The Origin Analysis of “reversal foreset” of Late Carboniferous MKT Formation in Central Block of Pre-caspian Basin

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Abstract The configuration of “reversal foreset”, which is a common geologic sedimentary phenomenon in seismic exploration, has been fully understood on its mechanism. In central block of pre-caspian Basin, a series of NE “reversal foreset” configurations were found. This kind of reflection is completely opposite to the paleogeomorphology which is high in the west and low in the east. It is difficult to clarify the origin mechanism of the “reversal foreset” configuration without sufficient data and understanding of regional tectonic evolution. Interpretations provided by previous studies did not reach a consensus understanding of the tectonic and sedimentary structures in the area. In this paper, based on well and regional data, the previous interpretations are analyzed, and the idea is put forward that the “reversal foreset” configuration represents superimposed retrogradation bodies developed in the process of rapid water flooding, and its formation is controlled by three factors -- “weak supply of single source”, “rapid transgression (weak source supply)” and “low and gentle depositional slope”. This recognition helps understanding the sedimentary evolution characteristics of the Late Carboniferous MKT formation in central block of Pre-caspian basin and promotes the later exploration of lithologic reservoir.

Keywords. Pre-caspian Basin, Central block, Reversal foreset, Superimposed retrogradation bodies

1. Introduction
The central block, located on the east edge of the Zahnanoor-Termel uplift in the southeastern margin of the Caspian Basin, covers an area of approximately 3500 km² and its east is adjacent to the
southeast depression (Figure 1). MKT Formation is one of the caprocks in this area. Its interior consists of a series of “foreset” superimposed westward. Due to the regional structural background of being high in the west and low in the east during the deposition of MKT Formation, this type of “foreset” in the direction opposite to that conventional foreset is classified into the typical “reversal foreset” (Figure 2). In view of the origin of this configuration, currently there are many kinds of understanding (such as “prograding body”, “differential deformation”, etc.) (Zhu Yixiu et al. 2014; Miao Qianyou et al. 2013; Liang Shuang et al. 2013; Hu Yang et al. 2014). Due to the large differences, there still have some ambiguities in understanding the law of sedimentary evolution of the Late Carboniferous in the study area, thereby restricting the subsequent exploration work on lithological reservoirs. With the improvement of basic data involving seismic and well logging data, and combining with regional sedimentary and tectonic settings, this paper discerns and analyzes the existing understandings, clarifies the Characteristics of “reversal foreset” configuration of MKT Formation and its controlling factors, and finally establishes developmental models for facilitating subsequent exploration.

2. Characteristics of MKT Formation

MKT Formation belongs to the Upper Carboniferous, with a thickness of 0-600 m in the study area. The lithology is dominated by a thick set of gray mudstones with thin clastic rocks and limestone (Figure 3). The formation is sandwiched between two sets of platform limestones, KT-I and KT-II. It is in abrupt contact with the KT-II at the bottom, and in gradual contact with the KT-I at the top. This formation is basically a slope striking NE, dipping upward in the east and with less developed faults (Figure 2). The thickness of the formation varies uniformly and gradually pinches out from east to west, and decreases slowly from NE to SW.

Figure 1. Location map in the study area and structural event table
Figure 2. Current structural section in the study area

Figure 3. Columnar section of MKT Formation in Well AL-1

3. Characteristics of “reversal foreset” configuration

The “reversal foreset” is the basic unit of MKT Formation, which is generally developed inside the Formation. It is subject to the overall development of thick mudstone. Its seismic responses are mostly medium-weak and continuous reflections with medium-weak amplitude and medium-low frequency. There are many interfaces between the foreset layers, showing as cluttered responses and quick lateral
variation, making them difficult to track (Figure 4A-C).

There are also differences in the configuration of “reversal foreset” in different positions. The “foresets” in the southern and central parts of the study area are mostly oblique. The layers are dipped slightly westward and short with good continuity. The oblique angle is relatively large, and the continuity is relatively poor (Figure 4A, B). In the north, the “reversal foresets” are more complicated and different in scale, and the internal layers are parallel or intersect with each other. From the point of striking, the “foresets” are mostly horizontal or downlapping to the KT-II top at a small angle which slightly increases at the southwestern margin under the control of the low-amplitude uplift (Figure 4C). There is no obvious relationship between the “reversal foreset” and the lithology. Seismic facies analysis shows that both the area with low frequency-weak amplitude representing thick mudstone and that with relatively higher siltstone and limestone show the development of “reversal foreset”. In the same foreset, laterally, the amplitude and frequency also vary frequently, indicating alternating development intervals of mudstone and non-mudstone.

4. Analysis of the origin of “reversal foreset” configuration

According to previous studies on the genesis of the “reversal foreset” inside MKT Formation, there are four genesis types involving “foreset”, “differential compaction”, “structural inversion” and “starvation retrogradation” (Figure 5). Using available data, the four types are analyzed and demonstrated in this paper.

4.1. Origin model of “foreset” configuration

(1) Foreset
This type of genesis suggests that the “foreset” structure in MKT Formation is inside fan delta (delta), which formation and development were controlled by local uplift and erosion outside the study area during the deposition of MKT Formation. This type of genesis can be divided into two subtypes. The first one is an early orogenic model (Figure 5A), that is, during the deposition of MKT Formation, reversal orogeny occurred in the southeastern rift of the Caspian Basin, formed a structural pattern high in the east and low in the west and developed a fan delta striking EW. The central block is located in the fan delta front, which is an axial area with relatively deep water and higher clayey content. In addition, with good inheritance, there are developed foresets dipping westward. The second one is a lateral uplift model (Figure 5B). When MKT was developed, there might be a local uplift and a small-scale delta spreading from NE to SW on the north of the study area. The central block is located on the western wing of the delta front. The foreset dipping westward on the NW-SE profile through this location is actually the lateral accretion configuration of the lateral wing of the delta front.

(2) Differential compaction
This type of genesis suggests that the “foreset” is the result of burial compaction (Figure 5C). In MKT, limestone and siltstone included by mudstone were approximately lenticular and developed into a configuration similar to “foreset” in the process of burial, under the compression much smaller than that to the mudstone.

(3) Structure reversal
This type of origin suggests that MKT is saturated sediment, and each set of “foreset” inside it represents the original water level at the time of deposition. This also indicates that the study area covered a slope dipping eastward at a large angle during the early deposition of MKT Formation, and
the formation of the “foreset” configuration is the result of the structural reversal uplifting in the east and subsiding in the west. The reversal type can be divided into two subtypes. The first is a syndeposition model (Figure 5D), that is, the deposition and structural reversal of MKT Formation occurred simultaneously. The second one (Figure 5E) generally shows fast structural reversal and flattening on the east side after homogenous deposition of MKT Formation.

(4) Starvation retrogradation
This origin mainly argues that the “foreset configuration” in MKT Formation is a lateral overlay of sedimentary subduction bodies resulted by water invasion in a steep slope environment. This view suggests that there is a large sedimentary slope in the deposition of MKT Formation. Due to the rapid rise of water body and relatively weak source supply, a series of retrogradation wedges overlying westward formed in the starvation environment on the east side and there was a structural reversal “uplifting in the east and subsiding in the west” as a whole, making the overall inclination slow down. Generally, it entered the deposition stage of the platform limestone in the KT-I (Figure 5F).

Figure 4. Flattened top profile and paleogeographic map of MKT Formation

Figure 5. Proposed MKT models by previous studies
4.2. Previous Study

(1) Foreset

Recent regional study indicates that the deposition of MKT Formation on the southeastern margin of the basin generally took place in a continental slope environment (Figure 4D) (Zhu Yixiu et al. 2014; Miao Qianyou et al. 2013; Liang Shuang et al. 2013; Hu Yang et al. 2014), and the syndepositions of flysch carbonate rocks-terrigenous clastic sediments drilled in the footwall of the eastern fault (the downslope of the continental shelf) are not coarse clastic rocks formed with orogenic erosion, indicating that the southeastern margin of the basin was in a deepwater development stage (Hu Yang et al. 2014; Liang Shuang et al. 2013). The statistics of drilled lithologies in the study area (Figure 6) show that the zones with relatively high content of clastic rocks are mainly concentrated in the middle and west parts of the central section, reflecting the characteristics of the source from west while not from west in the northern part. Therefore, there may be something wrong in the foreset origin deemed uplifting in the north or orogeny in the east.

![Figure 6](image.png)

**Figure 6.** Thickness, lithological statistics and foreset distribution of MKT Formation

(2) Differential compaction

During the processes of sedimentation and diagenesis, mudstone is more easy to compress than limestone and fine siltstone, so the compressive deformation of mudstone is much higher than those of sandstone and limestone at the same pressure (Jiang Jugang et al. 2013; Zhang Boquan et al. 1992; Huo Liang et al. 2017). Therefore, in the differential compaction mode, the compression deformation of
mudstone should be higher than that of limestone, and the clastic rock should be inclined more than the non-clastic rock and limestone. The above-mentioned seismic facies characteristics and drilling response indicate that the foreset is developed in mudstone, limestone and sandstone, and that it also has lithological variations laterally (Figure 4). There is no significant correlation between the position of foreset and lithology on plane (Figure 6). Therefore, differential compaction can’t explain the “foreset configuration” in the target layer.

(3) Structure reversal
The origin of structural reversal requires that the sedimentary floor (KT-II top) is a slope dipping eastward at a large angle (10-15 degrees) during the initial deposition of MKT Formation. Regional studies show that during the sedimentary period of the Carboniferous, the southeastern margin of the basin generally uplifted and subsided with no significant structural deformation (Abitkazy Taskyn et al. 2014; Ren Yu. 2002; Zheng Junzhang et al. 2009). The limestones in the KT-I and KT-II near the upper and lower members of MKT Formation are both thick in the study area and slowly increase eastward with stable depositional facies, indicating that the central block continued to be a flat and low-angle eastern slope at the Moscow Stage. In addition, the transition between the top of MKT Formation and bottom of the KT-I Formation is a gradual contact, showing no variation of lithologies. Therefore, there is no structural reversal and uplifting erosion during the deposition of MKT Formation, making it difficult to meet the basic requirement of “structural reversal”.

(4) Starvation retrogradation
“Starvation retrogradation reversal” is similar to that of “structural reversal”, and the study area can’t meet the requirements of early high-angle sedimentary basement and late structural reversal and denudation. Therefore, this origin is not the formation pattern of the “foreset” configuration in MKT Formation.

It is indicated from comprehensive analysis that the internal “foreset” in MKT Formation should belong to a sedimentary configuration. Although the high-angle slopes, late structural reversal and denudation required in the “starvation retrogradation” model are not consistent with the actual tectonic settings in the study area, the proposed lateral superposition of retrograded bodies in a water invasion environment is more suitable for interpreting the development of these sedimentary configurations than the other three types of origin. Combined with the actual sedimentary tectonic settings, it is speculated in this paper that the “foreset” configuration in MKT Formation may be a special sedimentary configuration formed with the superposition of the landward migration bodies formed during rapid transgression under gentle slope background.

5. Characteristics, controlling factors and developmental process of “foreset configuration”

5.1. Characteristics and controlling factors
Previous study carried out some researches on the origin of landward “foreset configuration” in the transgression stage. Experiments conducted by Cattaneo (2003), Cartigny (2011) (Antonio Cattaneo et al. 2003; Matthieu J.B et al. 2011) indicate that when the sedimentary slope is less than 10 degrees and the source supply is relatively weak, it usually forms landward “foreset configuration”, which actually belongs to the lateral superposition of the retrograded bodies in the transgression process (Figure 6A).
Po Renhai (2003), a Chinese scholar, pointed out that this type of configuration is mainly affected by three factors: single source, weak supply and low slope in the study of deposition of mudstone (Pu
Renhai et al. (2003). Combining with the actual conditions of the target layer, this paper argues that the internal MKT structure is mainly controlled by the following three points:

(1) Unilateral source
The unilateral source controls the overall developmental direction of the retrogradated body. Since the retrogradation configuration is related to the direction of major sources, the retrogradation direction also indicates the direction of the source. Multiple sources often lead to complicated directions of retrogradation configuration. Drilling statistics in MKT Formation show that sandstone, siltstone and limestone debris are mainly from the uplifted area on the west side and it is also the main source of clay material in the target layer. The foreset configuration inside MKT Formation, showing westward dipping overall, has a good correlation to the source direction and shows the characteristics of unilateral source.

(2) Rapid transgression and weak supply
Weak source supply and variable water body not only control sedimentary lithology, but also control the pattern of sedimentary configuration. It can be seen from Figure 7 that the rapid rise of water level and weak source supply lead to the gradual shift of sedimentary shoreline landward. Moreover, the sedimentary configuration within the slope break zone Changes from horizontal superposition to coastal foreset superposition to scattered hummocky distribution. In the depositional period of MKT Formation, the southeast of the basin rapidly subsided as a whole, resulting in the rapid increase of the water body. At the same time, weak source to the western uplift led to the convergence of the sedimentary shoreline trajectories at lower angles and formed a series of superimposed depressions.

Figure 7. Transgressive shoreline trajectory model (1) and sedimentary evolution of MKT Formation (2) (Figure A adapted from Cattaneo, 2003)

(3) Depositional slope
A less-dipping depositional slope is basic for the formation of landward foreset superposition. Cartigny (2011) conducted fluid experiments and found that the “reversal foreset” in the sedimentary body formed on the depositional slope dipping at less than 10 degrees is easier to dip toward the uplifting direction (Matthieu J.B et al. 2011).
The relative size of the depositional slope may also determine the complexity of the foreset configuration. As mentioned above, the foreset configuration in MKT Formation is evident in the southern and central parts, representing the characteristics of typically oblique superposition. There are many different foreset configurations in the north, which belong to composite foresets. Although the overall depositional slope of MKT Formation is relatively broad, there are still some differences. In the study area, the internal structure of MKT Formation is more complicated in the southern part near the western uplift edge (the depositional gradient increases rapidly). In the northern part of the study area, the dip of the sedimentary basement is slightly larger than that of the southern and central parts. It not only makes the sedimentary thickness in the northern part larger than that in the southern and central parts and more complex foreset configurations.

5.2. Development process
Combining with the regional geological Section, this paper divides the development of internal foreset configurations in MKT Formation in the study area and its eastern side into three stages:
(1) Overall regression
After the deposition of KT-II, the whole southeastern part of the basin was uplifted, the water level rapidly retreated to the rift zone on the eastern side of the study area. The duration of deposition was a short period, therefore, no obvious weathering and denudation was observed on the top of KT-II in the study area (Figure 6B-1).
(2) Early transgression
After a transient uplift, the whole southeastern part of the basin began to settle down and the water body increased rapidly. Early deposits of MKT Formation appeared in the rift. They were mainly mudstone due to weak denudation and collapsed deposition of flysch limestone developed near the fault. In that period, the eastern internal structure speculated to be retrograding superposition from east to west, and the west internal structure speculated to be onlap on the fault surface horizontally as a whole (Figure 6B-2).
(3) Late transgression
When the horizontal plane rapidly diffused over the KT-II limestone platform on the west side, the terrain changed from an early steep section to a gentle slope. The platform began to accept the late deposits of MKT Formation. It is dominated by mudstone due to insufficient source. In terms of configuration, the whole surface is retrograded and superimposed from east to west. Compared with the early stage, the terrain (near the study area) is open on the west side (there wasn’t an earlier fault as a barrier). And the strata overlap from horizontally to westward, and constitute the illusion of the “foreset” configuration (Figs. 6B-3, 4).

6. Conclusions
(1) The “foreset” configuration in MKT Formation is essentially a superimposed retrogradation body extending westward in the process of rapid transgression. Its formation is controlled by three factors including single source, rapid transgression (weak source supply,) and low and gentle depositional slope.
(2) During the depositional period of MKT Formation, the study area was a low and gentle dipping eastward slope, uplifting and subsiding entirely. There were no local uplifting, structural reversal or differential compaction.
(3) To clarify the characteristics and the origin of the internal configuration in MKT Formation helps understand the tectonic and sedimentary features in the middle Moscow Stage in the study area and helps the later exploration of lithologic reservoir.

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