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# Structure of the Mesozoic rocks in the Kuqa Basin (NW China)

*Estructura de las rocas mesozoicas de la cuenca de Kuqa (NO China)*

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## ABSTRACT

*The deformation of sub- and supra-salt structures in the Kuqa Basin exhibits a clear decoupling relationship. Difficulty in identifying deep structures below the Eocene regional detachment level has led to controversy over Cenozoic deformation affecting Mesozoic rocks and Mesozoic deformation itself. This work aims to revise and compile published data (geological and geophysical data and detrital zircon U-Pb ages) to understand the structure affecting the Mesozoic rocks of the Kuqa Basin. The results indicate significant Mesozoic basement-involved structures which were subsequently modified by Cenozoic compressional tectonics. Further investigation of this phenomenon is critical for understanding the overall tectonic evolution of the Kuqa Basin.*

**Key-words**: *Kuqa Basin, Mesozoic, Structural deformation, Thin-skinned.*

## RESUMEN

*La deformación de las estructuras sub- y supra-salinas en la Cuenca de Kuqa muestra una clara relación de desacoplamiento. La dificultad para identificar las estructuras profundas bajo el nivel de despegue regional de edad Eoceno ha llevado a controversias sobre cómo afecta la deformación Cenozoica a las rocas Mesozoicas y la deformación Mesozoica que tuvo lugar. Este trabajo tiene como objetivo revisar y recopilar datos publicados (datos geológicos, geofísicos y edades U-Pb de zircón detrítico) para comprender la estructura que afecta a las rocas mesozoicas de la cuenca de Kuqa. Los resultados indican estructuras mesozoicas con implicación del basamento que fueron posteriormente modificadas por la tectónica compresional cenozoica. Una investigación más profunda de este fenómeno es crucial para comprender la evolución tectónica general de la Cuenca de Kuqa.*

**Palabras clave:** *Cuenca de Kuqa, Mesozoico, Deformación estructural, Cabalgamiento de piel fina, Cabalgamiento de basamento*

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## Introduction

The presence of salt detachment layers within the pre- and syn-tectonic sequence represents an important factor controlling the geometry and kinematics of deformation on compressional scenarios. The Kuqa Basin, located in the northern part of the Tarim Basin and piedmont of the Southern Tianshan Mountains, represents a natural laboratory for the study of the role played by salt layers on deformation and their influence on thin- versus thick-skinned tectonic style.

The Kuqa Basin is characterized by different detachment levels (e.g. Izquierdo-Llavall et al., 2018). The main detachment level corresponds to Eocene syncontractional salt units that controlled the development of thrust systems and decoupled deformation above and below salt during the Cenozoic. While deformation above the Eocene salt level is increasingly understood, the nature of deformation beneath salt and affecting the Mesozoic rocks remains under debate due to the lack of high-quality seismic data. Various models, including thin-skinned and basement-involved thrusting, have explained the structure of sub-salt units (Izquierdo-Llavall et al., 2018). The interpretation of different deformational models has important implications for hydrocarbon exploration, particularly for identifying the possible presence of Mesozoic-age hydrocarbon source rocks and their distribution at depth.

This work aims to revise and compile already published data (geological and geophysical data and detrital zircon U-Pb ages) to understand the structurae affecting the Mesozoic rocks of the Kuqa Basin.

## Geological setting

The Kuqa Basin is a sub-basin located in the northern part of the Tarim Basin, which is surrounded by the South Tianshan, West Kunlun, and Altyn Tagh mountains in northwestern China (Fig. 1A). The Kuqa Basin extends in a narrow 500 km-long per 40-90 km-wide, W-E elongated strip. The long-term geodynamic evolution of this region has been characterized by a series of orogenic events driven by lithospheric accretion (e.g. Jolivet et al., 2010). These orogenic events occurred successively from the Palaeozoic, leading to the final accretion of the Central Asian orogenic belt during the Permian, the Permian-Triassic Cimmerian orogeny and closure of the Palaeo-Tethys ocean, the Cretaceous accretion of Lhasa block, and finally the Cenozoic collision of India. These multiple Mesozoic-Cenozoic deformation episodes are responsible for the tectonic complexity of the Kuqa Basin (e.g. Yin et al., 1998).

## Outcrop and well data

A series of east-west trending thrusts and anticlines are the main structural features of the Kuqa Basin at surface (Fig. 1B). These structures are from north to south (Fig. 1): the South Tianshan Thrust Belt (STTB), the Northern Monocline (NM), the Kelasu Thrust Belt (KTB), the Baicheng Syncline and the Qiulitage Thrust Belt (QTB). The STTB forms the

 

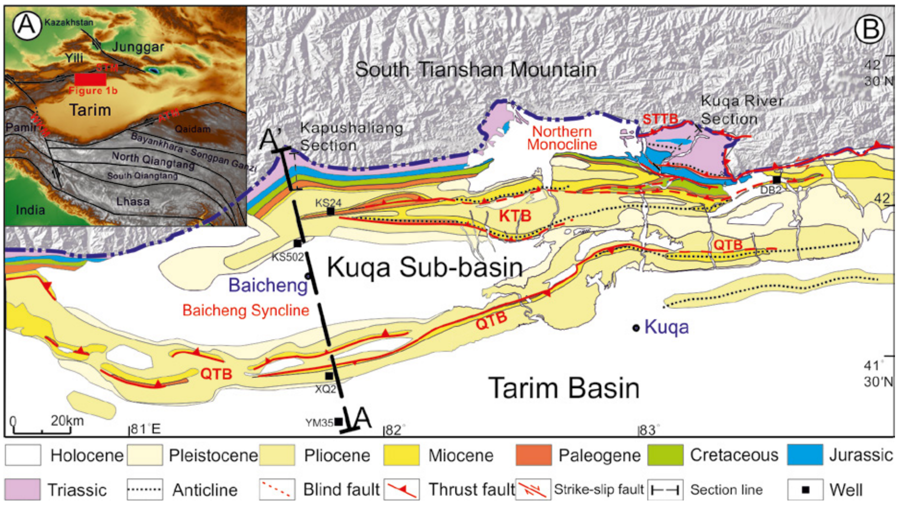


**Fig. 1.- A) Plate tectonic configuration around the Tarim Craton. (B) Geological map of the Kuqa Sub-basin, highlighting the Mesozoic and Cenozoic strata and structures. STTB, South Tianshan Thrust Belt; KTB, Kelasu Thrust Belt; QTB, Qiulitage Thrust Belt. See color figure in the online version.**

*Fig. 1.- a) Configuración tectónica de placas alrededor del Cratón Tarim. (b) Mapa geológico de la subcuenca del Kuqa, destacando las formaciones y estructuras mesozoicas y cenozoicas. Las estructuras principales incluyen: STTB, cinturón de pliegues y cabalgamientos de Tianshan del sur; KTB, cinturón de pliegues y cabalgamientos de Kelasu; QTB, sistema de pliegues y cabalgamientos del Qiulitage. Ver figura en color en la versión web.*

present boundary between the Kuqa Basin and the South Tianshan Mountains, consisting of a series of south-directed basement-involved thrusts. The Northern Monocline is characterized by a series of south-dipping, heavily eroded Mesozoic strata, prominently exposing large areas of Triassic formations. The KTB, located between the Northern Monocline and the Baicheng Syncline, is composed of several tight and doubly plunging anticlines (Fig. 3). The hinge zones of these anticlines expose Mesozoic muddy and coaly layers or Cenozoic evaporitic units. Small outcrops of Mesozoic strata overlapped with Cenozoic strata can be observed in the core of the KTB outcrop. The QTB consists of a series of box anticlines or a fan-shaped thrust-related anticlines, with salt diapir structures appearing only in the western part. The central part of the QTB is similarly composed of two tight anticlines. The Baicheng Syncline is a broad, gently deformed syncline with thick sedimentary deposits, situated between the KTB and the QTB.

Well data further revealed the structure and contact relationship of strata at depth in the KTB and QTB (see also Izquierdo-Llavall et al., 2018) (Fig. 2). The thickness of Eocene salt and gypsum becomes abnormally thick near the KTB and QTB (Fig. 2), which is likely due to the formation of salt domes. The maximum thickness of Mesozoic sediments is 5700 meters, predominantly consisting of fluvial and lacustrine sandstones and mudstones. The upper Triassic and Jurassic strata contain exploitable coal seams. The thickness of the Mesozoic strata gradually increases towards the north, with no significant angular unconformities. Compared to the YM35 well in the Tarim Basin and the KS502 well in the Baicheng Syncline, wells adjacent to the Qiulitage and Kelasu fold-and-thrust belts in the Kuqa Basin show stratigraphic repetition related to thrusts. In wells XQ2 and KS24 of the KTB and QTB, Paleogene strata are found to be thrusted over Neogene strata. In the eastern KTB, the DB2 well reveals multiple thrusts within the Jurassic strata, causing stratigraphic repetition. The thrust detached into Jurassic and Triassic coal units is found at surface in the eastern part of the KTB, in agreement with well data (Qi et al., 2023).

## Seismic data

The analysis of seismic profiles across the Kuqa basin has greatly helped to infer its structure (see Izquierdo-Llavall et al., 2018; Qi et al., 2023). In this work we show seismic line AA', composed and already interpreted by Izquierdo-Llavall et al. (2018) and Qi et al. (2023) (Fig. 3A). The utilisation of high-quality seismic data and field outcrops has enabled the characterisation of the suprasalt deformation features of and the discovery of the decoupling relation between suprasalt and subsalt deformation.

Seismic line AA' shows the development of four large growth strata units and three unconformities on the northern edge of the basin from the upper Jidike Formation to the upper Kuqa Formation (Wen et al., 2016). The aforementioned growth strata and unconformities indicate that the KTB and the QTB, which accommodated the majority of the shortening, developed primarily from the late Miocene to the Pleistocene (Izquierdo-Llavall et al., 2018). These structures were significantly influenced by the Eocene salt units of lacustrine origin, which functioned as the main detachment layer. In contrast to the pronounced detachment observed in the Cenozoic strata above the salt, the Mesozoic strata below the salt in the QTB exhibit evidence of minor faulting and brittle deformation. However, in the KTB, the subsalt layers are characterized by the development of imbricate thrusts and multiple stratigraphic repetitions. The seismic data quality of the Mesozoic and Paleozoic subsalt sequences is poor due to the influence of surface landforms, lateral lithological variations, and complex structural deformation, which collective-

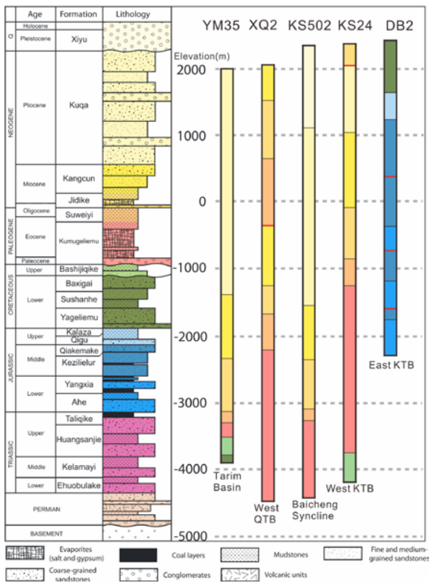


**Fig. 2.- The comprehensive stratigraphic column of Kuqa basin (modified from Li et al, 2012). Well data (YM35, XQ2 and KS502) modified from Izquierdo-Llavall et al. (2018). The red line in the well data is the interface between the repeated formations. The location of the wells are shown in Figure 1. See color figure in the online version.**

*Fig. 2.- La columna estratigráfica integral de la cuenca de Kuqa (modificada de Li et al., 2012). Datos de sondeos (YM35, XQ2 y KS502) modificado de Izquierdo-Llavall et al. (2018). La línea roja en el pozo es la interfaz entre las formaciones repetidas. La ubicación de sondeos se muestra en la Figura 1. Ver figura en color en la versión web..*

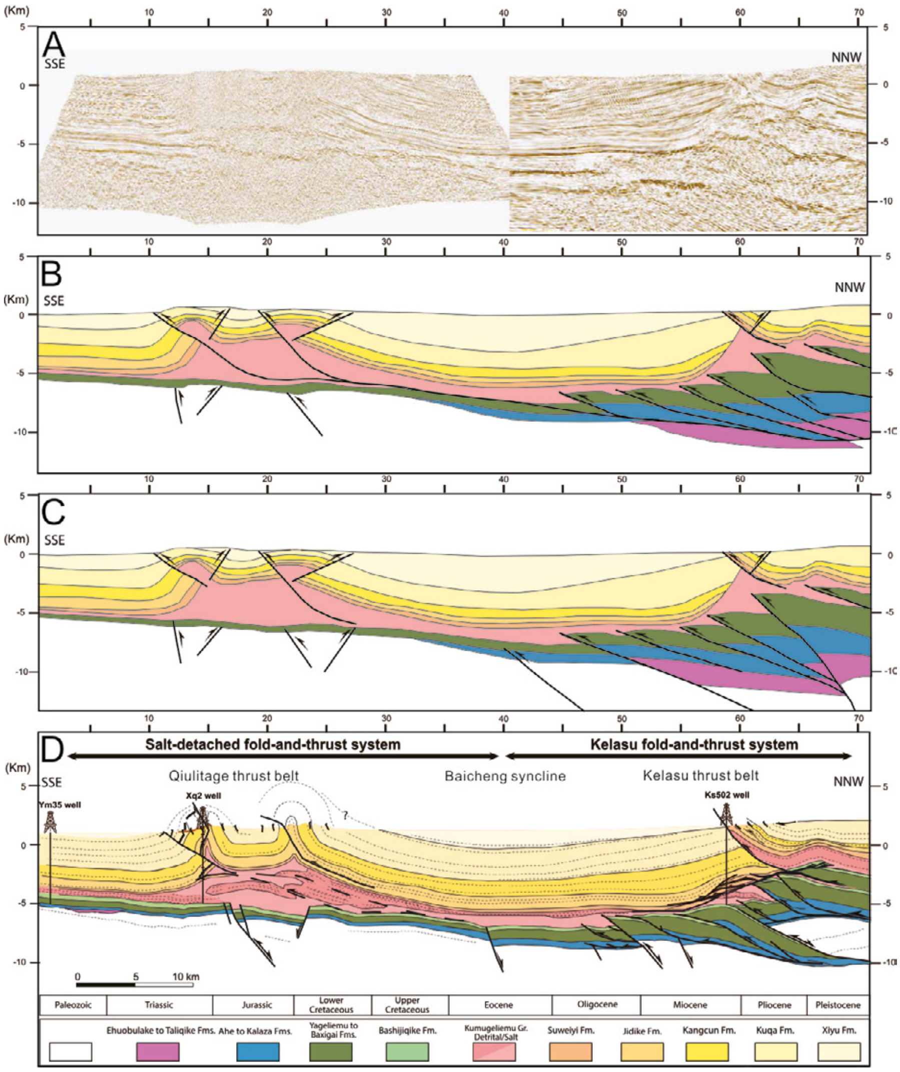


**Fig. 3.- Different structural interpretations for the Kuqa Basin. (A) Depth-converted composite seismic profile across the central part of the Kuqa fold-and-thrust belt (no vertical exaggeration) (modified from Izquierdo-Llavall et al, 2018). (B) Thin-skinned structural interpretation model below the salt (Xu and Zhou, 2007; (modified from Qi et al., 2023). (C) High-angle thrust faults with basement-involved structural interpretation model below the salt (modified from Qi et al., 2023). (D) Interpretation model of inversion of normal faults, thin-skinned thrusts and basement thrusts coexisting below the salt (modified from Izquierdo-Llavall et al, 2018). See color figure in the online version.**

*Fig. 3.- Diferentes interpretaciones estructurales de la cuenca del Kuqa. (A) Perfil sísmico convertido en profundidad a través de la parte central de la cuenca de Kuqa (sin exageración vertical) (modificado de Izquierdo-Llavall et al, 2018). (B) Modelo de interpretación estructural de piel fina debajo de la sal (Xu and Zhou, 2007) (modificado de Qi et al., 2023). (C) Fallas de alto ángulo con un modelo de interpretación estructural del basement por debajo de la sal (modificado de Qi et al., 2023). (D) Modelo de interpretación de fallas invertidas, tectónica de piel fina y cabalgamientos de basamento que coexisten debajo de la sal (modificado de Izquierdo-Llavall et al, 2018). Ver figura en color en la versión web..*

ly make it challenging to clearly identify the associated thrust fault assemblages. It remains unclear whether the thrusts below the KTB have a unified detachment surface and whether the Cenozoic thrust faults were influenced by the inherited faults from the Paleozoic and Mesozoic.

## Tectonic styles proposed for the Mesozoic deformation

Three different interpretations have been proposed to explain the deformation occurred below the main regional Eocene detachment level in the Kuqa Basin: the thin-skinned thrust model (Xu and Zhou, 2007; Fig. 3B), the high-angle basement-involved thrust model (Qi et al., 2023; Fig. 3C) and the inversion structure model in which thin-skinned and basement-involved structures coexist (Izquierdo-Llavall et al., 2018; Fig. 3D).

The earlier research indicated that deformation affecting the Cenozoic and Mesozoic strata was controlled by a single detachment level, leading to the formation of imbricate thrust models with thin-skinned characteristics (Xu and Zhou, 2007) (Fig. 3B). Later, Qi et al. (2023) proposed that the deformation of the Mesozoic strata was influenced by high-angle faults, based on continuous electromagnetic profiles obtained across the front of the STTB, Northern Monocline, KTB and Baicheng syncline. Electromagnetic data obtained close to the location of seismic profile AA' exhibits distinct resistivity characteristics from south to north within the QTB, KTB, and NM indicating that the deep structures are significantly different from north to south (Qi et al., 2023). These authors suggested that there is no unified detachment surface, and proposed a high-angle basement-involved thrust model for the subsalt structures on the KTB.

The two aforementioned models assume scarce deformation during the Mesozoic, implying that the Kuqa Basin did not undergo Mesozoic regional extensional and compressional tectonic events. Nevertheless, recent studies characterizing the Triassic Cimmerian Orogeny and Jurassic regional extensional tectonic events (Morin et al., 2018) provide increasing evidence suggesting that the Kuqa Basin was influenced by far-field tectonic effects during the Mesozoic.

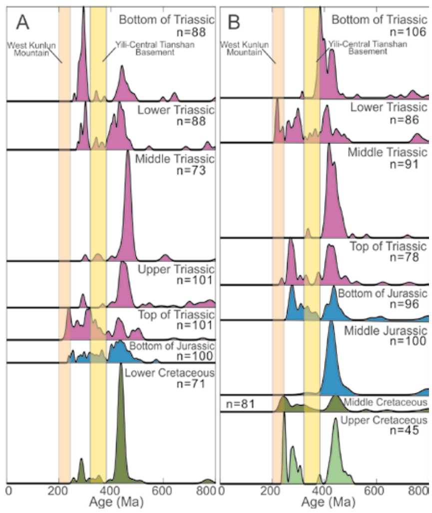


**Fig. 4.- U-Pb age spectra of detrital zircons of Mesozoic strata in Kuqa Basin. (A) The Kapushaliang Section in the west Kuqa Basin. (B) The Kuqa River Section in the east Kuqa Basin. Data from Liu et al. (2013), Wang et al. (2015), Han et al. (2016) and Qin et al. (2024). See color figure in the online version.**

*Fig. 4.- Espectros de edad U-Pb de zircones detríticos de estratos mesozoicos en la Cuenca de Kuqa. (A) La sección de Kapushaliang en el oeste de la Cuenca de Kuqa. (B) La sección del río Kuqa en el este de la Cuenca de Kuqa. Datos de Liu et al. (2013), Wang et al. (2015), Han et al. (2016) y Qin et al. (2024). Ver figura en color en la versión web.*

The third model proposed by Izquierdo-Llavall et al. (2018) suggested a decoupled deformation style affecting the Kuqa Basin during the Cenozoic contraction. For the subsalt deformation, the folds affecting Triassic rocks observed in outcrops and the multiple occurrences of subsalt stratigraphic thickness variations in seismic profiles were interpreted as the result of a sequence of thin-skinned thrusts detached on Triassic-Jurassic coal units and basement thrusts formed from the inversion of Mesozoic normal faults, respectively. This model posits that the subsalt thin-skinned thrusting partly predated the formation of basement thrusting and highlights their influence on the thin-skinned tectonics developed above the regional Eocene detachment level.

## Detrital zircon age data

Due to the difficulty in identifying Mesozoic geological structures in the deep parts of the Kuqa Basin and the heavy erosion of Mesozoic strata in the northern part of the basin, direct studies on the Mesozoic tectonic evolution are challenging. Some researchers have attempted to reconstruct source-to-sink relationships using detrital zircon geochronology data to indirectly study the Mesozoic tectonic evolution of the Kuqa Basin and the South Tianshan. This study collected and compared the main detrital zircon U-Pb age data (Discordance is less than 10%) from the Kuqa Basin, revealing multiple single-peak to multi-peak transitions in samples from both the Kapushaliang Section in the west Kuqa Basin (Fig. 4A) and the Kuqa River Section in the east Kuqa Basin (Fig. 4B), indicative of multiple changes in provenance. The appearance of multi-peak zircon populations is also accompanied by an increase in zircon grains with characteristic ages from the West Kunlun region (250–200 Ma) and the Yili-Central Tianshan region (310–380 Ma). Detrital zircons from the West Kunlun are considered indicative of significant regional uplift in the southern Tarim Basin (Xiang et al., 2023). The reduction of ancient detrital zircons and the increase of younger detrital zircons are considered to indicate a transient tectonic regime and low relief in an extensional environment from the Early Triassic to the Jurassic (Liu et al., 2013; Wang et al., 2015). However, another interpretation is that the Yili-Central Tianshan experienced further uplift as a far-field effect of the Qiangtang terrane collision. (Han et al., 2016). These changes in detrital zircon populations suggest that the periphery of the Kuqa Basin experienced multiple phases of tectonic uplift and/or intense erosion during the Mesozoic.

Additionally, the Triassic changes in provenance are associated with the development of compressional growth strata, implying that these Triassic transitions could be the result of tectonic uplift, while the Jurassic transitions may be related to regional planation in an extensional setting (see Qin et al., 2024). We conducted further identification of growth strata in this area and found similar growth strata in multiple sections of the same age in the northern part of the basin. The changes in sediment provenance indicated by detrital zircon populations are likely associated with these regional growth strata.

## Conclusions

The deep structure of the Kuqa Basin highlights that a different sub- and supra-salt deformational style exists. The limited occurrence of Mesozoic rock outcrops, combined with the presence of a regional detachment layer decoupling deformation, makes it challenging to unravel deformation affecting the Mesozoic rocks during the Cenozoic contraction and the preceding Mesozoic deformation. Increasing evidence suggests the existence of multiple structures within Mesozoic rocks, which may have developed during the Mesozoic and were subsequently modified by intense Cenozoic compression. The composition and origin of the structures within these Mesozoic rocks require further study.

## Author Contributions

Li Xiang performed data collection, created figures, and drafted the manuscript. Ruth Soto and Hou Guiting provided guidance and critically revised the manuscript for intellectual content.

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