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Spatial Arrangement of Fold Types in the Zagros Simply Folded Belt, Iran, Indicated by Landform Morphology and Drainage Pattern Characteristics

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Spatial arrangement of fold types in the Zagros Simply Folded Belt, Iran, indicated by landform morphology and drainage pattern characteristics

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Abstract: The spatial arrangement of fold types within the Zagros Simply Folded Belt was analysed using satellite images, a digital elevation model and a digital drainage network. Distinct fold geometries, principally fault-bend folds and detachment folds, can be identified by characteristic interactions with streams flowing SW from the High Zagros Mountains into the Persian Gulf. In addition, the morphology of the landforms is reflected in the minor channel patterns across the folds. This morphology can also be categorised using geomorphic indices, L/W ratio and symmetry index. The distribution of fold types is shown for the region N27°-N30°, E50°-E54° at a scale of 1:750,000. Anomalously long, high-aspect ratio folds, coincident with topographic steps, were inferred to be fault-bend folds, crossed by multiple wind gaps, overlying major thrust faults. These faults formed sequentially as the deformation front migrated from the collision zone towards the SW, causing diversion of stream channels. Movement up thrust ramps created fault-bend folds behind which serial detachment folding developed in the cover.

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1. Introduction

Fold-thrust belts form the frontal regions of major contractional orogens and are frequently important hydrocarbon provinces. In this short paper, the geometry and geomorphological attributes of the surface folds have been used to investigate the distribution of fold types within the Zagros Simply Folded Belt. The Zagros Simply Folded Belt is eminently suitable for satellite image analysis because of low vegetation coverage and well exposed outcrops in an arid climate. For this study, a section of the Fars region, to the east of the Kazerun fault zone (Figure 1) has been chosen. In this region, the folds are capped by the Oligocene Asmari Limestone (Blanc et al., 2003; McQuarrie, 2004) and the sedimentary cover sequence is floored by the Hormuz Formation, a dominantly evaporite formation, which acts as a major decollement horizon (Bahroudi and Koyi, 2003; Alavi, 2004). All folds investigated in this study have been taken from the Fars region in order to minimise any variation in deformation style caused by differences in the rheological profile of the cover succession along the strike of the belt.

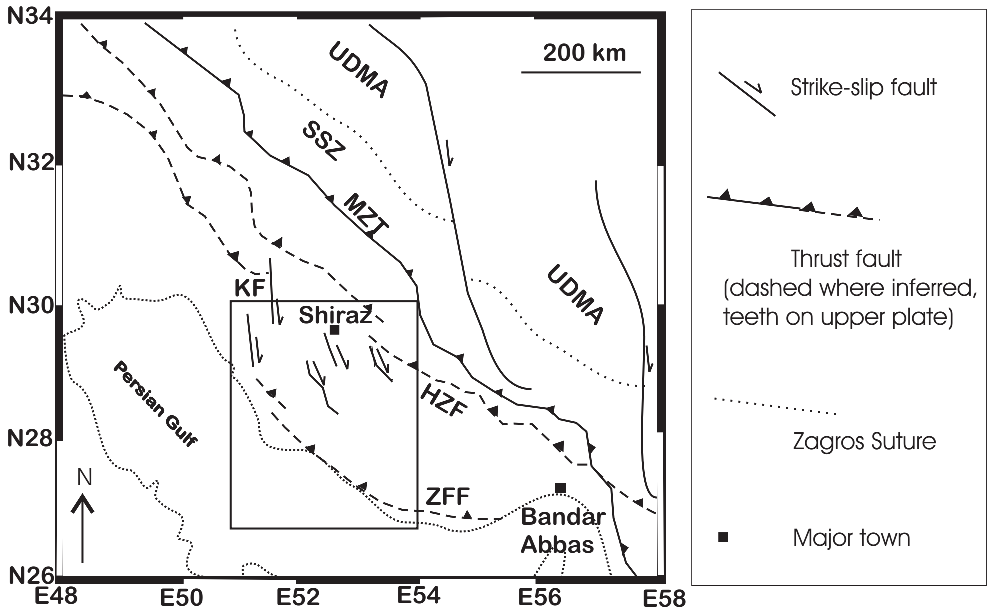

Figure 1. The setting of the Zagros Orogenic Belt (Molinaro et al., 2005). The High Zagros Fault (HZF) forms the NE limit of the Simply Folded Belt, and the Zagros Frontal Fault (ZFF) marks the edge of the surface expression of deformation. UDMA, Urumieh-Dohktar Magmatic Arc; SSZ, Sanandaj-Sirjan Zone; MZT, Main Zagros Thrust; KF, Kazerun Fault. The box highlights the study area.

Fold-thrust belts have been considered to contain principally detachment folds (Sattarzadeh, 1997; Vita-Finzi, 2005), however, the presence of fault-bend folds and a continuum of geometries between the end-member types are revealed by an investigation of the surface geomorphology. An additional significant fold geometry in such regions is an asymmetric detachment fold with a thrust cutting the forelimb (McQuarrie, 2004; Sherkati and Letouzey, 2004; Sherkati et al., 2005; Sepehr and Cosgrove, 2006). The distribution of landforms such as detachment folds, asymmetric detachment folds and fault bend-folds can be mapped using satellite image analysis, drainage network analysis and geomorphological indicators (Jordan, 2003; Bishop, 2007). In the Zagros Simply Folded Belt, these observations directly correlate to the structural geometry, which is reflected topographically, by concordant landform morphology. The two end-member fold types can be recognised based on characteristic drainage pattern diversions, aspect ratio, hinge length and symmetry (Figure 2). Detachment folds have low aspect ratios and near perfect symmetry, whereas fault-bend folds have high aspect ratios and a more asymmetric profile (Sattarzadeh, 1997; Cosgrove and Ameen, 2000; Blanc et al., 2003). An additional significant fold geometry is that of an asymmetric detachment fold, with a relatively low aspect ratio but low symmetry.

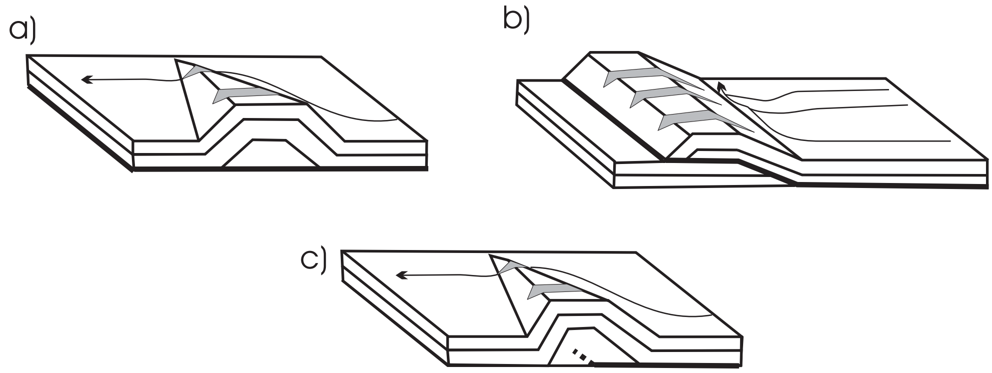

Figure 2. Specific fold types mentioned in the text, showing characteristic aspect ratio, asymmetry and drainage diversion; a) detachment fold with low aspect ratio and short hinge length showing a wind gap in the centre of the structure and a water gap at the end, b) fault-bend fold with a high aspect ratio and long hinge length showing wind gaps and defeated streams diverted parallel to the fold hinge line and c) asymmetric detachment fold with steepened forelimb and incipient thrust fault in the core.

Detachment folds have a characteristic amplification pattern predicted from the theoretical analyses of folding, which varies in time and space and is reflected in the fold geometry (Summers, 1979). At a specific point on the fold the uplift rate will vary with time and at a particular time the uplift rate will vary along the fold hinge. Continued shortening may be accommodated by the development of thrust faults in the forelimb, creating asymmetric folds. In contrast, fault-bend folds are formed by uplift above a thrust fault at depth. Consequently, the uplift rate is approximately uniform along the hinge length.

Drainage systems adapt to changes in the surface slope, recording fold growth and evolution (Jackson et al., 1996; Holbrook and Schumm, 1999). The stream network is a good substitute indicator of the landform organisation and the density of the lowest order streams clearly delimits the landforms (Cudennec and Fouad, 2006). Mio-Pliocene deformation in the Zagros Simply Folded Belt (Molinaro et al., 2005) has altered the drainage network by defeating and diverting streams. Water gaps form where fold uplift rate is slow relative to the stream downcutting rate, generally at the end of detachment folds. Wind gaps form where the uplift rate is higher, i.e. nearer the central point of a detachment fold, causing abandonment of the stream channel. In contrast, depending on the uplift rate of the underlying block beneath a fault-bend fold, the stream will either keep pace with uplift in which case water gaps will occur along the length of the fold, or the stream will be deflected, resulting in wind gaps along the fold (Burbank et al., 1999; Burbank and Pinter, 1999).

2. Methods

False colour composite satellite images were created by combining Landsat 7 ETM+ bands 5, 3, 1 as red, green and blue, which highlights variation in lithology, and suppresses vegetation (Drury, 2001). Colours were balanced using the Balanced Contrast Enhancement Technique (Liu, 1991). Carbonate layers appear in pink, here picking out the folds which are capped by the Asmari Limestone. Fold axial traces were identified from the closures of the top Asmari marker. In addition, stream channels were manually digitized from these images. In areas of confusion, the concentration of vegetation around streams visible on a 432-RGB image was used to separate stream beds from dry valleys.

In addition, a digital stream network was generated from a Shuttle Radar Topography Mission digital elevation model (DEM) using the D-infinity method within RiverTools, where streams were categorised by the Strahler system (Strahler, 1964). This idealised digital stream network was used as a reference point to cross-check the viability of the manually digitized stream network and to enable the identification of major channel diversions and water gaps. Water gaps were identified as points were channels cross-cut the structural closure of a fold nose (Figure 3) and have the expected convex-up long profile. Lastly, apparent abandoned channel reaches which were not present on the idealised network were identified from this comparison and were considered to be wind gaps. These wind gaps display the expected convex-up long profile (Figure 4). Once the comparison of the digital and manually-picked networks was completed, a map of the locations of stream diversions was generated.

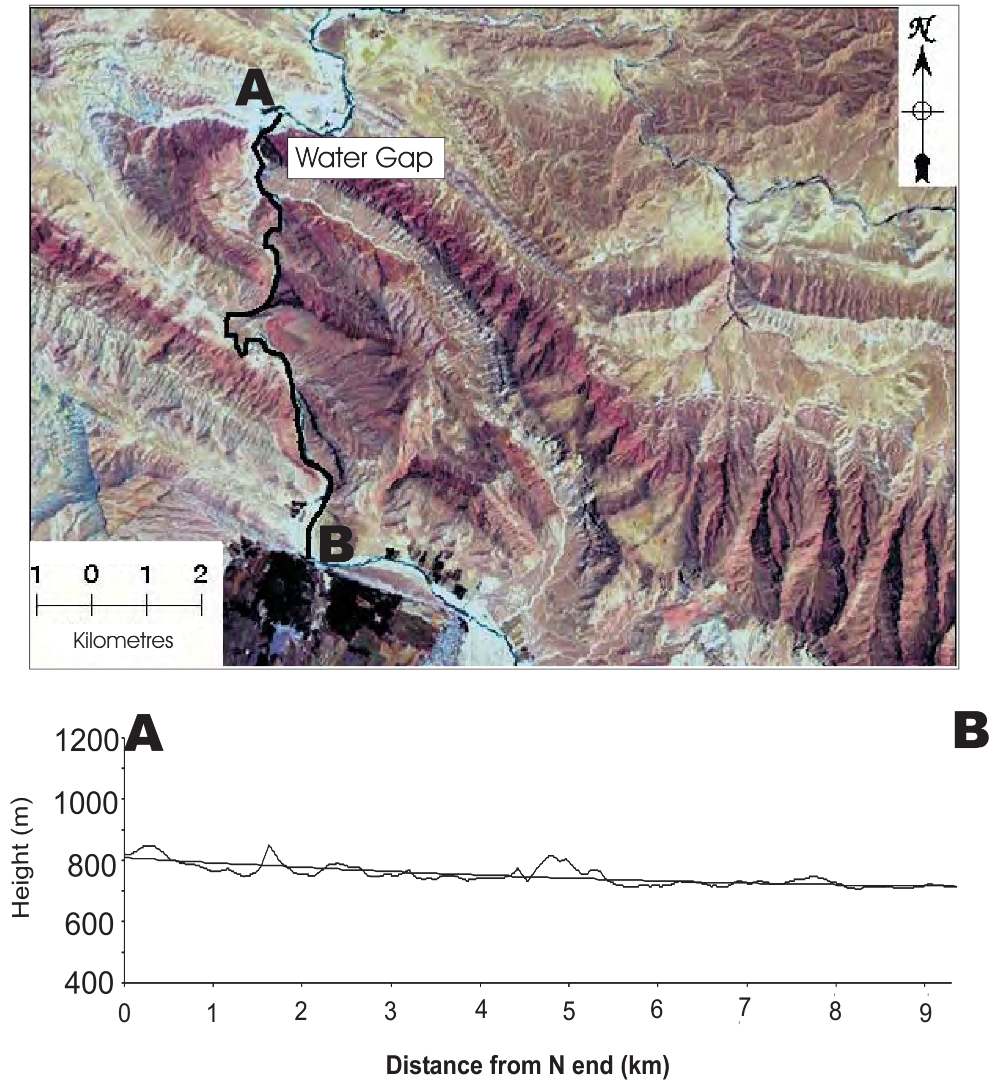

Figure 3. A characteristic water gap on an enhanced image (top) and in topographic profile (bottom), showing a concave profile, and cutting through the end of a fold. Vertical exaggeration of the topographic profile is 3x.

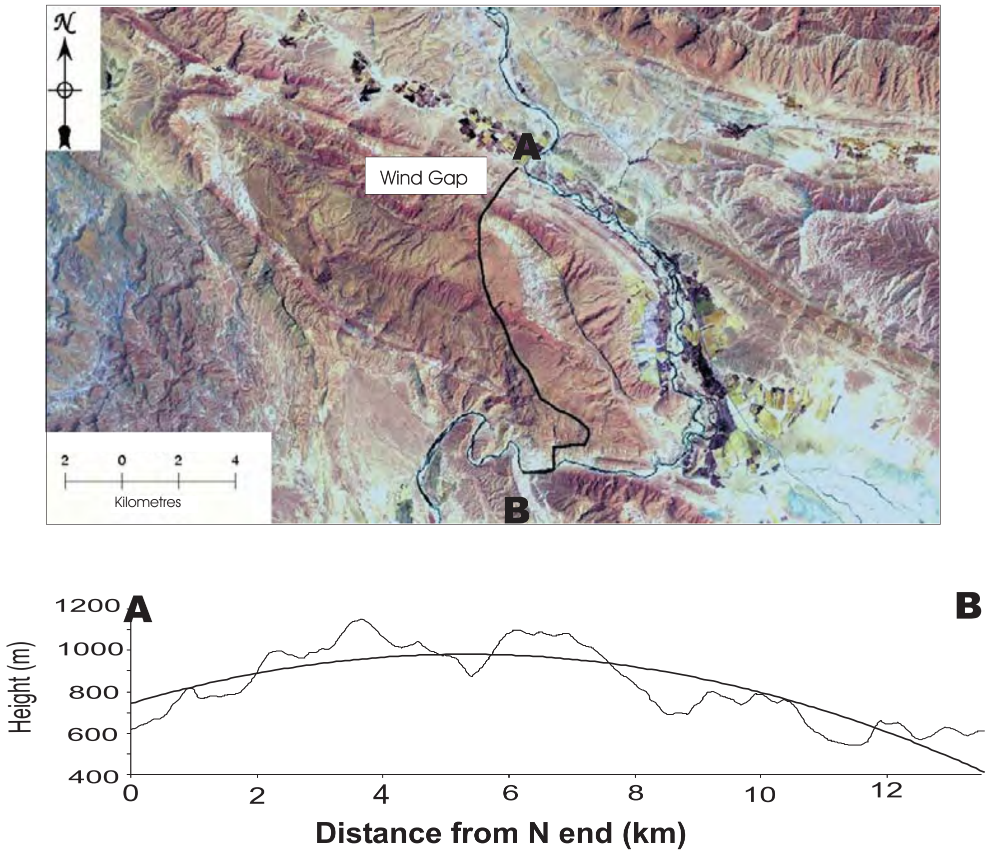

Figure 4. A characteristic wind gap, on an enhanced image (top) and in topographic profile (bottom) showing a convex profile, cutting across a fold. Vertical exaggeration of the topographic profile is 3x.

Thirdly, folds identified from satellite image analysis were categorised using the indices length:width ratio and fold symmetry index. These measurements were made from a contour map generated from the DEM tiles such that the morphology of the fold was marked by an abrupt break in slope (Figure 5). In the study region, the arid climate reduces subaerial erosion processes, thus the surface morphology can be taken as a proxy for the structural geometry of the fold. For folds where there is an independent field dataset of structural dips, the asymmetry is shown to be consistently underestimated by about 5%, that is, landform symmetry is higher (fold symmetry index closer to 1) than the symmetry of the dipping beds. This implies that, despite the expected influence of surface processes, the observed variation in fold symmetry index can still be used as an indicator of fold type.

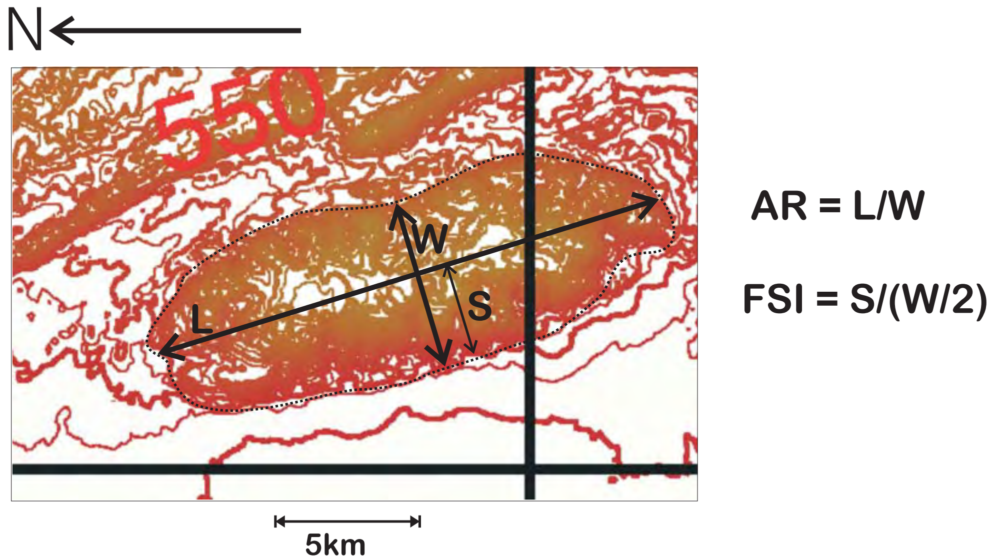

Figure 5. Measurement of Length (L), Width (W) and forelimb width (S) from contour maps, in order to calculate the L/W (aspect) ratio and the Fold Symmetry index (FSI). The dotted line marks the prominent break in slope and hence the extent of the fold.

3. Results

Each of the folds in the study area was classified using the length:width ratio and the fold symmetry index plotted against hinge length, together with the distribution of wind and water gaps. These categories and this method were first tested on a region in the Dezful embayment, for which a detailed cross-section has been drawn from field data (Sepehr and Cosgrove, 2006). Four of the folds on the cross-section can be identified as fault-bend folds and four as detachment folds (Figure 6). Within the present study area, fault-bend folds can be seen to fall on a specific trend, whereas the clustering of the data for detachment folds implies a separate statistical population (Figure 7). Folds with short hinge lengths and low aspect ratios were found to correlate with the locations of diverted streams and were inferred to be detachment folds. In contrast, folds with long hinge lengths and high aspect ratios were crossed by multiple wind gaps (Figure 8) and spatially associated with major stream diversions, and inferred to be fault-bend folds.

The pre-folding drainage system is likely to have been a dendritic system (Oberlander, 1985) with the dominant direction of flow approximately from NE to SW i.e. towards the Persian Gulf. Present-day higher order streams show a deviation from the dendritic pattern to a trellis pattern, with the prominent stream direction parallel to the NW-SE trending fold hinges (Figure 9a). Individual fold shapes are delimited by lower order streams. Symmetric stream network patterns are taken as representative of detachment folds (Figure 9b) and asymmetric stream network patterns are found across fault-bend folds.

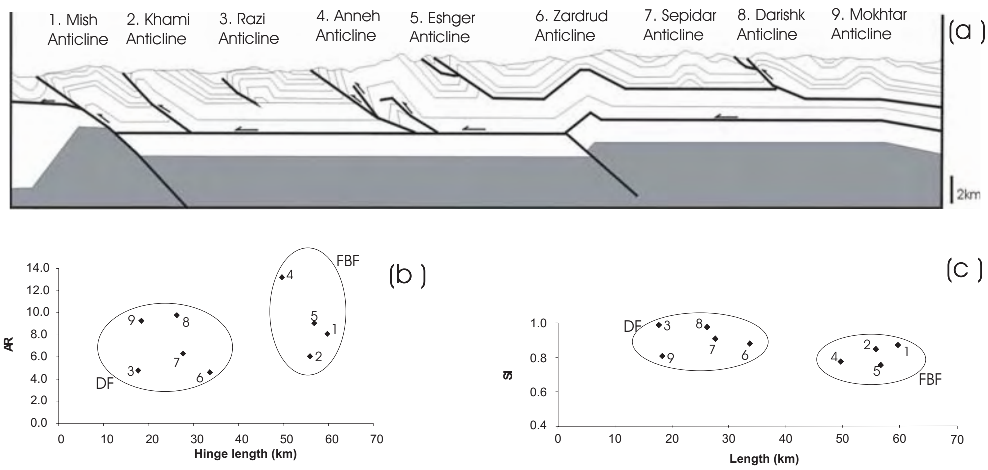

Figure 6. Cross section (a) of a region where the structure of the folds has been determined by fieldwork (Sepehr and Cosgrove, 2006) and associated geomorphic indices (b; AR, c; FSI) measured from remote data. The folds in the section can be clearly separated into those likely to be fault-bend fold and those likely to be detachment folds.

4. Conclusions

The resulting map indicates that the different fold types (detachment folds and fault-bend folds) can be identified on satellite images using their interaction with drainage patterns, length:width ratio and symmetry. The fault-bend folds are spatially associated with the major thrust faults - the High Zagros Fault, Mountain Front Fault and Zagros Frontal Fault. The relationship is most pronounced to the east of the map area, where the deformation is not influenced by the basement-related Kazerun fault. These faults formed sequentially as the deformation front migrated to the SW. As the fault-bend folds amplified, propagation of the thrusts became progressively more difficult and the compressive stress rose. This resulted in the development of detachment folds by serial folding in the cover behind the fault-bend folds. The presence of asymmetric detachment folds implies that additional shortening may have been accommodated by thrust development in the core of detachment folds.

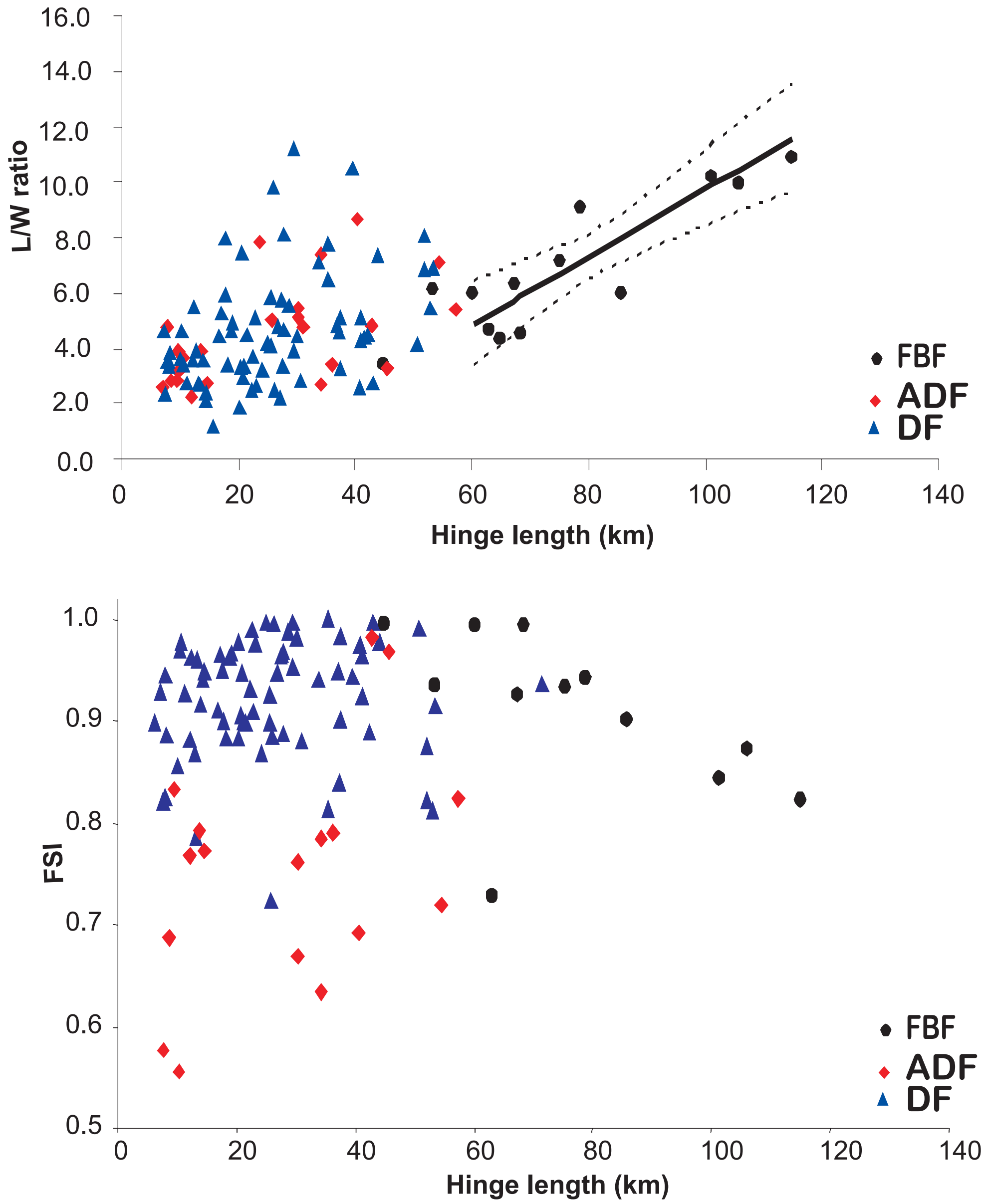

Figure 7. Separation of fold types (detachment folds, fault-bend folds and asymmetric detachment folds) within the Zagros Simply Folded Belt study region, by geomorphic indices L/W ratio (top) and Fold Symmetry index (bottom) plotted against hinge length. R^2 for the trend-line plotted in the upper graph is 0.76 and the dotted lines mark a confidence envelope of one standard deviation.

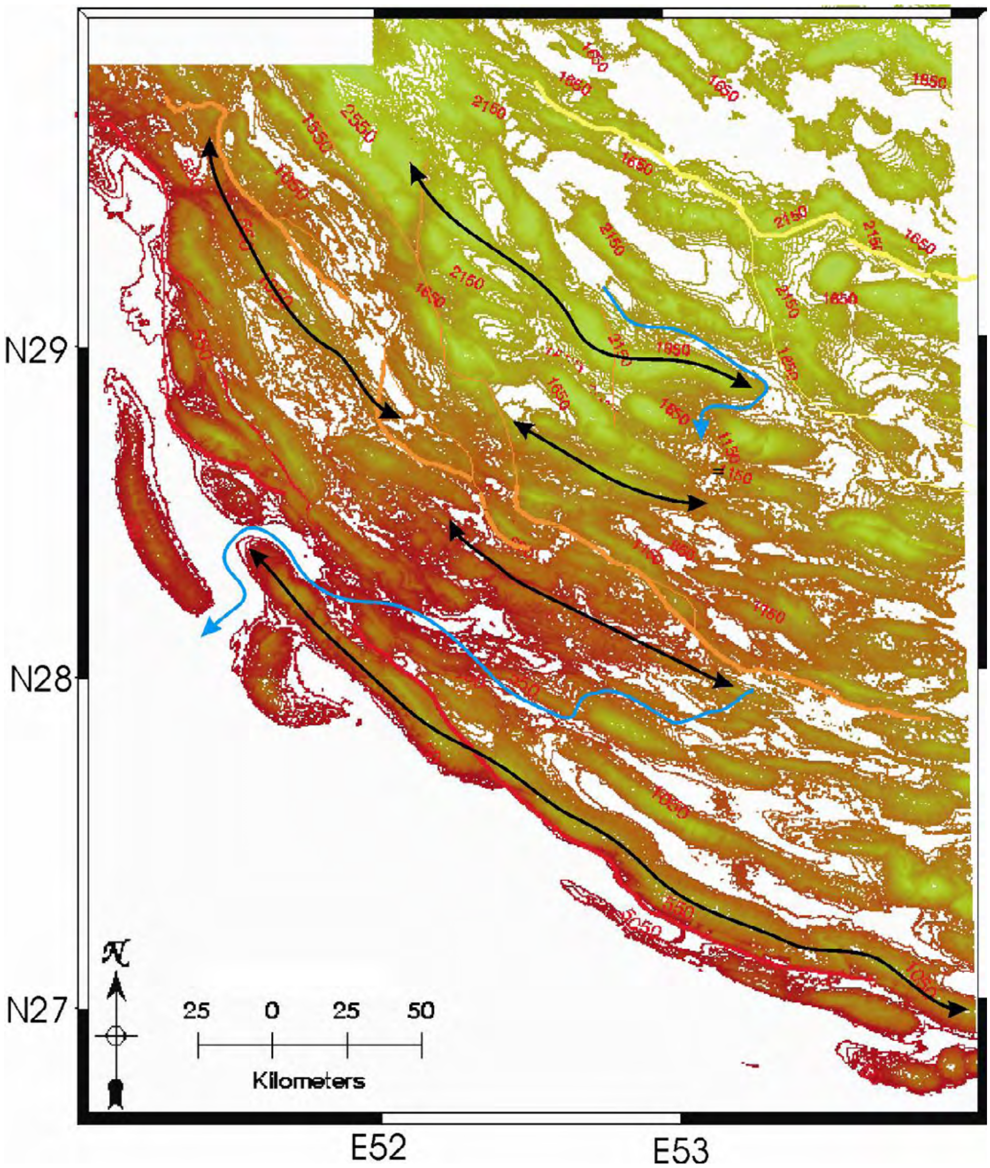

Figure 8. Composite contour map showing the spatial relationships between major stream diversions, trends of wind gaps (black) and the major thrust faults. The wind gap trends parallel the hinge lines of long, high aspect ratio folds which are spatially associated with major thrust faults. Fold polygons are marked by distinct breaks in slope at the base of each fold limb.

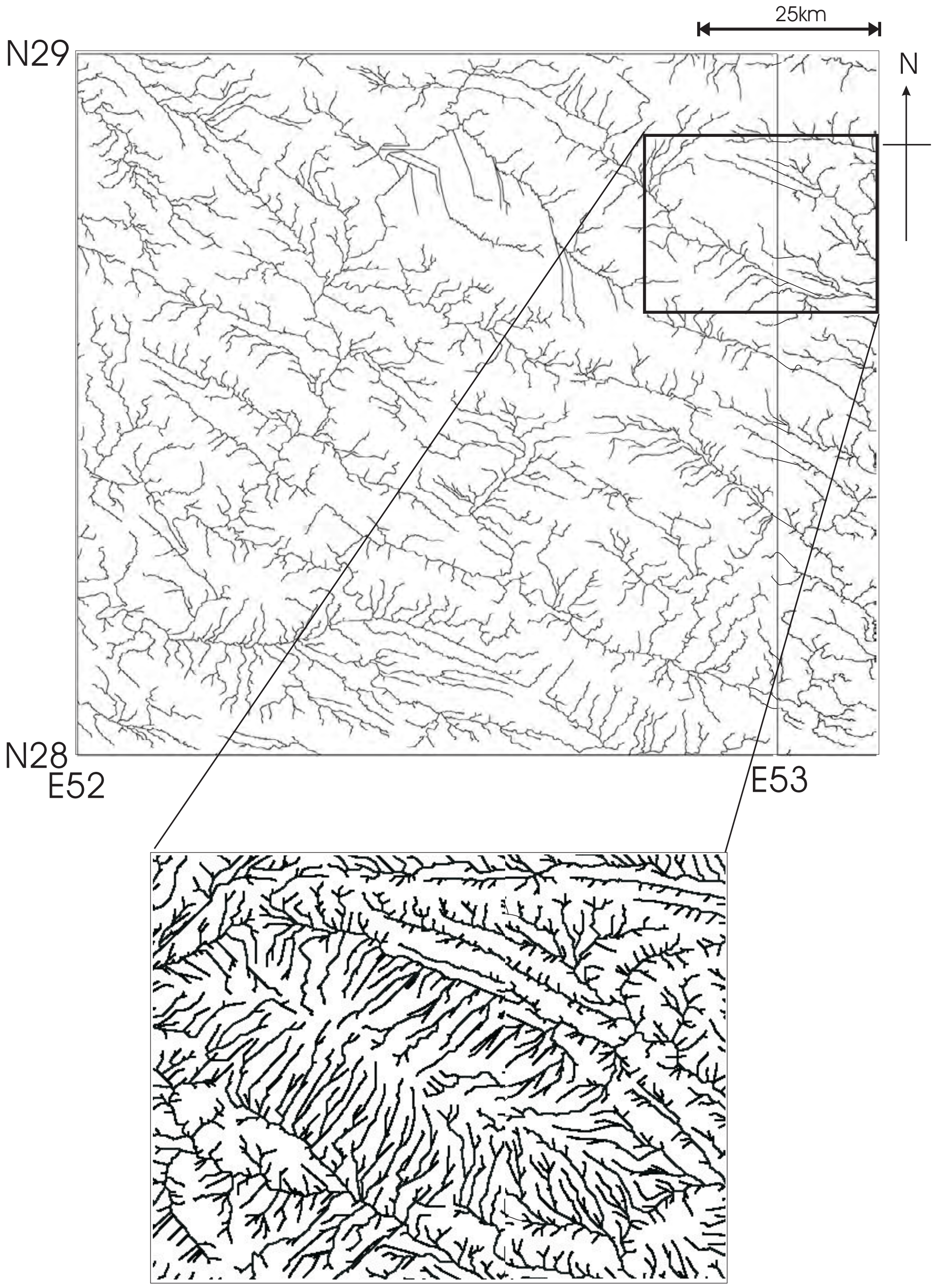

Figure 9. Drainage patterns in the Zagros simply folded belt; a) high order streams displaying a trellis pattern with the prominent direction paralleling the fold hinge lines and b) low order streams showing a symmetrical pattern around a detachment fold.

Software

The map was produced using satellite image processing (in ER Mapper) and processing of DEM files to generate the base contour maps. The stream network, including wind and water gaps, was created by systematic examination of satellite data, DEM data and a digital drainage network generated using RiverTools (Rivix LLC.). Geomorphic indices were measured from the contour maps using Didger (Golden Software Inc.). The final map outline was drawn in ER Mapper and edited in CorelDraw.

Acknowledgements

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