjer, S., R. Bendick, A. Ischuk, S. Kuzikov, A. Kostuk, U. Saydullaev, S. Lodi, D.M. Kakar, A. Wasy, M.A. Khan, P. Molnar, R. Bilham, and A.V. Zubovich, 2010, Partitioning of India–Eurasia convergence in the Pamir-Hindu Kush from GPS measurements. Geophysical Research Letters, v. 37/4. Website accessed January 17, 2018, http://onlinelibrary.wiley.com/doi/10.1029/2009GL041737/full.

Reynolds, K., A. Copley, and E. Hussain, 2015, Evolution and dynamics of a fold-thrust belt: the Sulaiman Range of Pakistan; Geophysical Journal International, v. 201, p. 683-710.

Smewing, J.D., J. Warburton, T. Daley, P. Copestake, and N. ul-Haq, 2002, Sequence stratigraphy of the southern Kirthar Fold Belt and Middle Indus Basin, Pakistan, *in* P.D. Clift, D. Kroon, C. Gaedicke, and J. Craik, editors, The Tectonic and Climatic Evolution of the Arabian Sea Region: Geological Society, London, Special Publications, no. 195, p.273–299.

Szeliga, W., R. Bilham, D. Schelling, D.M. Kakar, and S. Lodi, 2009, Fold and thrust partitioning in a contracting fold belt: insights from the 1931 Mach earthquake in Baluchistan:. Tectonics ;v. 28, TC5019, 13p. Website accessed January 17, 2018, http://onlinelibrary.wiley.com/doi/10.1029/2008TC002265/epdf.

Tectostrat, 2001, International Tectostrat Geoconsultants B.V. (2001): Mehar Block Study (unpublished report).

University of Peshawar (S. Ahmad and G. Rehman), 2012, Structural Evaluation of the Mitto Anticline, Northern Mehar Block: Geological field work study for OMV Pakistan (unpublished report).

Yamada, Y., and K.R. McClay, 2004, 3-D Analog modeling of inversion thrust structures, *in* K.R. McClay, editor, Thrust Tectonics and Hydrocarbon Systems: AAPG Memoir 82, p. 276-301.

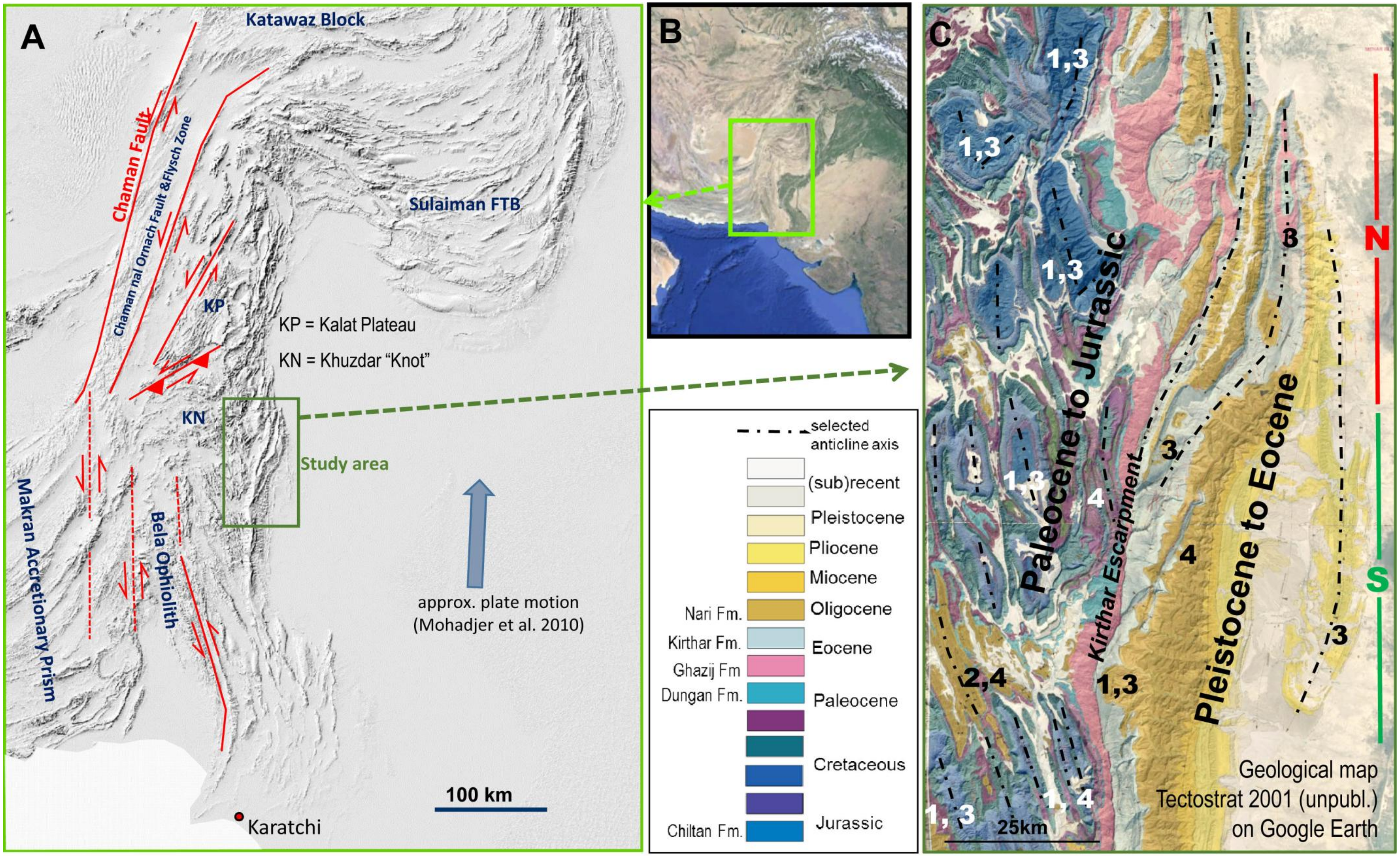

Figure 1 A) Simplified structural sketch of the wider Kirthar fold-belt area. Location is indicated in Google Earth image in B). C) Geological map in the study area in Google Earth. The maps shows lithostratigrapy and is from an unpublished study in the area (Tectostrat, 2001). Northern and southern sectors of the study area are indicated. Numbers are discussed in the text.

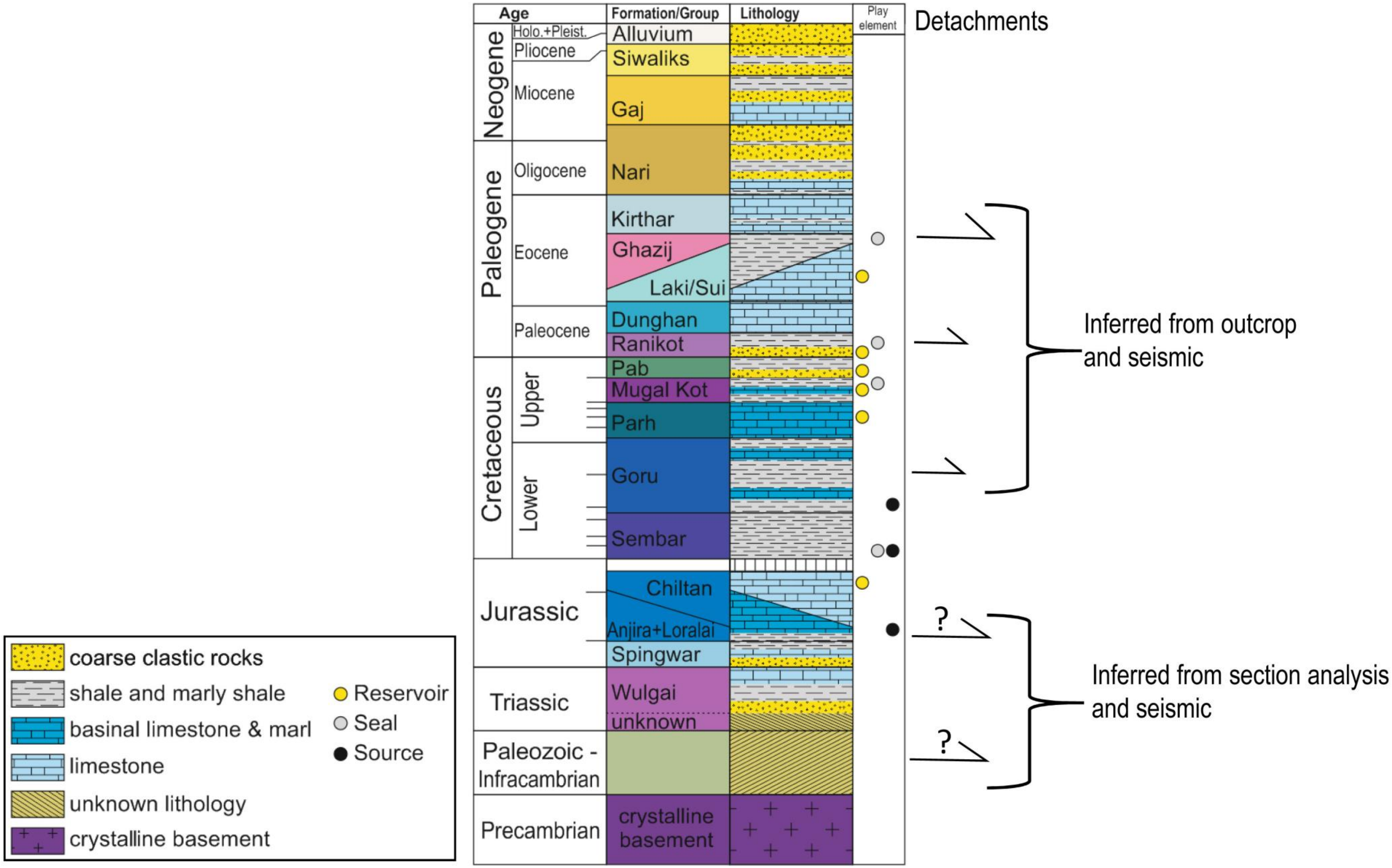

Figure 2 Litostratigraphic overview + petroleum elements (after Tectostrat, 2001; Smewing et al., 2002; Kadri, 1995; and own observations.

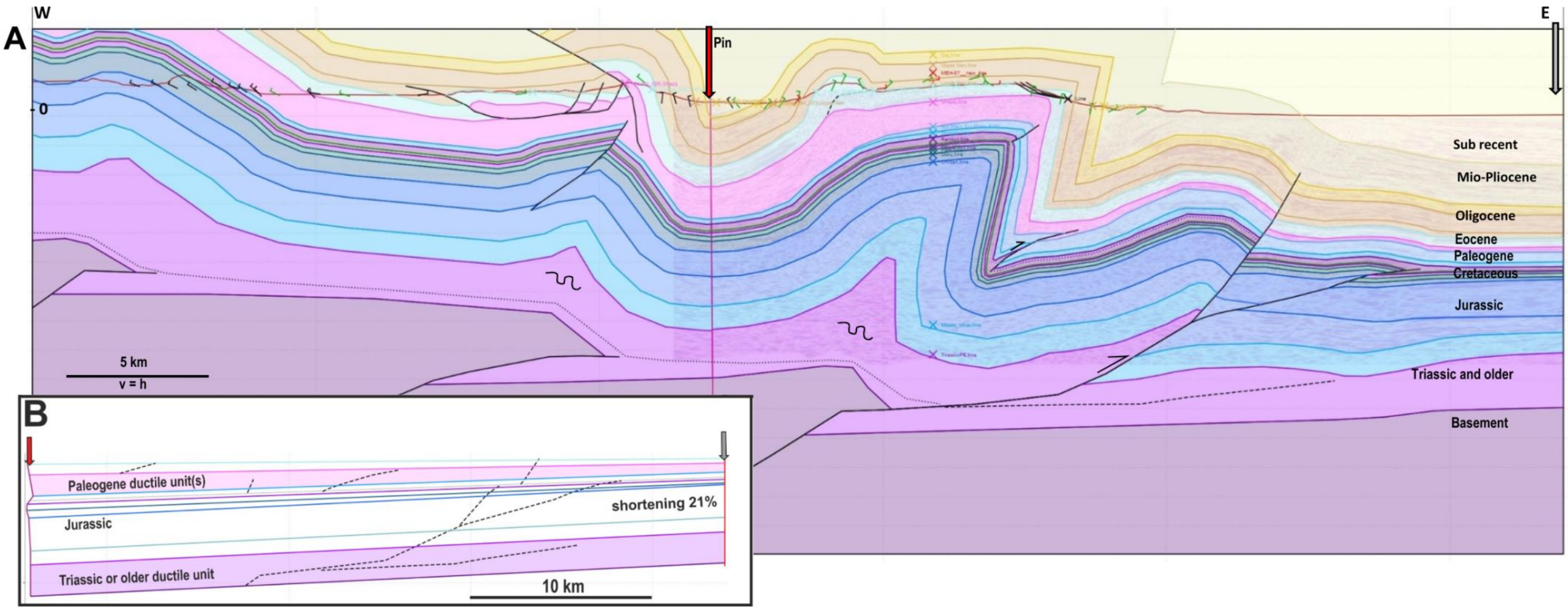

Figure 3 A) Constructed W-E section in the northern sector of the study area with PSDM seismic in the background. The section is balanced between the pins. B) Restored section (line length and area balancing) of section between the pins. Calculated shortening is approx. 8.5 km or 21%.

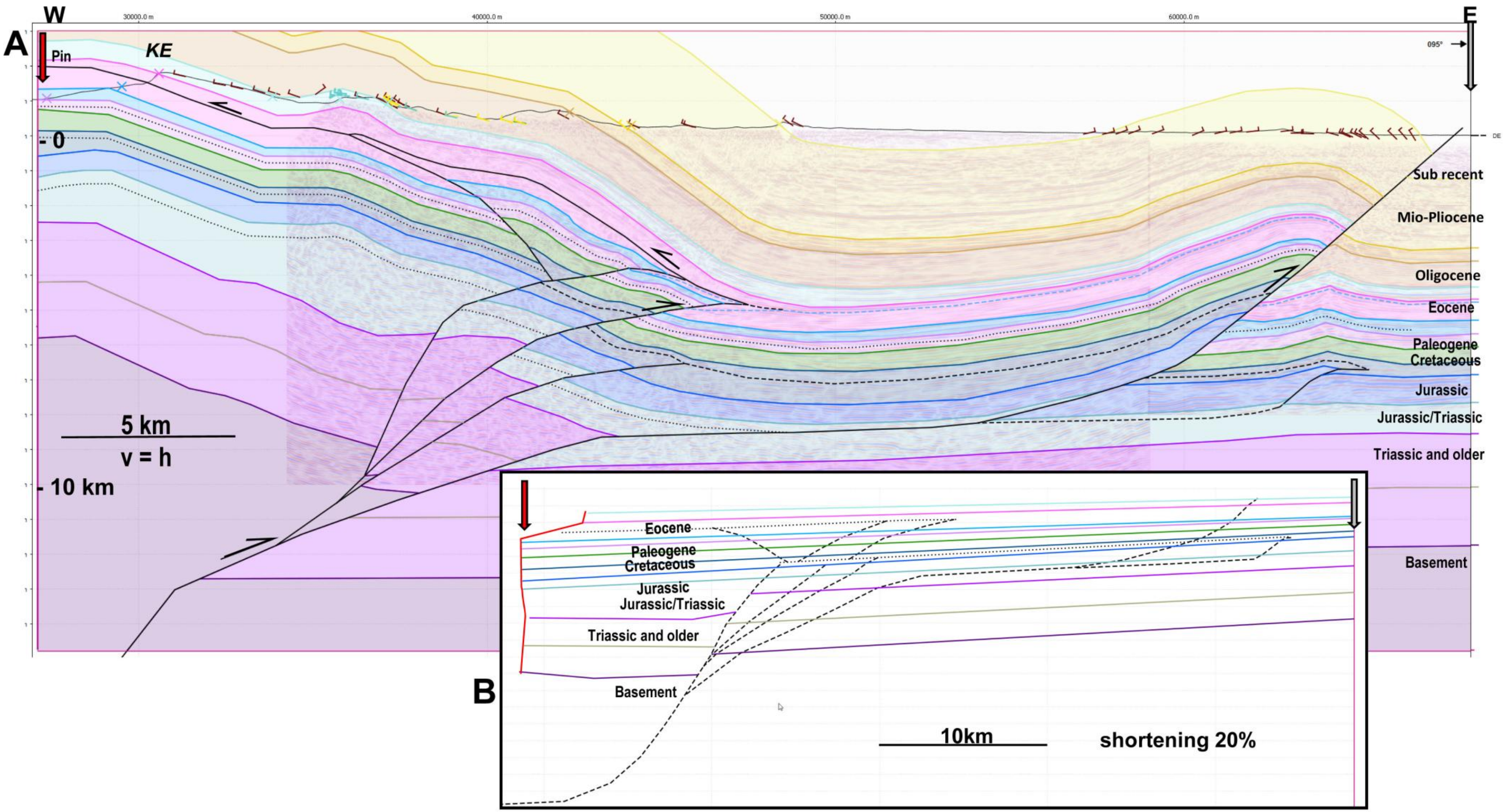

Figure 4 A) Constructed W-E section in the southern sector of the study area with PSDM seismic in the background. The section is balanced between the pins, KE = Kirthar Escarpment. B) Restored section (of section between the pins). Calculated shortening is approx. 10 km or 20%.

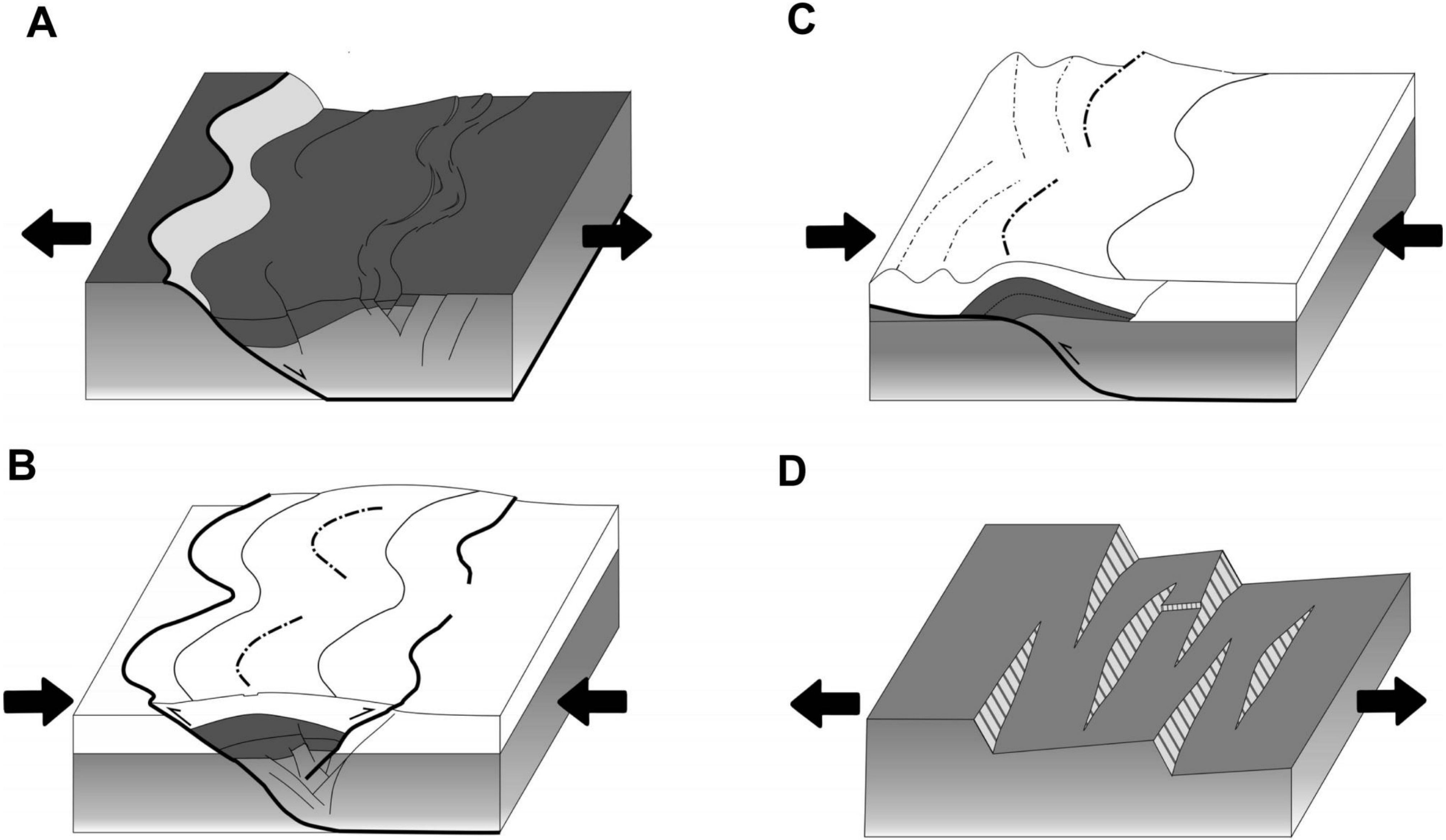

Figure 5 A+B) Model of extension with subsequent inversion on curved linked faults (modified after Yamada and McClay, 2004). C) Adding a thin-skinned element to the sketch of inverted curved linked fault system. D) Sketch of half-graben systems with overlapping faults