

Effect of Mega-Shear Fractures / Strike Slip Faults on Entrapment Mechanism in Sulaiman Fold Belt, Pakistan*

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Abstract

Mega-Shear Fractures (MSF) / strike slip faults are frequently distributed in Sulaiman Fold Belt and have resulted in dislocation of the axial traces of some of the folded structures. These are conjugate sets of shear fractures with dominant NE and NW strike, developed during folding phenomena; these were subsequently affected by strike movement provided by wrench tectonics related to transform fault zone at western terminus of Indian Plate and southward movement of Sulaiman Fold Belt relative to Sibi Trough in southwest and Punjab Platform to the east. MSF are easily interpreted on both satellite imagery and seismic lines oriented along the axis of folds. Significant displacement, observed along MSF in Sulaiman Fold Belt, might have caused breaching of traps related to folding due to nonexistence of lateral seal across MSF; however, it may create compartmentalization of this structure if it is laterally sealed by a different rock unit due to complex juxtaposition across MSF. Mega-Shear Fractures, being younger than folding and extending to significant depths, could damage the entrapment mechanism for hydrocarbon accumulation in traps associated with folding. A mathematical relationship has been derived to estimate quickly the risk of structural breaching associated with Mega-Shear Fractures/strike slip faults. Integrity of lateral seal across the MSF depends on thickness of the seal, lateral displacement along MSF, dip angle of strata (inclination of limb) and angle between axial trace and strike of the MSF. Maximum risk is associated with traps having thin seal, huge displacement along MSF, steepness of the strata, and high angle between axial trace and strike of the MSF. A number of structures from Sulaiman Fold Belt have analyzed by using derived mathematical relation which shows satisfactory results.

Introduction

The study area, located in Sulaiman Fold Belt (SFB) between latitude 28°30'N to 31°30'N and longitude 68°00'E to 70°30'E, is one of the most hydrocarbon prolific regions of Pakistan with a number of gas fields (e.g., Sui, Loti, Pirkoh, Uch, etc.; ([Figures 1](#) and [2](#))). Many dry wells have been drilled in this region, and structural integrity of the traps is considered as one of the major causes of their failure. Lack of structural integrity could be attributed to the regional strike-slip movement that has been affected by reactivating the shear fractures

associated with folding in SFB. Regional strike-slip movement due to wrench tectonics related to transform fault zone at the western terminus of Indian Plate, southward movement of Sulaiman Fold Belt relative to Sibi Trough in the southwest and Punjab Platform towards the east, resulting in a transpressional deformation in Sulaiman Fold Belt. Conjugate sets of shear fractures are mostly affected by the regional sinistral movement, whereas occasionally dextral movement is also interpreted. While only major fractures (Mega-Shear Fractures) are considered, most commonly distributed, small-scale shear fractures are beyond the scope of this study.

Mega-Shear Fractures (MSF) are basically strike-slip faults developed by anomalous horizontal displacements that occurred along shear fractures associated with folding. Lateral displacement along these shear fractures has dislocated the axial traces of various anticlines in Sulaiman Fold Belt ([Figure 2](#)). For instance, axis of Loti Anticline is shifted by several hundred meters due to the displacement along these types of faults (Jadoon et al., 1992). Jadoon et al. (1995) also described small-scale strike-slip faults, present in Sulaiman Fold Belt, as acting as conduits or lateral seal for hydrocarbon migration.

This article gives a detailed analysis of Mega-Shear Fractures (MSF), their orientations, lateral or horizontal displacement,s and their effects on entrapment mechanism for hydrocarbon accumulation.

Geological Setting

The Sulaiman-Kirthar Ranges of northwestern Pakistan form part of a north-south-trending fold and thrust belt that links the main Himalayan continent plate boundary in the north, with the Makran accretionary prism in the south (Alleman, 1979; Bannert et al., 1992). Sulaiman Fold Belt is an arcuate belt, convex to the south and is bounded to the west and north by the left-lateral strike-slip Chaman fault system and the Zhob Valley ophiolites, respectively, developed by oblique subduction and northward movement of the Indian Plate (Alleman, 1979; Lawrence et al., 1981). The Sulaiman lobe is a broad and gentle fold and thrust belt that is still tectonically active (Jadoon et al., 1994). Different structural models have been proposed for the evolution of the Sulaiman Fold and Thrust Belt. Bannert et al. (1992) proposed a nappe style of deformation; Banks et al. (1986) proposed a passive-roof duplex style of deformation; Sarwar et al. 1979, Klootwijk et al. (1981, 1985) and Lawrence et al. (1981) have proposed that it might have developed by transpression as a result of left-lateral strike-slip movement along the Chaman fault and southward thrusting along the western terminus of the Indian subcontinent.

Uplift and compression in Sulaiman Fold Belt have been episodic since the Paleocene, but the main phase of compression and uplift was during the Pliocene to the present. The Pliocene-Holocene compression has folded the strata along the southern and eastern margins. Fracture system associated with that folding was also developed during the folding. Subsequently, that fracture system, associated with folding, has been influenced by the regional strike-slip movement related to wrench-faulting system. These fractures were subsequently reactivated and became one of the compensating features for ongoing compression and strike-slip movement.

Anticlinal traps along the southern, eastern, and northwestern margins of the SFB are hydrocarbon-bearing where primary reservoir targets are Eocene carbonates of the Sui Main Limestone, Cretaceous sandstone of Pab, and Jurassic carbonates of Chiltan Formation. Sui, PirKoh,

Loti, Dhodak, Savi Ragha, Rodho (Dewan), and Ziarat are all the hydrocarbon discoveries from the anticlinal structures of the fold belt in the area.

Fractures Associated With Folding

Fractures associated with folding are classified on the basis of their orientation and their genesis ([Figure 3](#)). The fracture set parallel to the fold axis is called as extensional or "release fractures" and geometrically named as "longitudinal fractures" (Billings, 1972). These types of fractures are formed at the point of maximum curvature and are caused by tension on the upper side of the folded strata (Nelson, 1985; Billings, 1972). In this case, folding must be related to neutral surface buckling or by tangential longitudinal strain, in which outer part of folded competent layer is stretched (Billings, 1972; Ramsay, 1988). The other fracture sets, oriented perpendicular to the fold axis are called as "extensional fractures" and geometrically named as "cross fracture". These resulted from slight elongation parallel to the axis of fold (Billings, 1972). Shear fractures or vertical diagonal fracture are oriented oblique to the fold axis and have very steep dip (Billings, 1972). They are formed at some acute angle to the maximum compressive principal stress direction (σ_1) and at an obtuse angle to the minimum compressive stress direction (σ_3) (Nelson, 1995). Shear fractures are formed when all three principal stresses are compressive. In this study, more specifically the shear fractures with anomalous horizontal displacement are considered. These shear fractures are named as Mega-Shear Fractures (MSF).

Mega-Shear Fractures in Sulaiman Fold Belt

Mega-Shear Fractures observed in SFB are formed as a result of anomalous lateral displacement and extend to considerable depths. These conjugate sets of fractures, having NE and NW strike, are genetically related to folding and regional strike-slip movement associated with western Indian plate boundary conditions. The strike-slip movement has influenced only some of the shear fractures. These shear fractures (MSF) are easily interpreted on both satellite imagery ([Figure 4](#)), as well as seismic lines oriented along the strike of folds ([Figures 5, 9a](#)). However, these can also be interpreted on dip lines when there is anomalous displacement ([Figure 6](#)).

Effects on Entrapment

Mega-Shear Fractures, being younger phenomenon than folding, could damage the entrapment mechanism for hydrocarbon accumulation. A number of structures are considered and analyzed with respect to MSF's effect on entrapment mechanism. Horizontal displacement along these MSF can breach the structure by bringing the reservoir in contact with non-sealing unit present above the seal. In this article, fault seal analysis based on mathematical relationship is proposed after detailed investigation and modeling. Entrapment integrity at any point on the trap along these MSF depends upon:

1. Thickness of top seal
2. Inclination of the strata

3. Displacement along MSF

4. Angle between MSF's Strike and orientation of axial trace

Following equations describe the relationship between above-mentioned factors:

$$T_{\text{eff}} = T_s / \cos(90 - \theta_{\text{Bdip}}) \quad (1)$$

Where:

T_{eff} = Thickness of effective seal against horizontal displacement ([Figure 7](#))

T_s = True Thickness of the seal

θ_{Bdip} = Dip of the bedding surface

$$D_{\text{eff}} = d(\sin \theta_{\text{ma}}) \quad (2)$$

Where:

D_{eff} = Effective lateral displacement along the MSF ([Figure 8](#))

d = Horizontal displacement along the MSF

θ_{ma} = Angle between axial trace and strike of the MSF

By using equations 1 and 2, integrity of lateral seal overlapping in the case of displacement along MSF is given below:

$$I_{\text{so}} = T_s / \cos(90 - \theta_{\text{Bdip}}) - d(\sin \theta_{\text{ma}}) \quad (3)$$

I_{so} = Integrity of lateral seal overlap or seal - seal juxtaposition

Resulting I_{so} values will determine the effectiveness of lateral seal:

$I_{\text{so}} > 0$: effective lateral seal

$I_{\text{so}} = 0$: no lateral seal-seal juxtaposition, only shale smear can provide lateral seal

$I_{\text{so}} < 0$: ineffective lateral seal

This equation can be applied at a number of points along the strike of MSF that may be present on anticlinal traps for determining its effect

across limb-hinge-limb of the fold. This equation has been applied on different tested structures having mega-shear fractures in Sulaiman Fold Belt.

Thickness of Seal (T_s)

Thickness of the seal has direct bearing on the seal integrity. Large horizontal displacement would be required along the MSF to breach structures having thick seal units and vice versa.

Minimum thickness of the seal required for lateral juxtaposition along these MSF can be estimated by using the following relationship derived from equation 3 by considering $I_{so}=0$.

$$T_s = d(\sin\theta_{ma}) \times \cos(90-\theta_{Bdip}) \quad (4)$$

Seal rocks in Sulaiman Fold Belt are mostly shales. Eocene shale units are very thick and can accommodate hundreds of meters of displacement along MSF. Loti gas field is one of the examples where axis of the anticline has been dislocated by anomalous horizontal displacement. Maximum thickness of seal above Cretaceous Pab Sandstone is 350m which consists of alternative beds of shale-sands. So, a careful fault seal analysis by using equation 3 is suggested for targeting Pab Sandstone in Sulaiman Fold Belt. Seal thickness and its lithological variation at target prospect are very important for effective analysis.

Dip of the Fold Limb

According to the equation, effective seal thickness (T_{eff}) depend upon $\cos(90-\theta_{Bdip})$. If θ_{Bdip} is steeper, then the value of T_{eff} will be low and vice versa. There is no risk of structure breaching when strata are horizontal. The equation should be used on both the limbs in case of asymmetric anticline. The limb dipping with high angle can achieve the breaching stage at small horizontal displacement along the MSF as compared to the limb dipping with low angle; hence the effect of high dipping limb will prevail on the hydrocarbon column.

In Sulaiman Fold Belt, folds become tight toward hinterland side. So, MSF's effect is maximum in hinterland where fold limbs are dipping steeply as compared to gentle folds in foreland.

Displacement along Fractures

This lateral movement has direct effect on the integrity of seal; i.e., the larger the displacement, the higher the risk of lateral seal failure. Lateral displacement basically brings the non-sealing unit against the reservoir across the MSF. This lateral juxtaposition causes the structural breaching.

Lateral movement along Mega-Shear Fractures present in Sulaiman Fold Belt ranges from few meters to hundreds of meters and can easily be observed on satellite imagery. Intensity of displacement increases as one moves towards the inner fold belt. Yet Loti Anticline, present in outer part of the fold belt, has been severely affected by these MSF.

Angle between Axial Trace of Fold and Strike of MSF

According to the derived equation, the smaller the angle between MSF's strike and axial trace of the fold, the lesser the risk of entrapment breaching will be. Orientation of these MSF with reference to the axial trace of the folded structure is very important; the effect will be maximum when MSF's and axial trace orientation becomes perpendicular to each other.

Orientation of folding in Sulaiman Fold Belt varies from ENE in the east to WNW in the west. On the other hand, MSF are conjugate sets having NE and NW strike and are basically associated with folds making angles of 50° - 70° with axial trace. Fold orientation in eastern Sulaiman Range is NE; so the set of MSF having NE strike makes a low angle with axial trace of the folds and therefore a low value of $D_{\text{eff}} \{d(\sin\theta_{\text{ma}})\}$. This low value will have a low impact on seal breaching. On the other hand the MSF set having NW strike makes higher angle with fold axis; hence the higher value of D_{eff} and high risk associated with seal breaching. When Mega-Shear Fracture becomes parallel to the axial trace then D_{eff} has zero value. It means, there is no effect along the dip of structure. Now, the case should be handled with respect to the closure along the strike. Dip of the limb (θ_{Bdip}) is replaced by plunge of the anticline.

Cases Based on Satellite Image/ Geological Map and Seismic Data Interpretation

Sui and Dabbar anticlines were analyzed in detail to understand the effects of the MSF on structural integrity and hydrocarbon entrapment. Sui and Dabbar anticlines are located in two different regimes of deformation intensity; the former lies in area of less deformation than the later one. These MSF are interpreted on 2D seismic lines and are also mapped. These MSF may have damaged the entrapment mechanism for hydrocarbon accumulation in Dabbar Anticline, but at Sui structure the presence of thick seal and very nominal movement along these fractures have preserved the integrity of the Sui structure.

Sui Anticline

Sui, an E-W-trending doubly plunging anticline developed at the southern mountain front of Sulaiman Fold Belt. It is a symmetrical anticline with limbs having gentle dips, i.e., 8° . Conjugate sets of shear fractures having NE and NW orientations are present on outcrop and can be observed on satellite image. These Mega-Shear Fractures, interpreted on 2D seismic sections, have penetrated the Cretaceous level that might have provided the conduits for gas migration from Sembar to Sui Main Limestone ([Figure 9a](#)). Time Structure Map at Sui Main Limestone (SML) level has been generated ([Figure 9b](#) and [9c](#)). Sets of MSF's present at SML level with major NE-SW orientation have displaced the strata up to 20 - 50m. Due to the presence of gentle dips, thick seal above Sui Upper Limestone (SUL) and the nominal displacement along these MSF, the chance of structure breaching is not expected at SUL level. Seal thickness above SML is very thin (18

meter); risk of structural breaching is expected where displacement along these fractures exceed 100 meters. Good-quality 3D data can help to estimate actual displacement along these MSF.

Dabbar Anticline

Dabbar is an E-W-trending anticline, located in comparatively more intensely deformed interior part of Sulaiman Fold Belt. The structure towards the west seems to be truncated by major tear fault as seen on Google image ([Figure 10a](#)). Dabbar-1 well was drilled on eastern plunge of the anticline. Due to alluvium cover at surface, there is no indication of MSF except some indication of strike-slip movement in its exposed northern limb, north of Dabbar well-1 ([Figure 10a](#) and [10b](#)). Sparse seismic coverage is available in this part of the anticline. Left-lateral, NW-SE-oriented MSF (interpreted on 2D seismic) has displaced the axis of the anticline by approximately 350m ([Figure 5](#), [6](#), and [11](#)). Limbs of the asymmetrical anticline are dipping 30° to North and 50° to South ([Figure 6](#)). Throw of the fault as evident on seismic lines increases at shallower levels ([Figure 5](#) and [6](#)). According to equation 3, the seal thickness required above the Chiltan level for avoiding structural breaching is estimated to be 300m and 250m for southern and northern limb, respectively. Apex or main culmination of the anticline lies to the west of mapped area where Dunghan Formation is exposed; Dabbar-2 well was drilled and it ended as dry hole ([Figure 10a](#)). Structural breaching could be one reason suggested for its failure.

Cases Based on Geological Map/ Satellite Image

Zin Anticline is an E-W-trending asymmetric anticline with southern steeper limb. Zin-1 well produced gas from SML with low pressure. Steeply dipping southern limb of the anticline is deformed by MSFs. Movement along these fractures is visible on satellite image and is also interpreted on available geological maps ([Figure 11](#)). With reference to the proposed equation, effect of the strike-slip movement on entrapment integrity is more on steeply dipping southern limb than on gently dipping northern limb. Low pressure previously attributed to shallow depth of the reservoir (Siddique, 2004) may actually be due to the partial breach of Zin structure by these mega-shear fractures. Fort Munro Anticline, having NE-SW trend, is located in the eastern part of the Sulaiman Fold Belt. Cretaceous Parh limestone is exposed in the core of anticline. It is tight and asymmetric fold with steep eastern flank (approximately 60°) and gentle west-dipping flank (approximately 20°). Shadani-1 drilled at the crest of the structure, drilled to the Triassic level, ended as a dry hole. Gas shows are reported from sands of Cretaceous Sembar Formation. A major NE-trending MSF south of Shadani- 1 well has offset the axis of this anticline for a considerable distance ([Figure 12](#)). Displacement along this MSF might have caused the breaching of Shadani structure; fault-seal analysis will undertaken later. Tadri Anticline is located in the central part of the Sulaiman lobe with Cretaceous exposed in the core. Several NE-SW-trending MSFs are observed on satellite image. These MSFs having a high-angle relationship (75°) with axial plane of the anticline show a lateral displacement of a few hundred meters ([Figure 4](#)). Minimum thickness of seal that is requires to prevent the breaching of structure due to the lateral movement up to 500m is estimated to be 450m. Tadri Main-1 was drilled on its western plunge (it missed the apex). The effects of other MSFs are mainly on limbs of the fold, and the seal is expected to be intact at the crestal part where gentle dips are expected. Khattan oil seep, possibly along one of the MSF, is also present at the western plunge of Tadri Anticline (Hunting Survey, 1960).

Conclusion

One of the key risks of structural breaching in Sulaiman Fold Belt is related to strike-slip movement along the conjugate set of shear fractures associated with folding. Mega-Shear Fractures, being younger phenomenon than folding, could damage the entrapment mechanism for hydrocarbon accumulation through breaching of lateral seal.

A mathematical relationship has been established to mitigate this risk through fault-seal analysis along Mega-Shear Fractures by using thickness of seal, dipping angle of limbs, displacement along MSF, and angle between fold trace and strike of the MSF. This relationship can be used at different points along the MSF on any prospect related to folding having MSFs for deciding the location of exploratory wells.

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Figure 1. Location map.

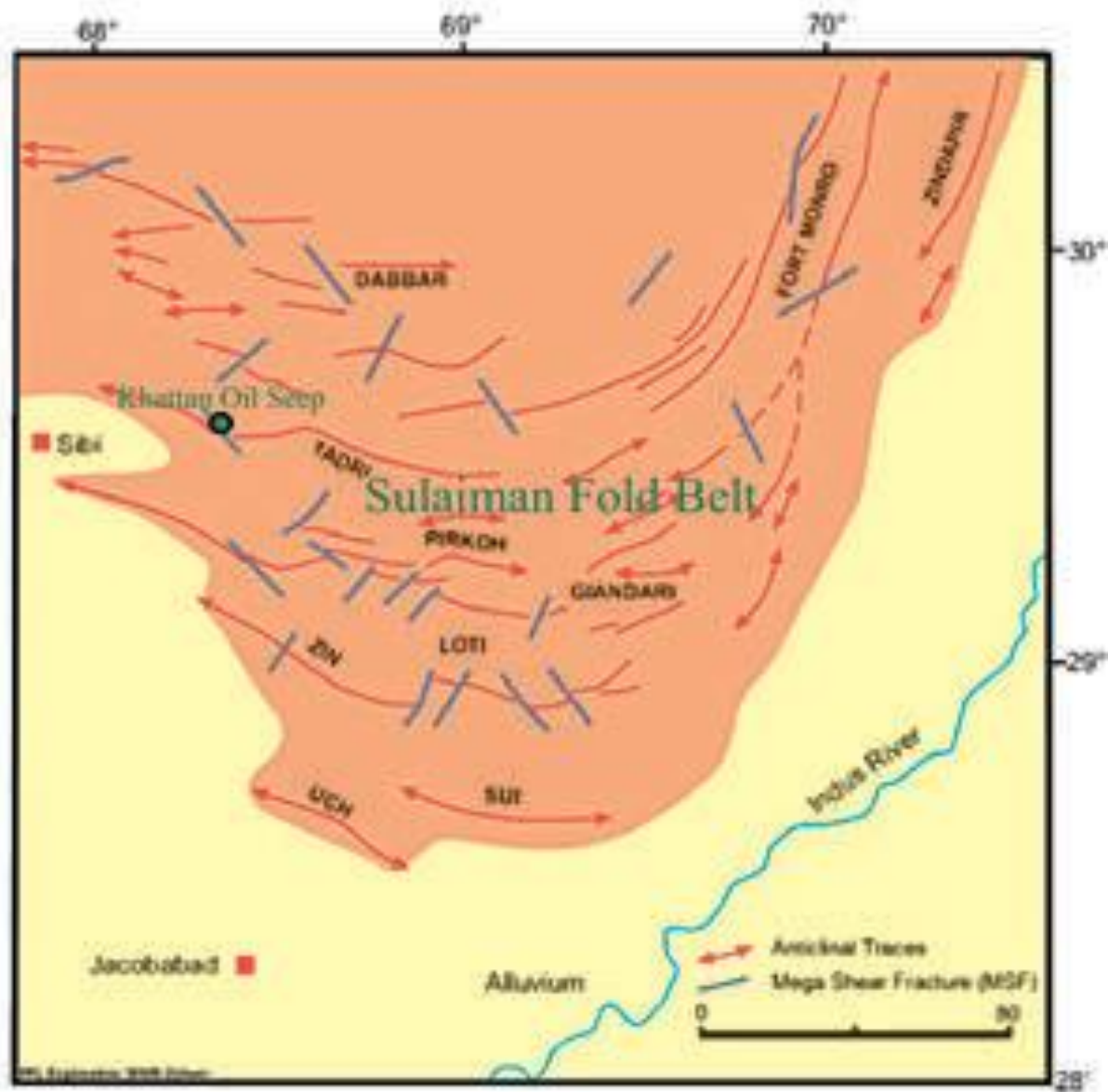


Figure 2. Map showing distribution of major anticlines and Mega-Shear Fractures (MSF) in Sulaiman Fold Belt, Pakistan.

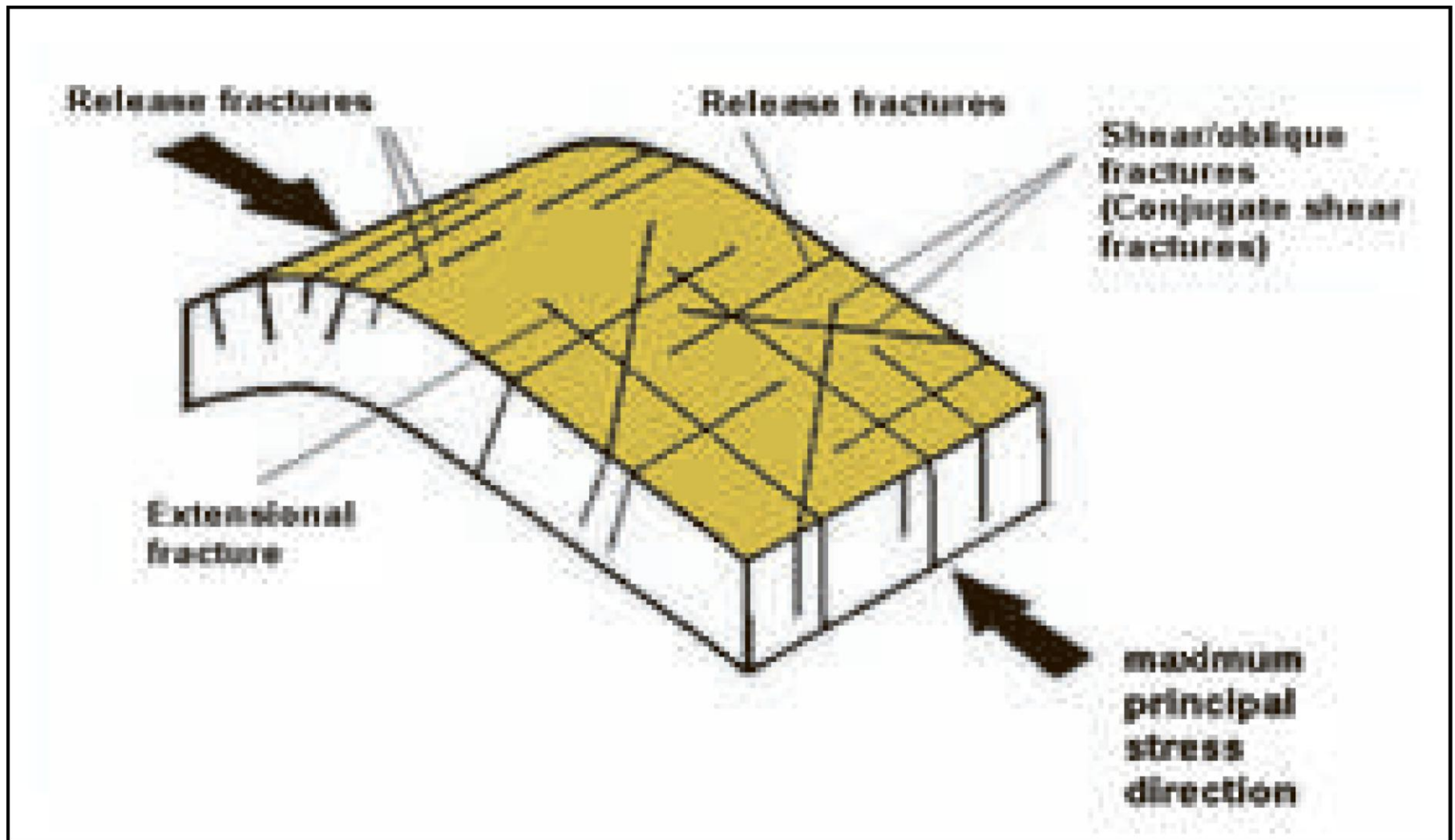


Figure 3. Fractures associated with folding.

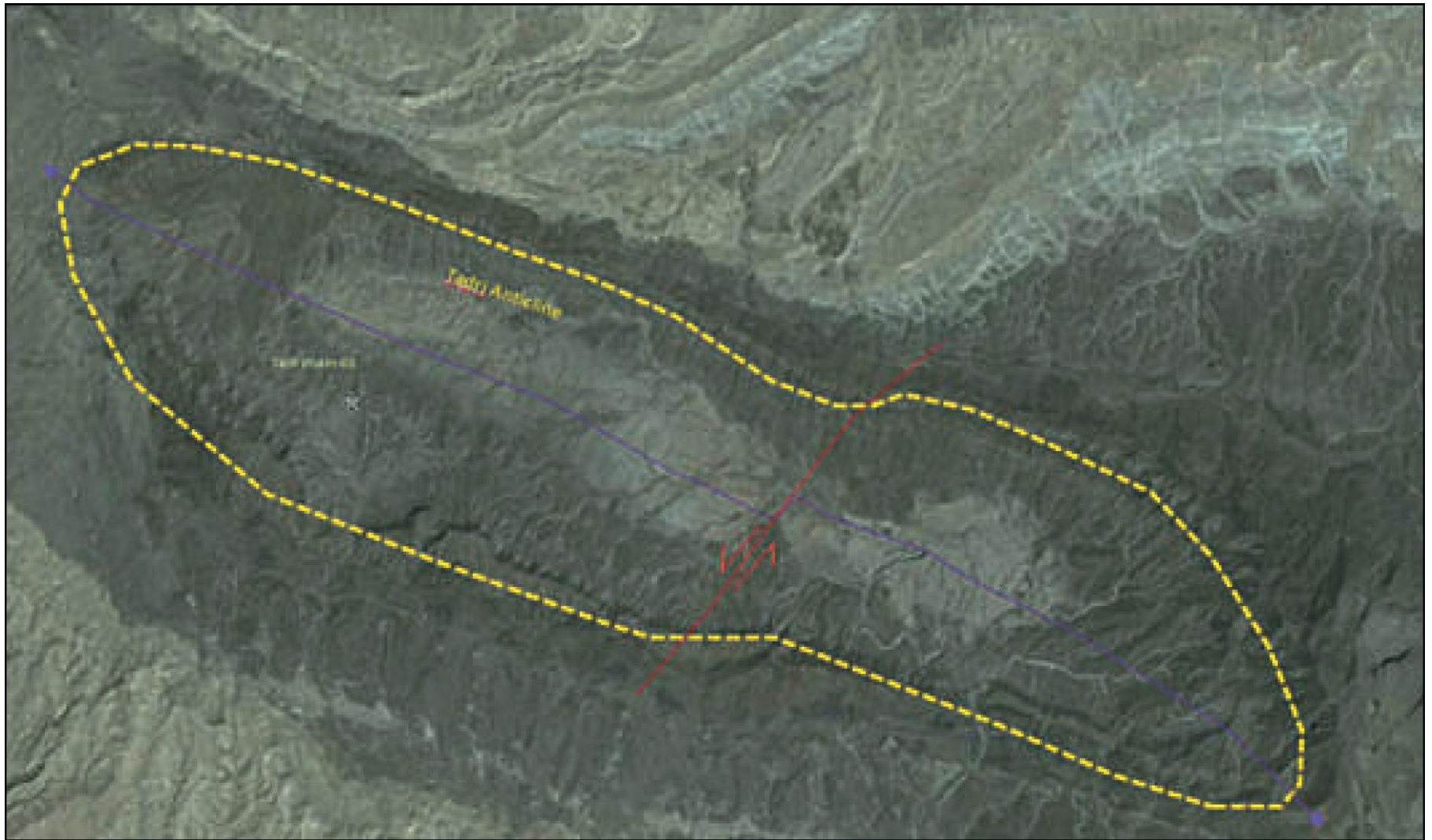


Figure 4. Large displacement along MSF at Tadri Anticline.

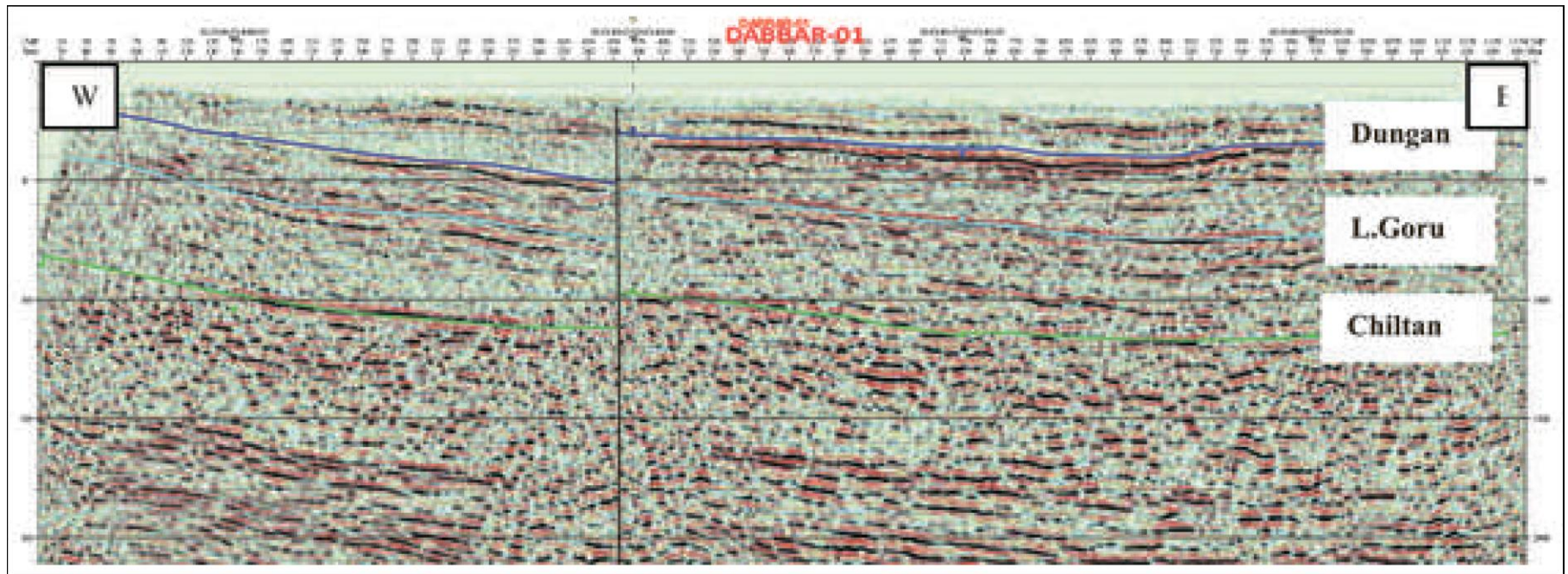


Figure 5. Seismic strike line-2, showing Mega-Shear Fracture, Dabbar Anticline.

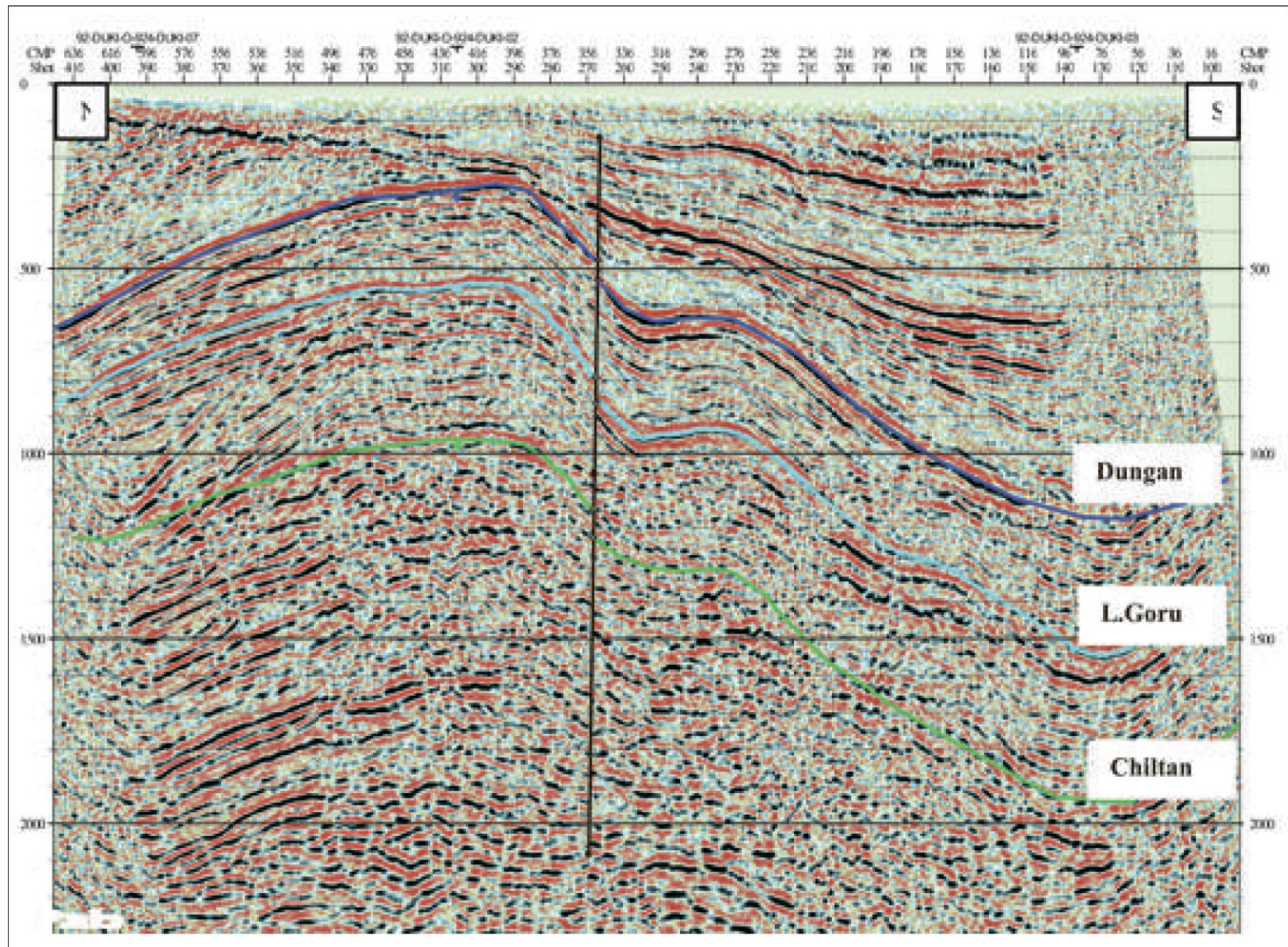


Figure 6. Seismic dip line-3, showing Mega-Shear Fracture, Dabbar Anticline.

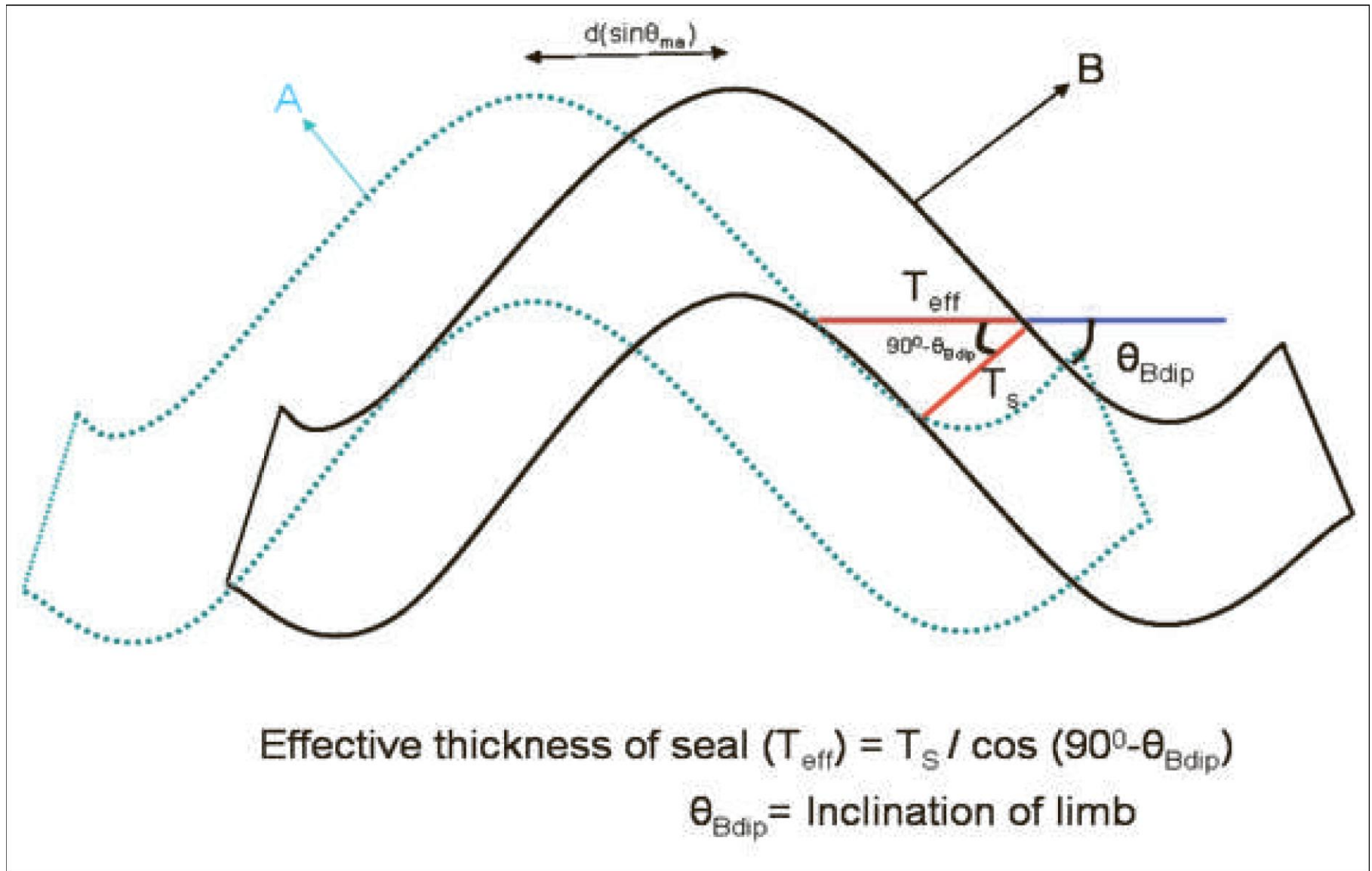


Figure 7. Cross section view of anticline displaced by MSF, showing attributes used in derivation of equation 1.

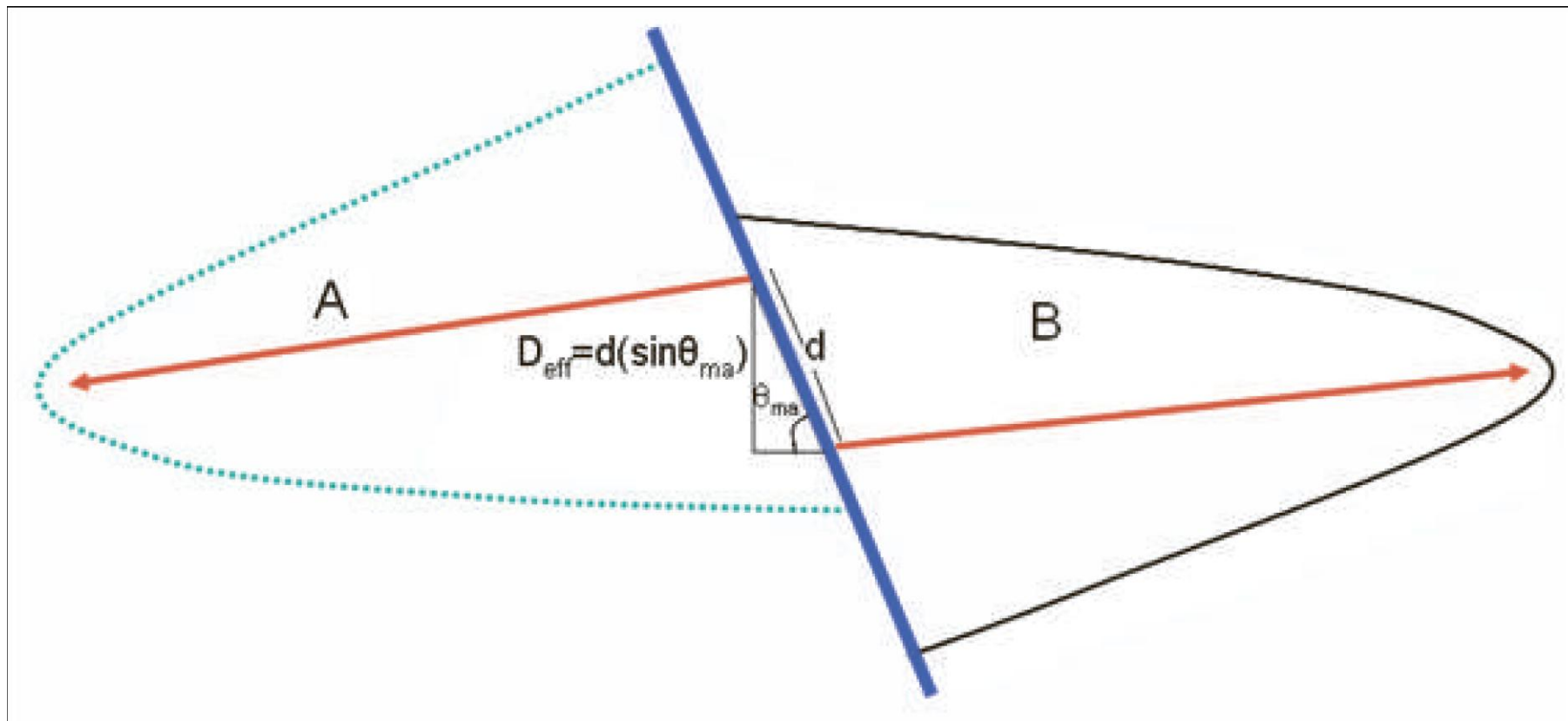


Figure 8. Plan view of anticline displaced by MSF, showing attributes used in derivation of equation 2.

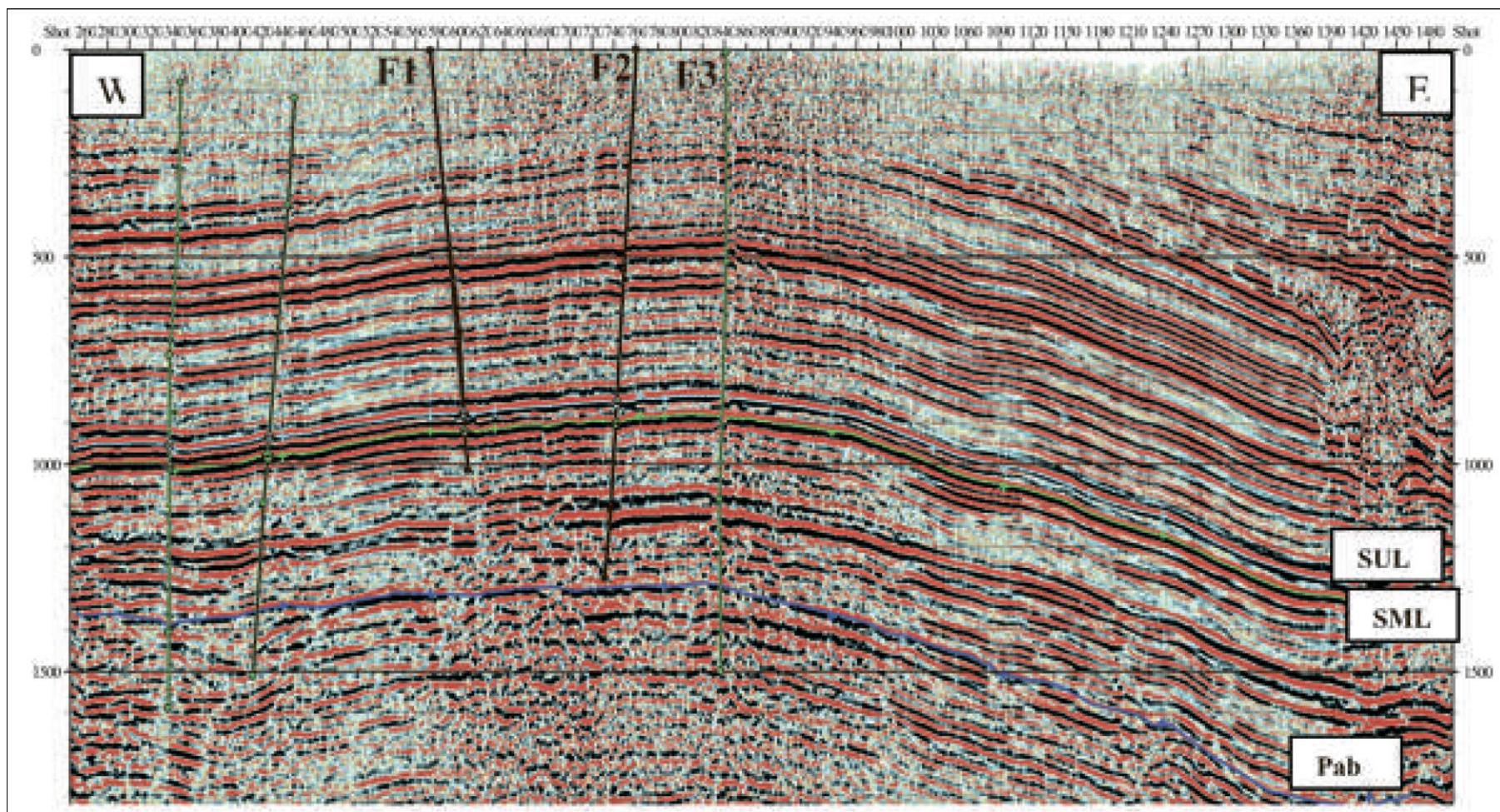


Figure 9a. Seismic strike line-1, showing vertical Mega-Shear Fractures, Sui Anticline.

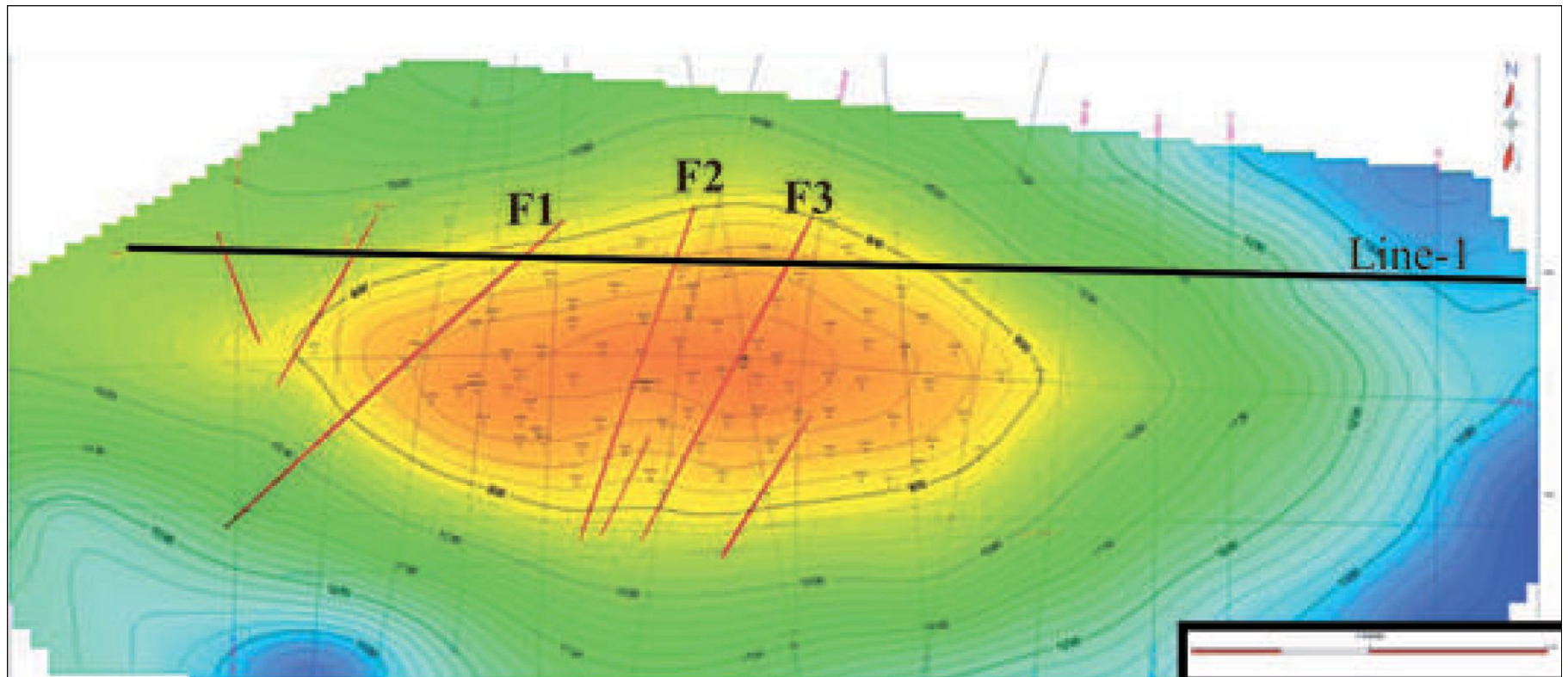


Figure 9b. Time structure map at SML level having lineament of Mega-Shear Fractures (MSF) over Sui Anticline.

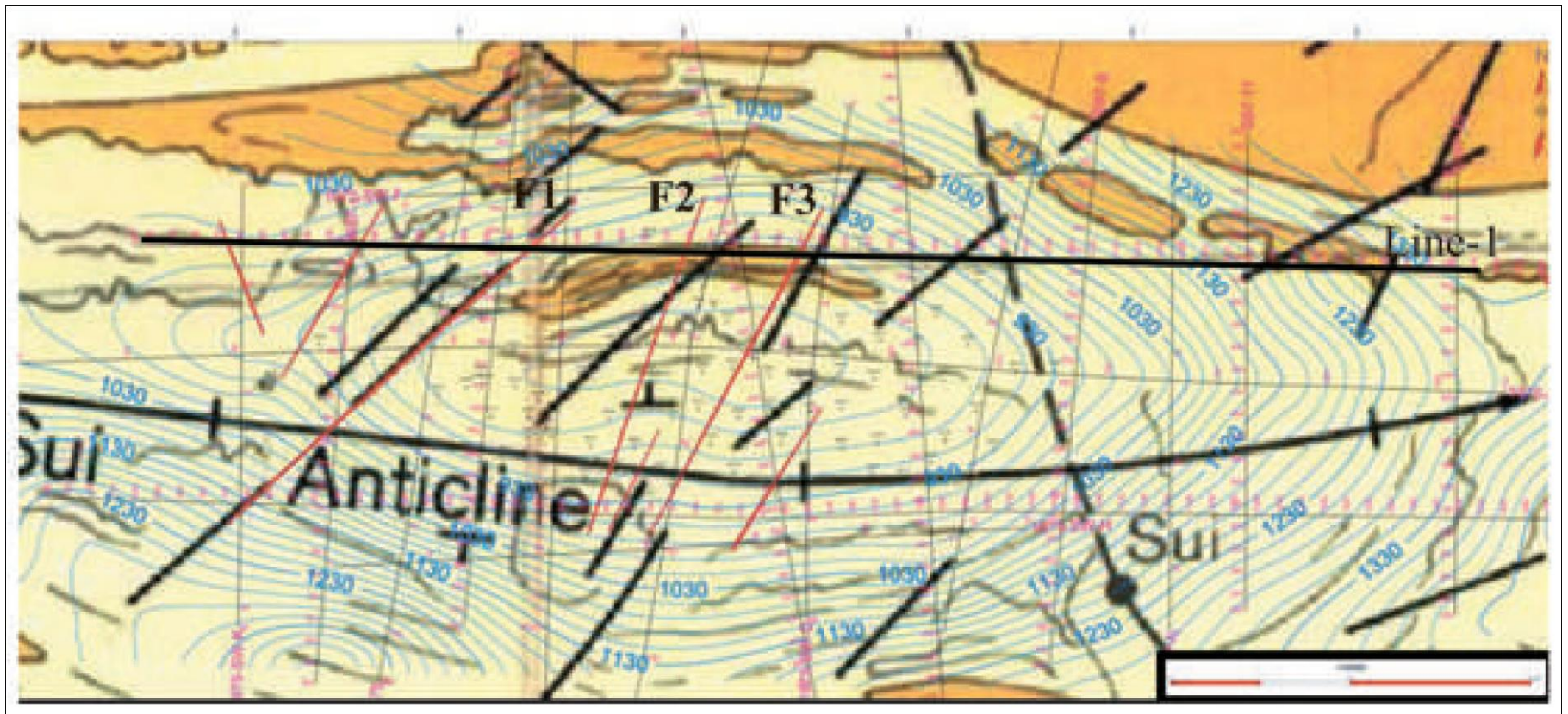


Figure 9c. Geological Map overlain by time contours at SML level, showing orientation of Mega-Shear Fractures (MSF), Sui Anticline.

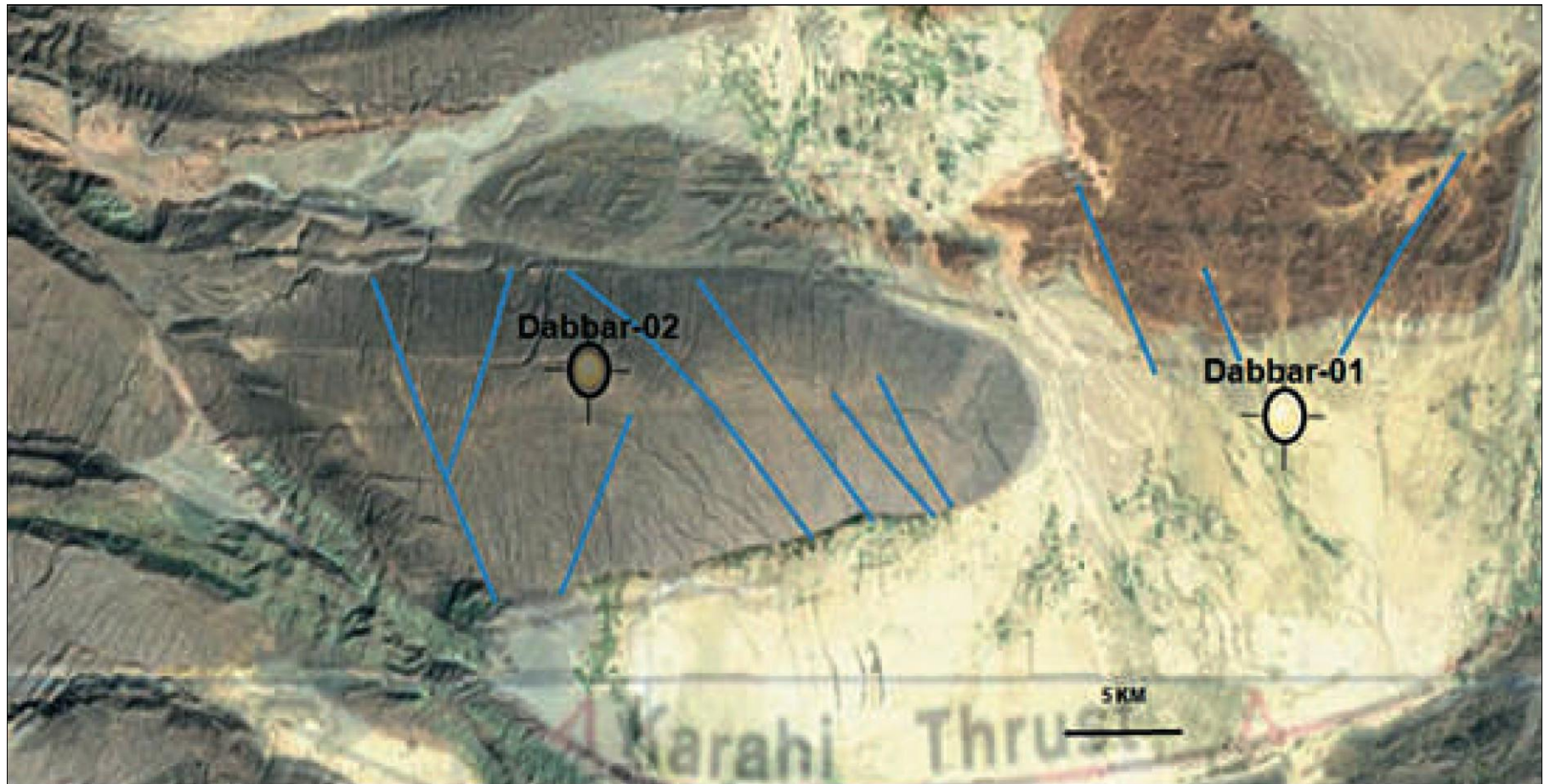


Figure 10a. Satellite image overlain by geological map, showing Mega-Shear Fractures (MSF), Dabbar Anticline.

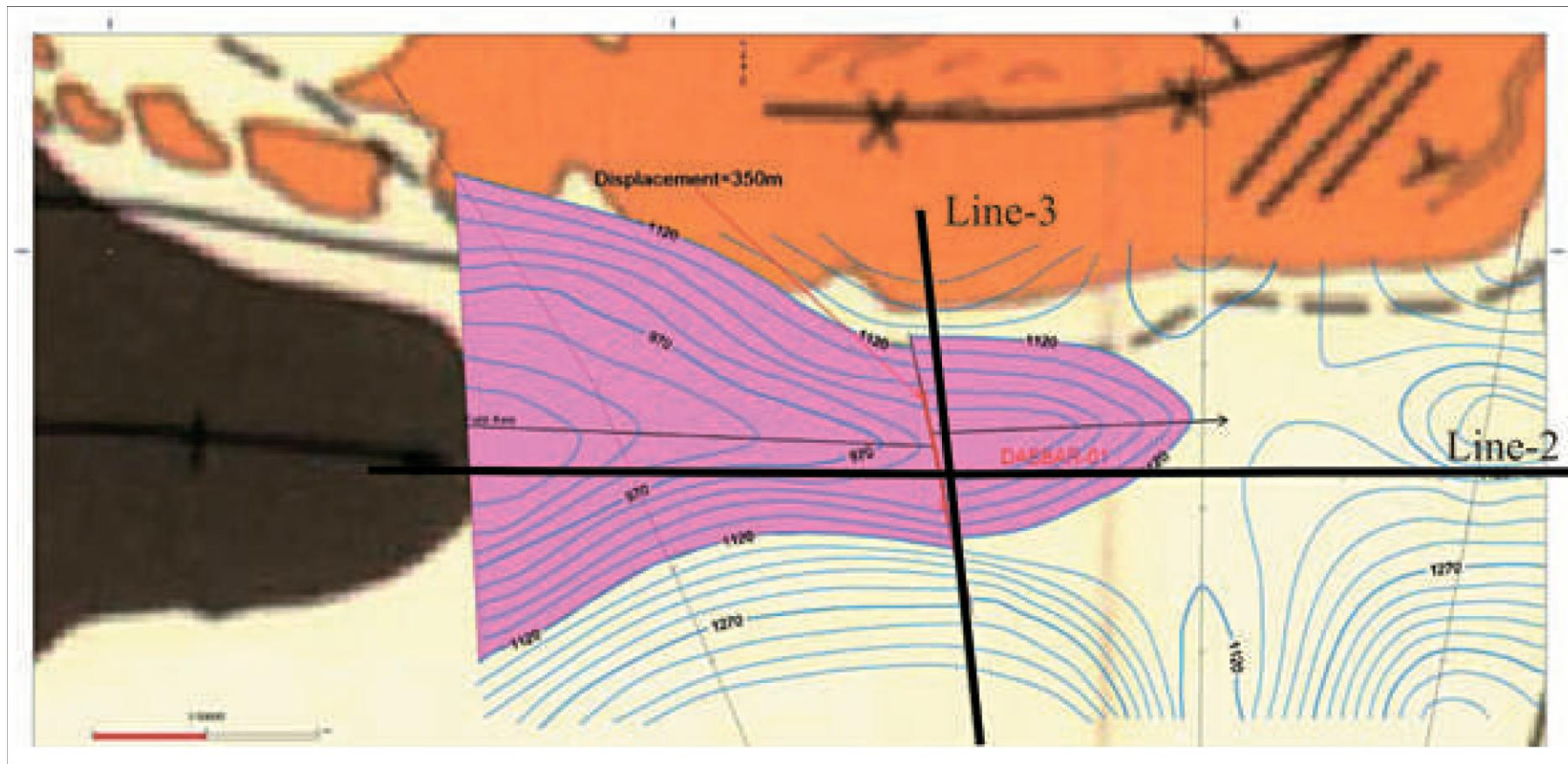


Figure 10b. Time contour map at Jurassic level superimposed on geological map showing orientation of Mega-Shear Fracture (MSF) over Dabbar Anticline.

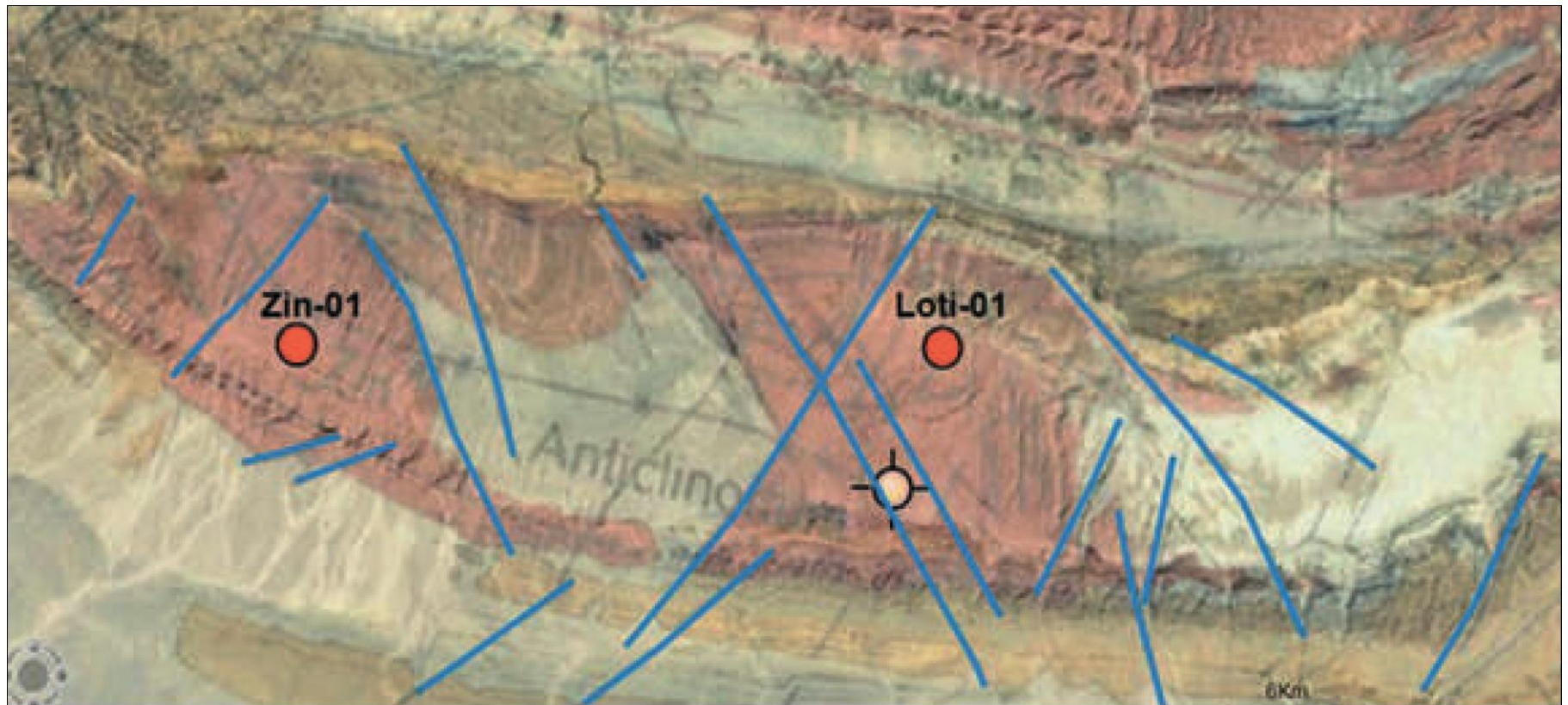


Figure 11. Satellite image overlain by geological map showing MSF which have displaced the southern limb of Zin Anticline and axial trace of Loti Anticline.



Figure 12. MSF cross cutting the Fort Munro Anticline, Eastern Sulaiman Fold Belt.