PS Fracture Patterns and Petrophysical Properties in the Kuqa Depression, Tarim Basin, and Their Relationship with Regional Folding*

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Abstract

The Kuqa Depression of the Tarim Basin hosts a prolific hydrocarbon system. The main reservoirs are characterized by tight sandstone with low-porosity and low-permeability, buried at more than 5000 m depth. In the Bashijiqike Formation, hydrocarbon production mainly comes from secondary porosity created by dissolution and fracturing. The Bashijiqike formation have undergone multiple phases of deformation associated with burial, uplift, folding, thrusting and rapid subsidence. With the aim of evaluating the reservoir quality, we studied fracture patterns and petrophysical properties of the Bashijiqike formation with data collected from Dabei and Kelasu anticlines. We document four fracture systems whose distribution is related to regional stress field, thrusting and local folding. In the Kelasu Anticline, the North-South system is parallel to the maximum horizontal principle stress, showing higher intensity closed to the ridge. Calcite veins filled in the fractures show a characteristic of bending, indicating they form earlier than folding or during folding. The East-West system is parallel to the fold axis, showing a trending of decreasing fracture intensity from limbs to hinge end to crest. Fractures observed on the cores show existence of E-W shearing. Crosscutting relationships suggest that the shearing fractures formed earlier than the tension fractures that due to the local outer arc extension. The Northeast-Southwest and Northwest-Southeast systems are symmetrical with respect to the fold. In the Dabei Anticline, the Northwest-Southeast system parallels to the maximum horizontal principle stress, showing higher fracture intensity than other systems. The Northeast-Southwest system parallels to the fold axis, showing lower fracture intensity at crest with local increments at the limbs. In addition, we analyzed petrophysical properties include porosity and permeability of the Bashijiqike formation in relation to their structural position within folds. The higher porosity and permeability are recorded in the hinges and forelimbs of the both anticlines. It is indicated the best reservoir quality is associated with dissolution and fracturing. The results show how fracture distribution and petrophysical properties depends on structural position and fold evolution. Our work illustrates the folding serve as controls on the fracture patterns and petrophysical properties, providing favorable reservoir targets for prospecting in the compressional basin.

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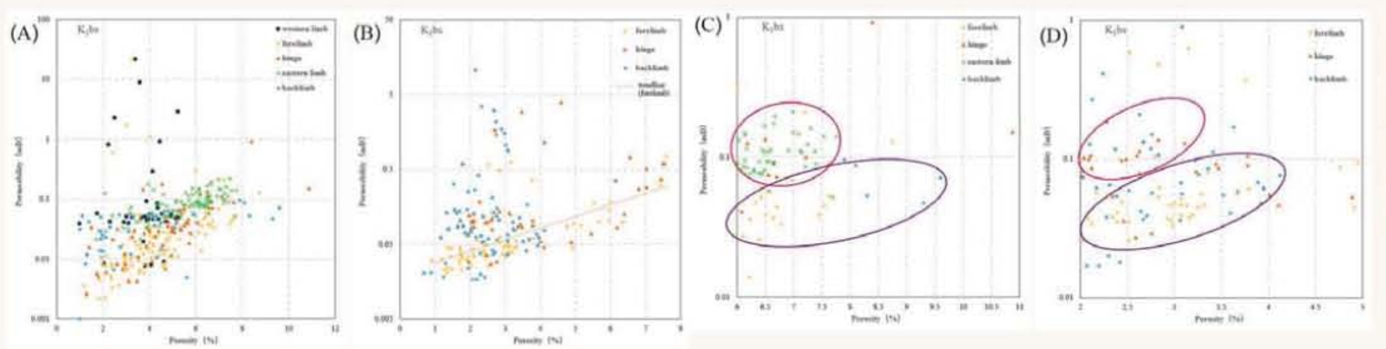
Abstract

The Kuqa Depression of the Tarim Basin hosts a prolific hydrocarbon system. The main reservoirs are characterized by tight sandstone with low-porosity and low-permeability, buried at more than 5000 m depth. In the Bashijiqike Formation, hydrocarbon production mainly comes from secondary porosity created by dissolution and fracturing. The Bashijiqike Formation have undergone multiple phases of deformation associated with burial, uplift, thrusting, folding and rapid subsidence. With the aim of evaluating the reservoir quality, we studied fracture patterns and petrophysical properties of the Bashijiqike Formation with data collected from Dabei and Keshen anticlines. We document four fracture systems whose distribution is related to regional stress field, thrusting folding and locally left-lateral strike-slip. In the Keshen anticlines, the north-South fracture system is parallel to the maximum horizontal principle stress, showing higher intensity closed to the ridge. The east-west fractures are parallel to the fold axis, showing a trending of decreasing fracture intensity from limbs to hinge. This system includes a moderate-dipping fracture set (dip angle between 25 ° to 80 °) and a vertical fracture set (dip angle >80 °). Crosscutting relationships and fracture surface textures suggest that the moderate-dipping fracture set consists of shear fractures and can be explained by intra-layer shear caused by thrusting. The vertical fracture set may be formed due to the local outer arc extension during folding. The northeast-southwest and northwest-southeast fractures show scattering in strike. This distribution suggests that these fractures may be related to a shear event of locally left-lateral strike-slip. In the case of the Dabei anticlines, the northwest-southeast fracture system is parallel to the maximum horizontal principle stress, and fracture intensities are higher with a increasing trend from limbs to hinge, showing that the fracture systems in the Dabei anticlines are not similar with the Keshen anticlines. Besides, we analyzed petrophysical properties include porosity and permeability of the Bashijiqike Formation in relation to their structural position within folds. It is indicated the best reservoir quality is associated with dissolution and fracturing. The best reservoir quality is suggested in the forelimb and hinge zone. The findings have given maybe helpful for providing favorable reservoir targets for prospecting in the compressional basin.

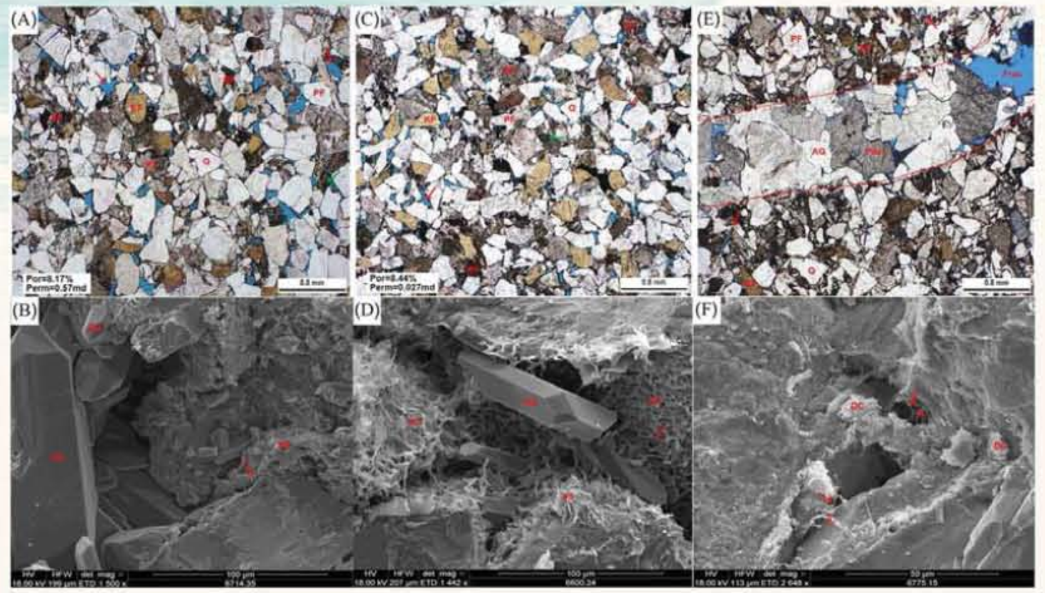
Petrophysical Properties and Petrologic Analyses

There are scatterings of the poro-perm data both in the Keshen and the Dabei structures. The permeability values range over five orders of magnitude due to the natural fractures. Even though the Bashijiqike Formation has low matrix porosity and permeability, fractures provide the essential reservoir permeability and some porosity. Besides, our results suggest the structural position on regional folds may control the distribution of porosity and permeability of the Bashijiqike Formation. In the Keshen structure, the hinge zone and eastern limb have higher permeability for a given porosity (>6%) than forelimb and backlimb. In the Dabei structure, fold hinge generally has higher permeability, followed by backlimb.

Natural fractures observed in section and SEM petrography are filled by calcite (C), gypsum and quartz (Q). Intergranular areas mainly filled by authigenic quartz (AQ), authigenic feldspar (AF), detrital clays (DC), dolomite (Dol) and authigenic illite (IL). It is notable that detrital clay flakes are tightly compacted, and micropores are mainly related to the authigenic illite. Authigenic fibrous illite is very fragile, and can break easily and cause fines migration. It is also sensitive to fresh water or undersaturated brine, and may become mushy and block pore throats. It indicates the higher permeability is due to well-connected intergranular pores.



Porosity versus permeability of the Bashijiqike Formation measured from core plugs of wells, the dataset has been classified according to the structural positions. (A) and (B) samples were collected at Keshen and Dabei anticlines, respectively. (C) porosity of Keshen anticlines greater than 6%; (D) porosity of Dabei anticlines range from 2%-5%. n= number of samples.



Microscopic characteristics of the Bashijiqike Formation. Quartz (Q), authigenic feldspar (AF), detrital clays (DC), rock fragments (RF), plagioclase (PF), authigenic illite (IL), K-feldspar (KF), calcite (C); intergranular macropores (red arrows), intergranular micropores (purple arrows), intragranular micropores (green arrows). Natural fracture (Frac) marked out by dashed lines, and partly filled by calcite (C) and quartz (Q). (A) and (B) well KS2-1-5 at hinge, depth 6739.26m, thin section and SEM from K1bs; (C) and (D) well KS208 at forelimb, depth 6600.24m, thin section and SEM from K1bs; (E) and (F) well KS2-2-5 at forelimb, depth 6775.15m, thin section and SEM from K1bs. (G) well DB302 at forelimb, 7207.99m, thin sections from K1bs. (H) well DB302 at forelimb, 7244.65m, thin sections from K1bs.

Conclusions

We have characterized the fracture systems at Dabei and Keshen structures within the central Kuqa Depression of Tarim Basin.

(1) Regional stress field, thrusting, folding and locally strike-slip may have played an important role in fracture development.

(2) The moderate-dipping set of hinge-parallel fractures is possibly formed due to thrusting. However, the vertical set may have been formed due to outer arc extension in the folds.

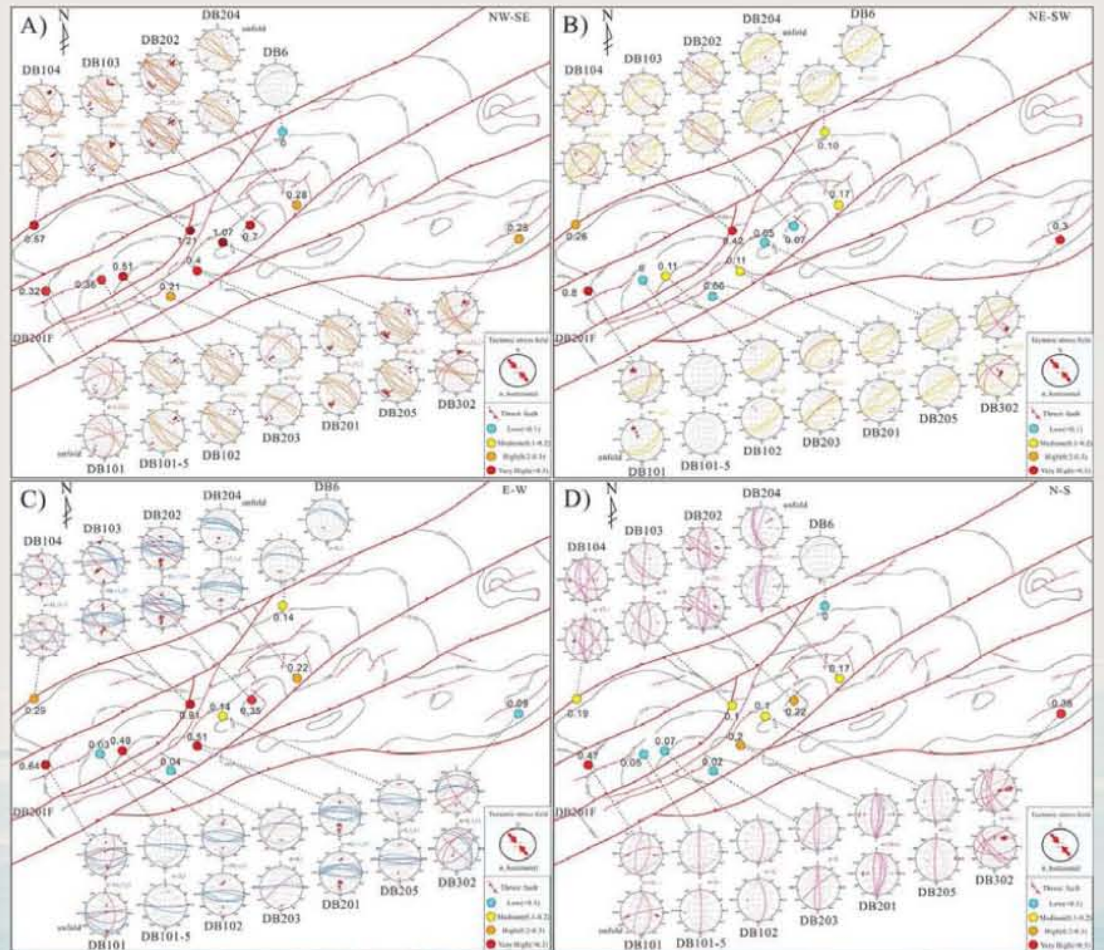
(3) A comparison between the Dabei and Keshen anticlines shows that the distribution of fracture systems are varies considerably.

(4) Fracture intensity may be controlled by regional stress field, thrust, and folding. The presences of thrusts always make local increments of fracture intensities in the general trends. Fold evulation may have an impact on the northwest-southeast fracture system in the Dabei structure, because the fracture intensity of this system increases from limbs to fold hinge.

(5) The structural positions have a potential impact on the petrophysical properties distribution.

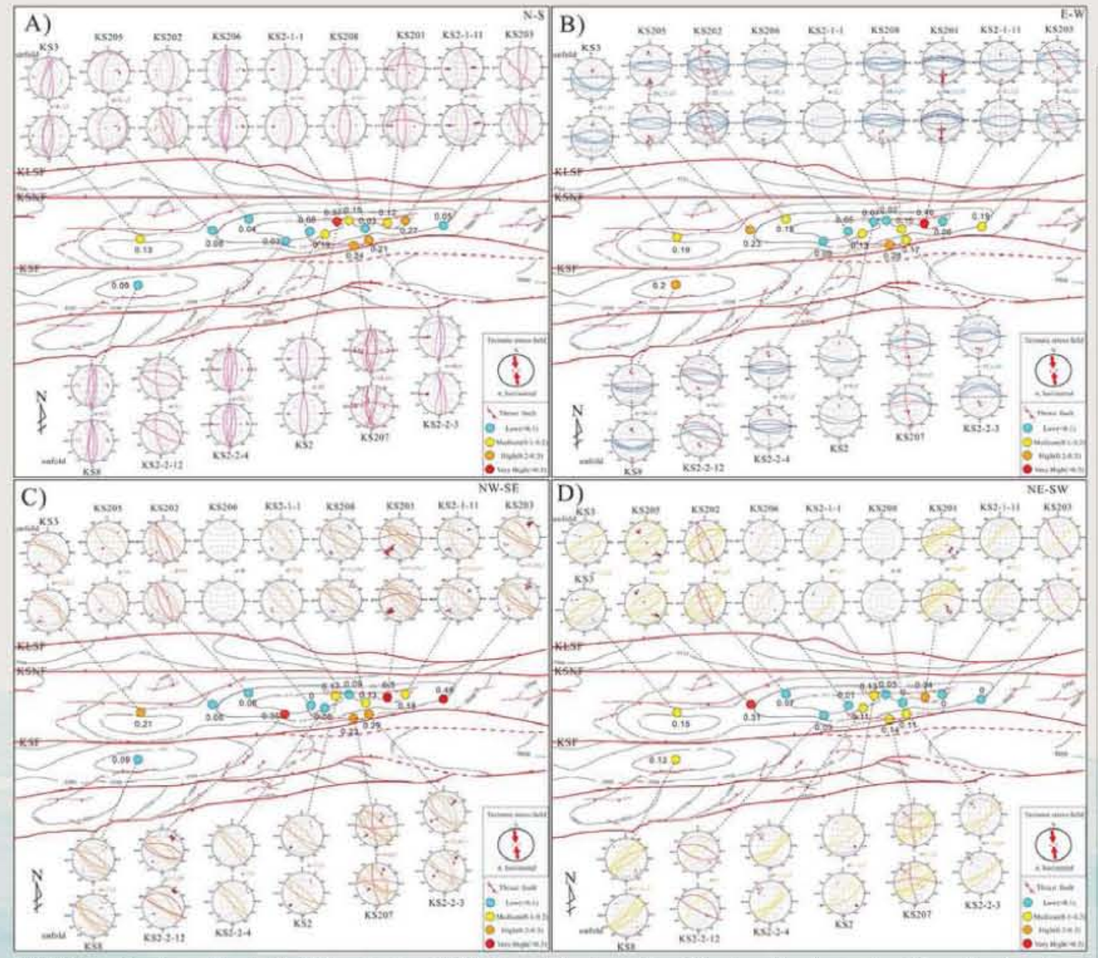
Fracture System

Dabei structure: The northwest-southeast fracture system is parallel to the maximum horizontal principal stress. Overall, this system presents very high fracture intensities, with a decreasing trend from hinge (0.7-1.07) to limbs (0.21-0.32). The northeast-southwest fractures parallel to the fold axis. Fracture intensities of the northeast-southwest fracture system increase from hinge (0.05-0.11) to the limbs (0.11-0.8). It consists of the moderate-dipping fracture set and the vertical fracture set.



Distribution of fracture systems in the Dabei structure. (A) Northwest-southeast fracture system; (B) northeast-southwest fracture system; (C) east-west fracture system; (D) north-south fracture system. Fracture intensity is represented by different colored circles. Stereographic projections show fractures system in colors and bedding planes in black. n= number of fractures. DB201F=Dabei 201 Fault.

Keshen structure: The north-south fracture system is parallel to the maximum horizontal principal stress. The east-west fracture system is parallel or sub-parallel to the fold axis. Fracture intensity shows a decrease from the limbs (0.19-0.29) to hinge (0.05-0.06). It includes the moderate-dipping fracture set and the vertical fracture set. The northwest-southeast and northeast-southwest fracture systems show scattering in strike. This scattering increases from west to east, and is consistent with the trend of the Keshen fault (KSF).



Distribution of fracture systems in the Keshen structure. (A) North-south fracture system; (B) east-west fracture system; (C) northwest-southeast fracture system; (D) northeast-southwest fracture system. Stereographic projections show fractures system in colors and bedding planes in black. n= number of fractures. KSF=Keshen fault; KSNF= Northern Keshen fault; KLSF=Kelasu fault.

A comparison between the Keshen and Dabei anticlines shows that the distribution of fracture systems varies considerably. The northwest-southeast fracture system is observed very high intensities at all structural positions and shows increasing trending of fracture intensities from limbs to hinge in the Dabei structure, whereas, in the Keshen structure, the high intensities are almost restricted near the faults. In a similar way, the general distribution of intensities shows that in the hinge region of the Keshen anticlines, intensities show low values, whereas in Dabei, the values are high. This is probably related to the folding mechanism.

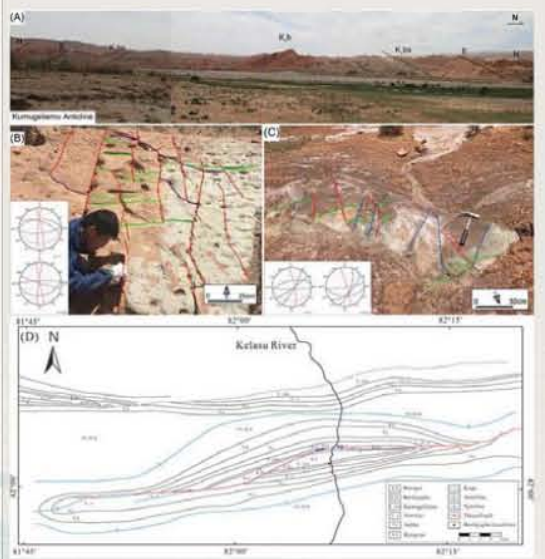
Slickenside kinematic indicators:

Fracture surfaces have typical kinematic indicators such as steps, mineralogical/crystallographic orientations and "V" markings. The oblique mineralogical orientation (OMO) of the moderate fracture surfaces are directly developed on the fracture wall, however, the rhombohedral structures (RS) developed on one side of OMO and steps, indicating shearing mode fracture propagation earlier and opening displacements postdate.

Calcite crystals with rhombohedral structures (RS) grow perpendicular to the fracture surfaces of the vertical set, indicating the vertical set may have formed due to outer arc extension of the folds.

Kinematic indicators on the fracture surface of cores. Well name and depth are provided in the figure. (A), (B), (H), (I), (J) and (K) shows mineralogical/crystallographic orientations, includes oblique mineralogical orientation (OMO) and rhombohedral structure (RS). (B), (F) and (G) show steps. (C) and (D) show "V" markings. (E) shows abutting relationship. MC=mineralogical/crystallographic orientations; VM="V" markings; CR=crosscutting and abutting relationships; OMO=oblique mineralogical orientation; RS=rhombohedral structure.

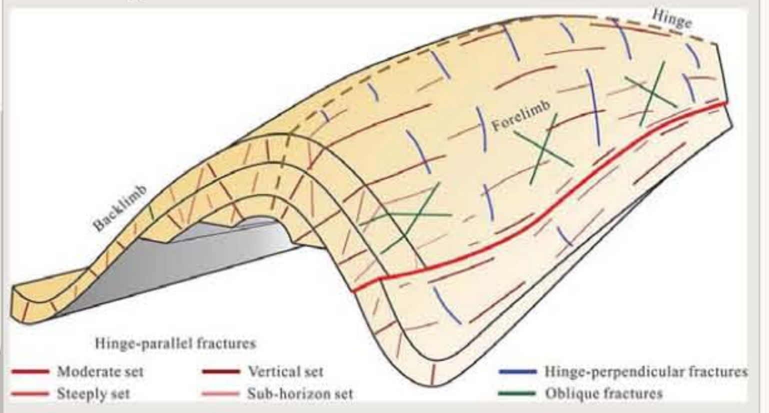
3D core-image of KS201 located at fold hinge. (A) Un-annotated figure. (B) Annotated figure. Fracture dip were corrected taking into account the trend and inclination of the well.



Fracture patterns at representative outcrops of the Kumugeliemu anticline. (A) Photograph of crest of the Kumugeliemu anticline. (B) Bashijiqike Formation at the forelimb (Hx3). (C) Bashijiqike Formation at the forelimb (Hx5). Hx3 and Hx5 refer to localities in (D), black dashed line in the stereogram is bedding plane; N=number of fractures in the stereogram. (D) Geological map of the Kumugeliemu anticline.

Crosscutting relationships suggest a first event developed the hinge-perpendicular fractures (northwest-southeast fractures in Dabei, north-south fractures in Keshen). A second event developed the moderate-dipping set of the hinge-parallel fractures (northeast-southeast fractures in Dabei, east-west fractures in Keshen), followed by a third event developed the vertical fracture set. The oblique fractures (east-west and north-south fractures in Dabei, northwest-southeast fractures and northeast-southeast fractures in Keshen)are proposed to have formed the last.

Conceptual fracture model:

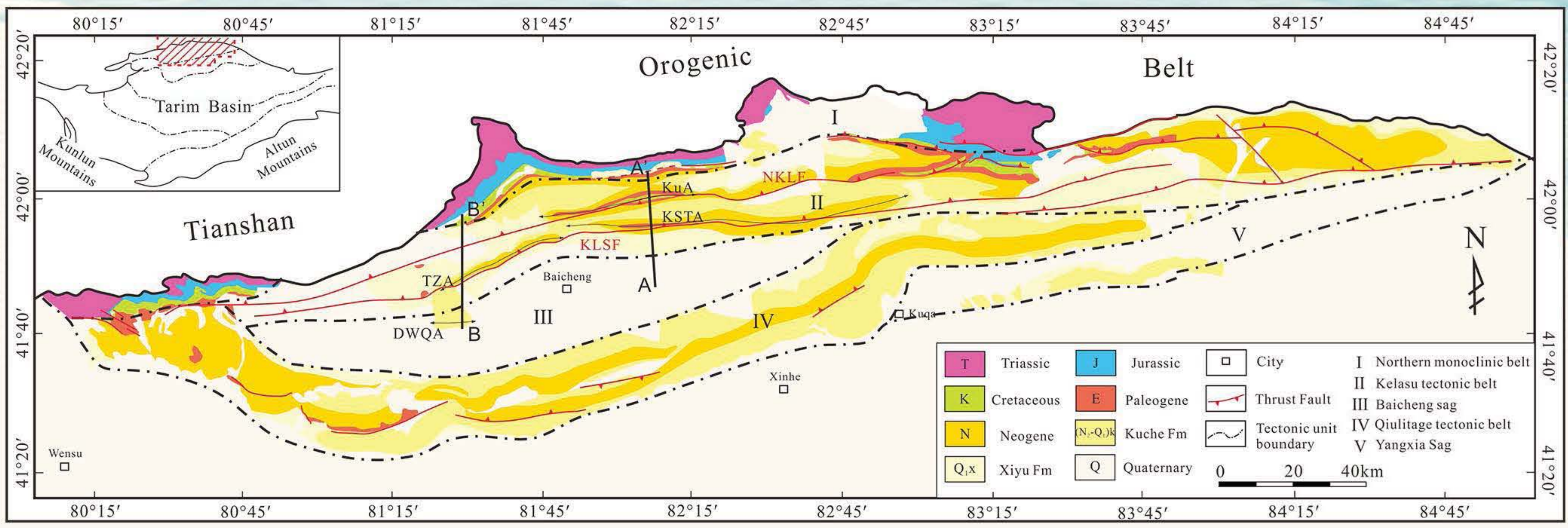


Schematic models for the developments of fractures sets. A pre-folding stage of hinge-perpendicular fractures is proposed to have been formed by the regional stress field during the collision between the Indian plate and the Eurasian Plate, whereas, in the Dabei structure, hinge-perpendicular fractures may be also related to fold evolution. The moderate-dipping set of hinge-parallel fractures is possibly formed due to thrusting. However, the vertical set may have been formed due to outer arc extension during folding. The oblique fractures are proposed to be related to the shear event of locally left-lateral strike-slip and limb rotation.

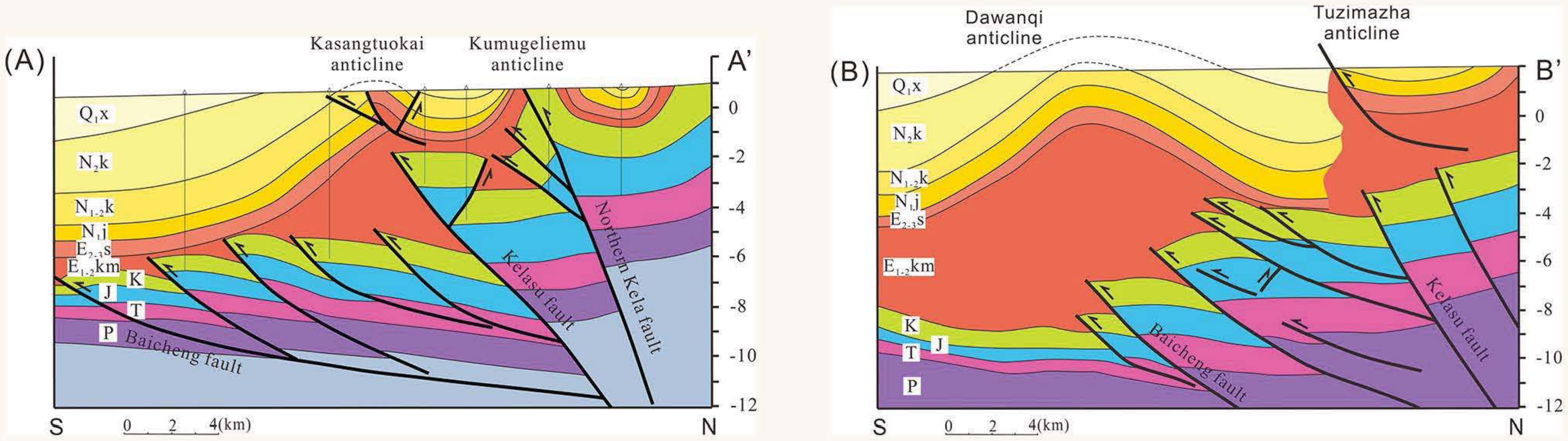
Heavy lines indicate fracture sets forming during each stage.

Geological Setting

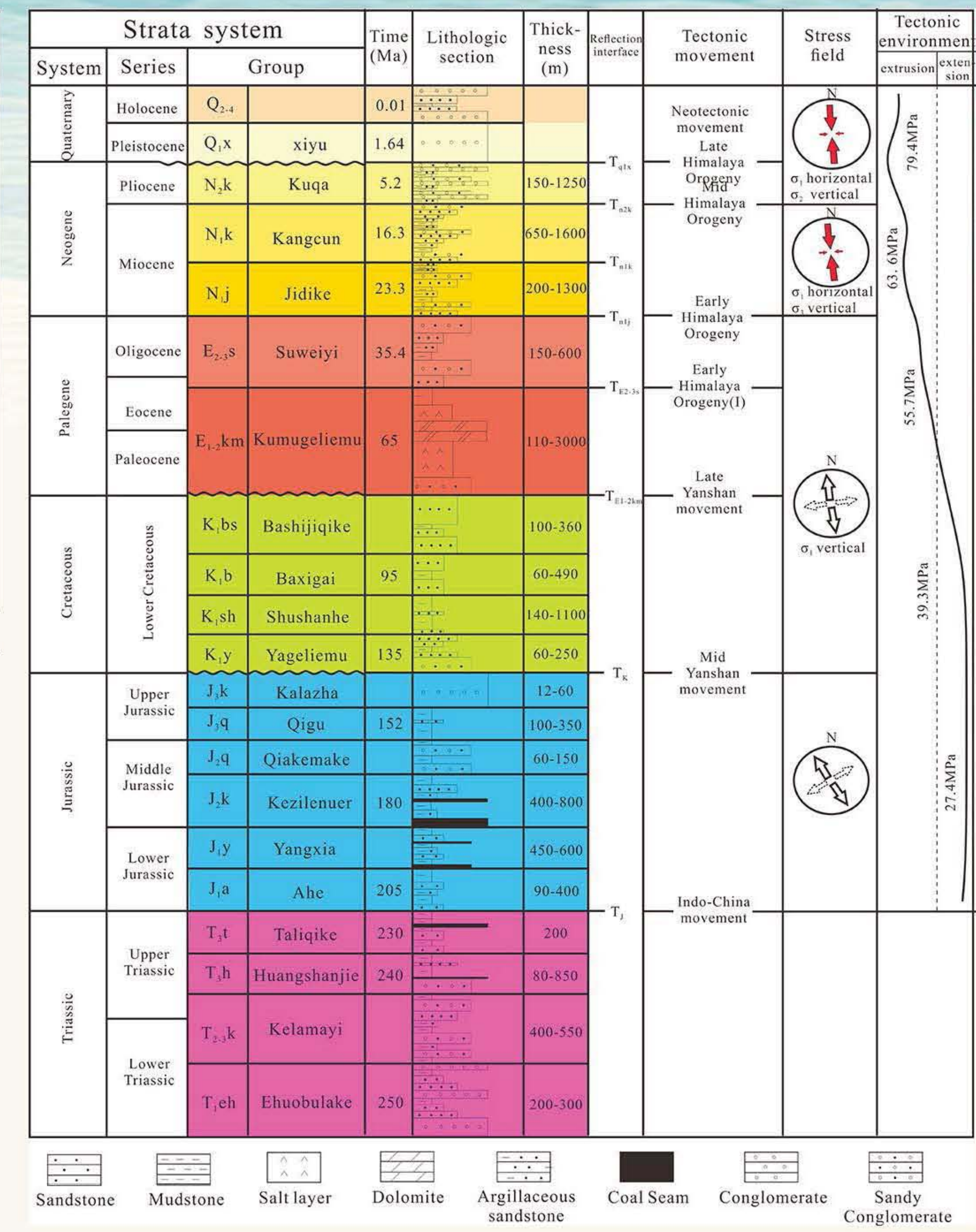
The Kuqa Depression developed in the northern Tarim basin near the foothill of the southern Mt. Tianshan. Due to the dual-action of vertical shear-force and extrusion induced by the strong uplift of the southern Mt. Tianshan, a series of fault-related folds have developed in the basin. Current contractional structural deformation in the Kuqa Depression is mainly due to the most intense tectonic deformation caused by Himalayan orogeny during Neogene-Quaternary. The stratigraphic units involved in the structures range in age from Triassic to Oligocene. The Cretaceous Bashijiqike Formation sandstones is buried at more than 6000 m depth and is the most important reservoir that has been explored in the past decade, despite its low matrix porosity (<9%) and ultra-low permeability (as little as 0.001mD). The Bashijiqike Formation is overlain by the Paleogene Kumugeliemu Group (E1-2km), an excellent regional seal with salt and gypsum unit. Natural fracture systems have a significant impact on reservoir performance.



Geological map of the Kuqa Depression with an inset map showing regional locations in northern Tarim Basin. Reference to fracture distribution maps and cross sections are shown. KuA=Kumugeliemu anticline; KSTA=Kasangtuokai anticline; KLSF=Kelasu fault; TZA=Tuzimazha anticline; DWQA=Dawanqi anticline (after Li et al., 2018).



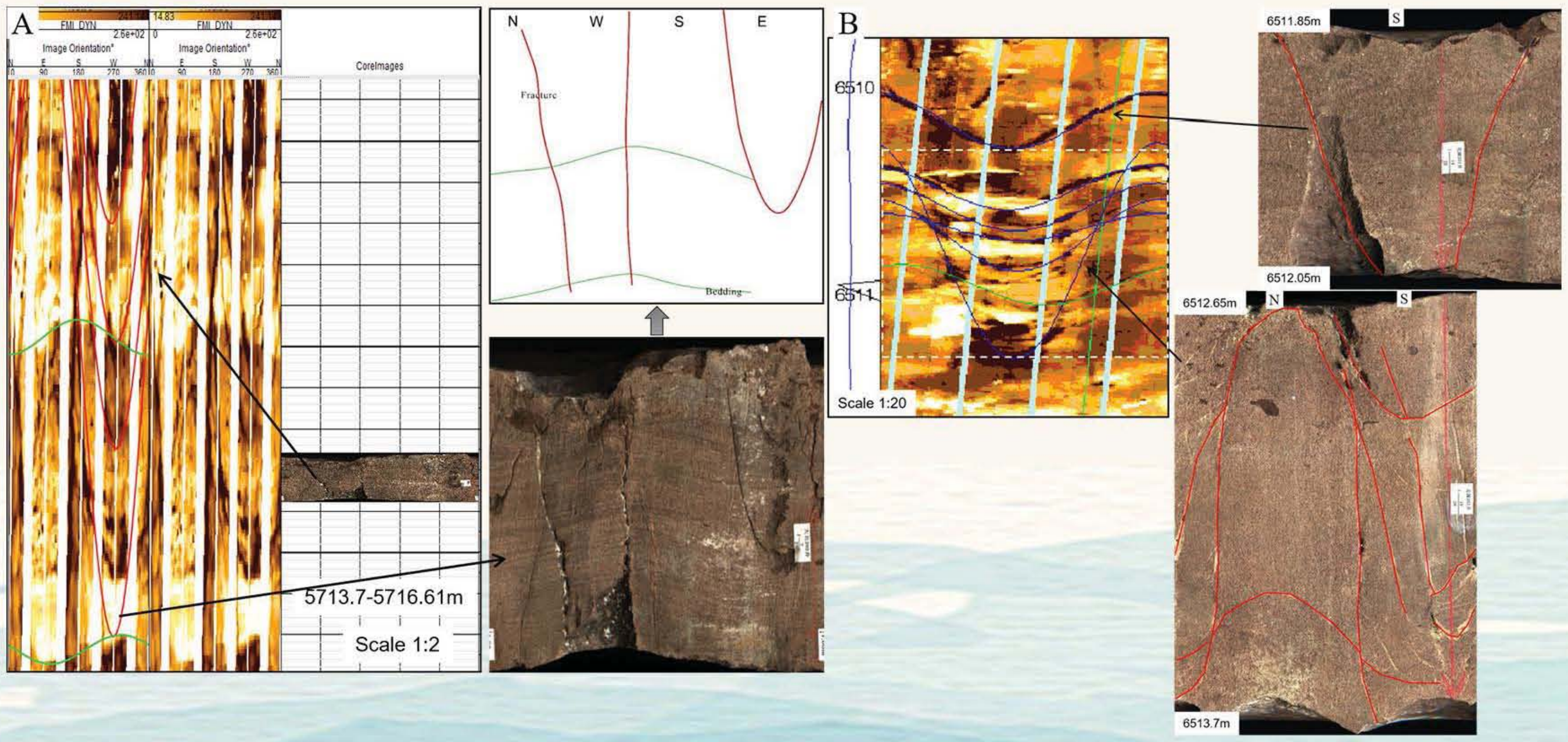
East to west change in structural style across the Kelasu tectonic belt in the Kuqa Depression. (A) Kumugeliemu anticline and Kasangtuokai anticline, and the Keshen structure below the Eocene Kumugeliemu (E1-2km) salt layer, (B) Tuzimazha anticline and Dawanqi anticline, and the Dabei structure below the Eocene Kumugeliemu (E1-2km) salt layer. Cross sections are modified from Qi et al. (2009a). For a key to formation colors see Figure 3.



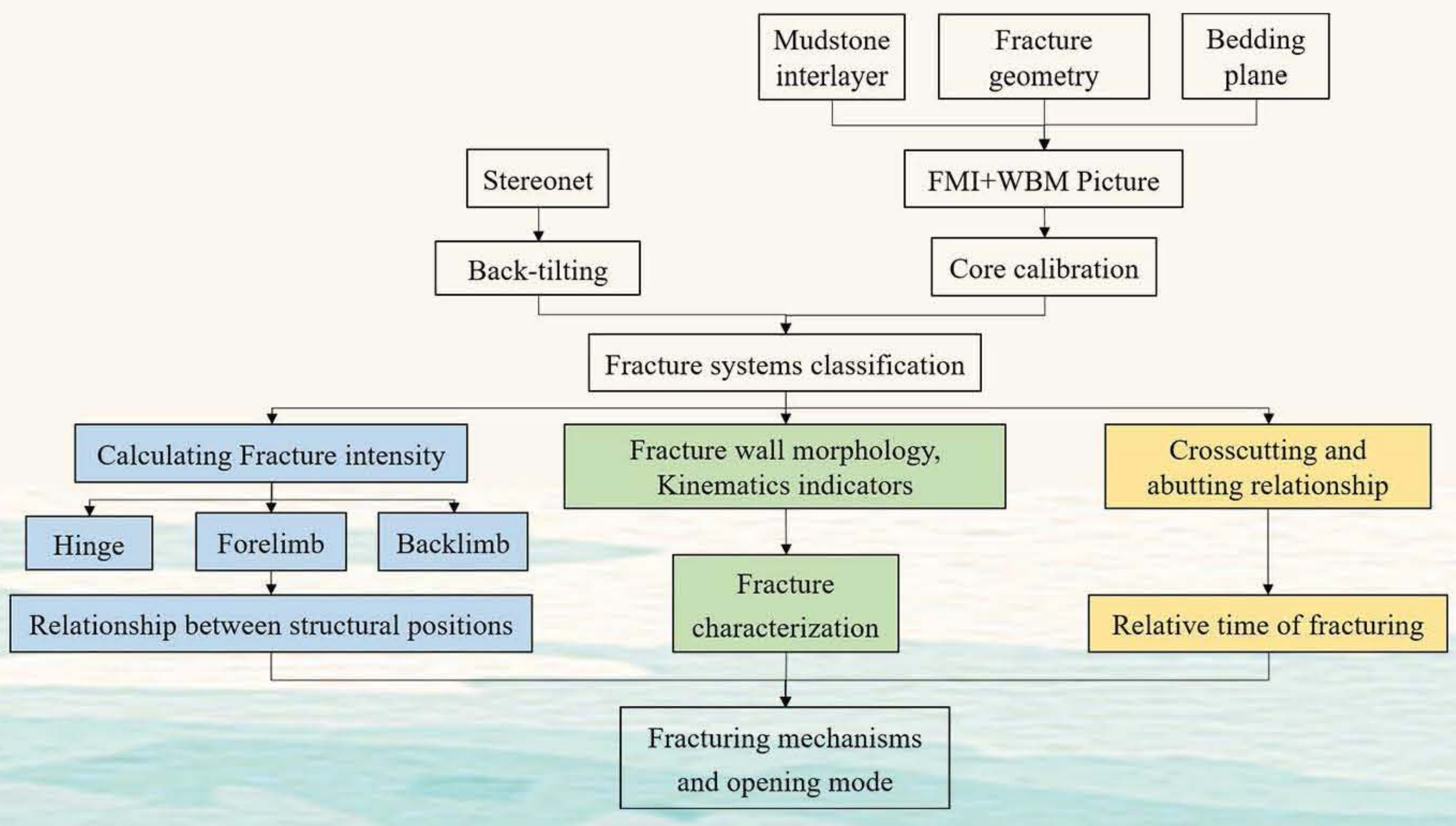
Lithostratigraphic column of the Kuqa foreland thrust belt, Tarim Basin

Methods

Subsurface data, including Formation Micro Imager (FMI) logs (31 wells), 3D core-images (7 wells), core pictures (15 wells) and contour map. Using stereographic technique, we document the subsurface fracture system. Bedding dip is restored to the horizontal. Fracture intensity (the number of fractures per meter) within sandstones was analyzed. Stereographic projections are used with different colors to represent fracture intensities. 3D core-images and core pictures provide information about fracture wall morphologies, kinematic indicators, and crosscutting relationships. The 3D core-images are compared with FMI data to orient them through markers such as mudstone interlayer, bedding plane and fracture geometry. Thus, orientation and dip azimuth of each fracture on the 3D core-image is obtained. Then, the relative timing between the various fracture sets were established based on crosscutting relationships, and subsequently related it to the regional structural context. The surface textures and fillings that could be diagnostic of relative displacements are used to determine the history of open fracture formation and fracture modes.



Core calibration by FMI log. The black arrow indicates the same markers between the 3D core-image and the FMI log. (A) FMI log and 3D core-image of well DB202. Red lines in the FMI log are conductive fractures. Green Lines in the FMI logs are bedding planes. (B) FMI log and 3D core-image of well KS201. Blue lines in the FMI log are conductive fractures. Green Lines in the FMI logs are bedding planes.



FFlowchart indicating methodology for the study.