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Research Article

Keywords: Structural deformation, Upper combination structural model, Kuqa Depression, Double salt layer, Structural physical simulation experiment

Posted Date: July 3rd, 2026

DOI: https://doi.org/10.21203/rs.3.rs-9240201/v1

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Additional Declarations: No competing interests reported.

Analysis of Deformation Characteristics and Controlling Factors of the Upper Combined Structure:A Case Study of the Structural Physics Simulation Experiment in the Zhongqiu-Dongqiu Area of Kuqa Depression

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Abstract

The research on the supra-salt tectonic model in the Zhongqiu - Dongqiu area of Kuqa depression is relatively shallow, and the deformation mode and mechanism under the control of double salt lakes are controversial. This study will systematically analyze the structural deformation patterns and models of each section and between sections of the super-salt strata,and discuss the control of gypsum-salt rocks, paleo-uplifts and syndeposition on the deformation patterns of the upper assemblages. The research shows that the thickness and distribution range of the gypsum salt rock layer are the core elements of the structural deformation mode above the salt in the study area. The regional gypsum salt layer presents the law of “double salt superposition” to “single salt distribution”. The study area can be divided into gypsum-rich salt area-gypsum-rich coordination conversion zone-double salt lake superposition area-salt-rich coordination conversion zone-salt-rich gypsum salt area from west to east. The structural deformation shows the conversion characteristics from high angle to multi-overlapping tiles. The properties of gypsum salt layer control the form of salt structure. The imbricate structure is common in areas with strong gypsum salt plasticity, and the high angle is common in areas with poor plasticity. The strength of gypsum salt plasticity directly affects the structural style. The thickness difference leads to the structural differentiation of salt pillow, salt uplift and salt welding, which further controls the evolution of the supra-salt trap type from small punch-up trap to large imbricate anticline trap.

Keywords:
Structural deformation
Upper combination structural model
Kuqa Depression
Double salt layer
Structural physical simulation experiment

0 Introduction

The close relationship between the geometric patterns of salt structures and hydrocarbon accumulation has become a research hotspot at home and abroad[1-2],The salt structure not only controls the formation of recoil faults and fault-bend folds in the upper assemblage, but also limits the sub-salt deformation, so that the sub-salt faults can not be transmitted upward, instead, they extend forward to form sub-salt wedge-shaped structures, and affect the development of traps. Previous studies have shown that the differences in salt-related structural styles are not only controlled by the thickness[3], properties[4] and spatial distribution [5] of gypsum rocks, but also restricted by the intensity of compression-extension-strike-slip[6] and the sequence of motion[7] under the superposition of multiple tectonic periods.

Previous studies mainly focused on the effect of single gypsum-salt intervals on overlying structural deformation. It is widely accepted that supra-salt structures in the Dongqiu area are dominated by fractured anticlines, synclines and monoclines, while those in the Zhongqiu area are dominated by detachment thrusts[8-9].The upper assemblage in the Zhongqiu-Dongqiu area shows segmented differential deformation caused by the combined response of gypsum-salt rocks, paleo-uplifts and stress states. These studies provide a basis for analyzing the genetic mechanism of upper assemblage deformation and explaining east-west segmentation. However, key problems remain:the weak link between supra-salt structures and salt-structure geometry[10], insufficient understanding of double salt-lake effects, and lack of explanation for structural changes in transition zones[11]. This study uses structural geometry, kinematics and dynamics combined with physical simulation to analyze supra-salt deformation characteristics, main controlling factors and dominant trap types in gypsum-rich, salt-rich and transition zones.

1. Regional geological background

1.1 Regional Location

The Tarim Basin is located in Xinjiang Uygur Autonomous Region, China. It is bordered by the Tianshan Mountains to the north, the Kunlun Mountains to the southwest and the Altun Mountains to the southeast[12]. The salt superstructure in the study area has the

characteristics of stratification and segmentation, and its core is controlled by the differences in the distribution, properties and thickness of the paste and salt layers[13]. The distribution characteristics, property characteristics and thickness characteristics of gypsum and salt rocks respectively correspond to the specific manifestations of the triple non-integration of longitudinal stratified difference superposition, transverse gypsum and salt quality difference distribution, and the decreasing peak difference of double salt lakes[14]. In the Dongqiu section, only the single plate-salt layer of the Jidike Formation is developed. In the Zhongqiu section, the double-salt superposition area, due to the differential flow of the double salt layers, intensifies the longitudinal zonation and non-integration degree of the salt superstructure. On the plane, the spatial distribution of salt structures is controlled by the lateral extension range of a single salt layer in the Jidike Formation. The tectonic deformation in the Zhongqiu section shows a zonal feature of “leading edge zone - uplift zone - compression and torsion core zone”, while in the Dongqiu section[15].

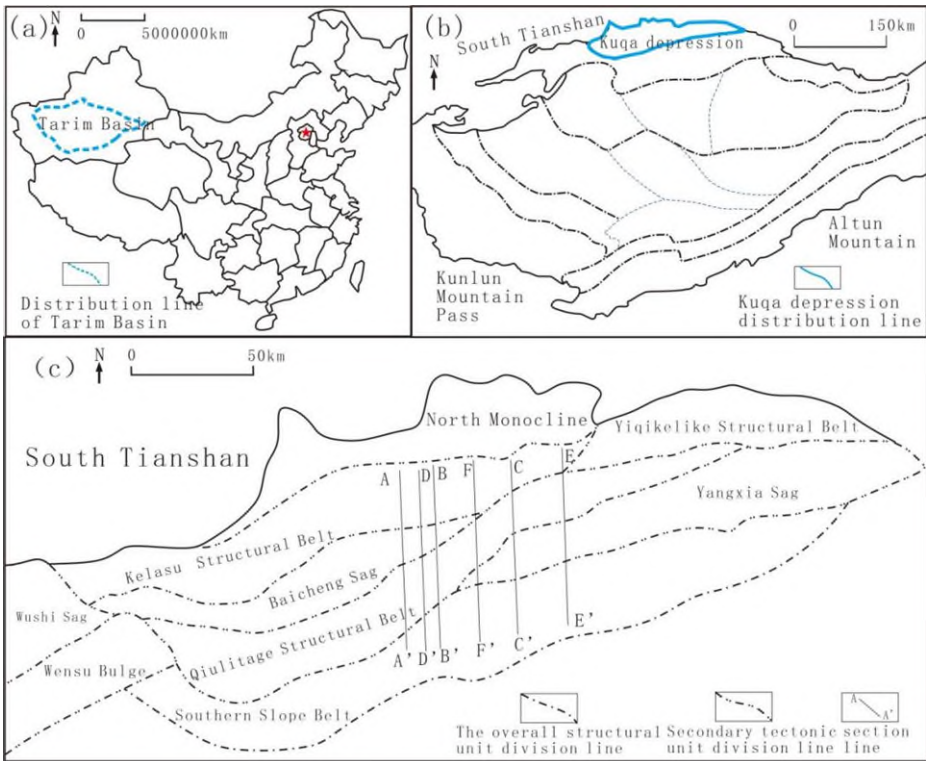


Fig. 1. Geographic and tectonic location of the Kuqa Depression. (a) Index map showing the position of the study area in China; (b) Regional tectonic map of the Tarim Basin; (c) Detailed geological and structural map of the Kuqa Depression.

1.2 Combine and construct the grid frame on the Zhongqiu - Dongqiu section

The composite layered deformation system in the Zhongqiu - Dongqiu section of Kuqa depression is mainly composed of five structural elements. In the order of strata from old to new, they are respectively the Paleogene Kumugeliemu Group ($E_{1-2}km$), Suweiyi Group ($E_{2-3}s$), Neogene Jidike Formation (N_1j), Kangcun Group (N_1k), and Kuche Group(N_2k).

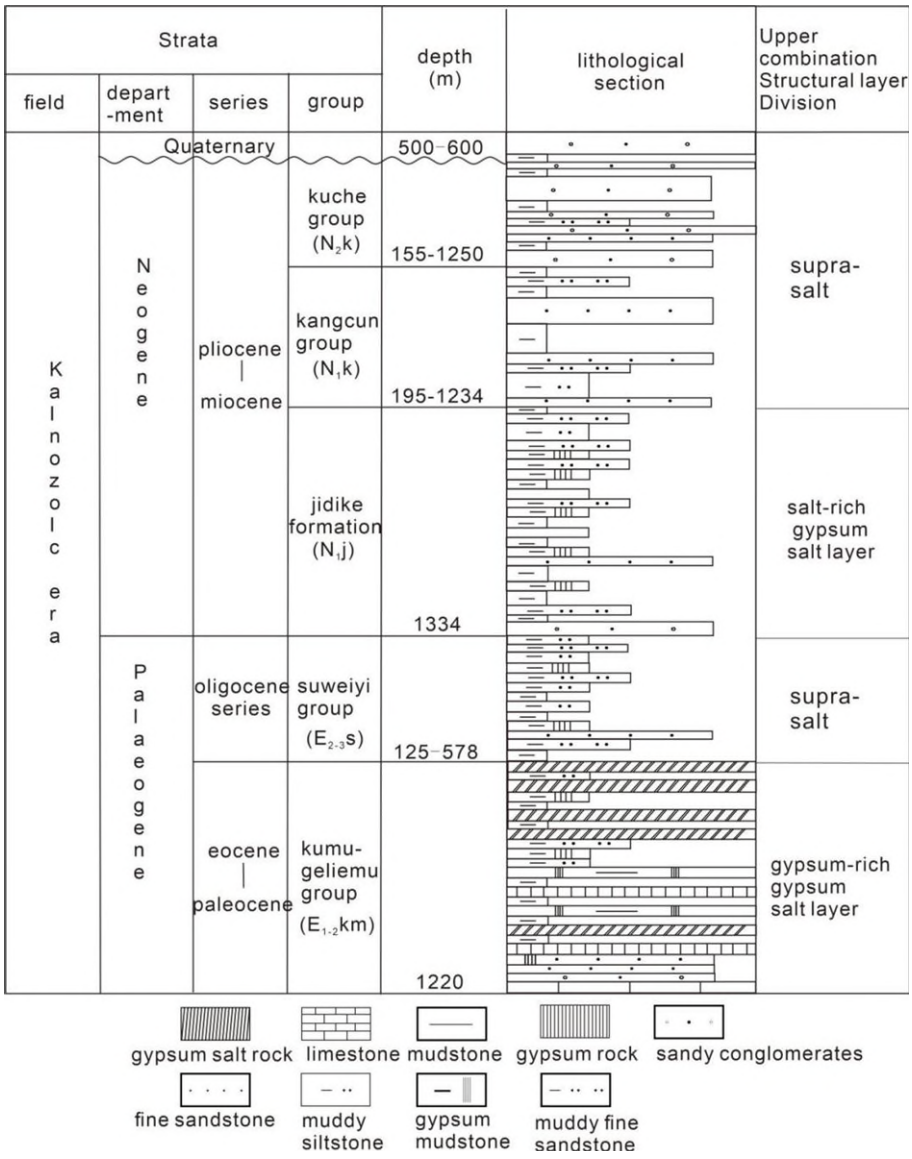


Fig. 2. Upper Composite Stratigraphic Column

The Zhongqiu - Dongqiu section is a typical area with the characteristics of transitioning from a double salt lake to a single salt lake. The differences in the properties, distribution ranges and thickness of the double paste salt layers jointly control the deformation characteristics of the upper combined structure. The salt layer of the $E_{1-2}km$ contains more paste and has greater toughness, while the salt layer of the N_1j contains more salt and has stronger plasticity. The area after the Zhongqiu west region is a double-salt lake area, with both salt layers serving as cover layers. According to the distribution map of gypsum salt layer in Zhongqiu-Dongqiu area

(Fig.3), it can be seen that the pinch-out line of $E_{1-2}km$ is distributed along the southern margin of the northern Tianshan piedmont tectonic belt and Baicheng sag. The peak thickness area is formed in the middle part of Kelasu tectonic belt and the north of Baicheng sag, and the thickness gradually decreases from the transition zone to the edge of the sag. The gypsum-salt layer of the N_1j is mainly confined to the eastern part of the Baicheng Sag and the Yangxia Sag. The pinchout line is close to the northern edge of the sag, and the thickness decreases rapidly to the edge of the sag. The scale of gypsum-salt rock development of the N_1j in the west and south of the Baicheng Sag is small.

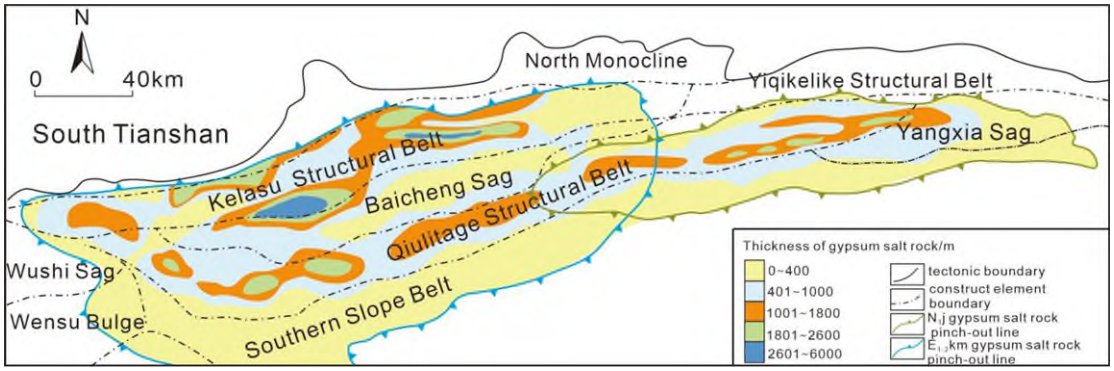


Fig. 3. Distribution of Salt Layer in the Zhongqiu - Dongqiu Regions

The $E_{2-3}s$ of the Paleogene is a major oil and gas reservoir stratum. When exploring the types of oil and gas accumulation and trapping, it serves as a primary reference layer and is of great significance for oil and gas exploration and development. The overall lithology is mainly sandstone, and the overlying N_1j gypsum salt layer acts as a cap rock. The Jurassic-Triassic strata under the salt are used as the oil source layer, and the faults are formed by tectonic movement and extrusion deformation to form oil source faults. The oil and gas are transported to the storage of the $E_{2-3}s$, but the gypsum salt layer of the $E_{1-2}km$ is developed at the bottom of the $E_{2-3}s$, which leads to the difficulty of oil and gas migration. Therefore, the storage of the $E_{2-3}s$ is only near the fault. In the second half of the Dongqiu area, the $E_{1-2}km$ exists in the form of sandstone and is no longer used as a cap rock, so that oil and gas are well stored in the $E_{2-3}s$.

The Neogene strata are shallowly distributed, strongly affected by syntectonic sedimentation, and the thickness changes obviously. It is an important research object to study syntectonic sedimentation. The overall lithology is dominated by sandstone. The thickness of the strata in the Zhongqiu - Dongqiu area remains basically unchanged. The strata in the northern tectonic transformation zone are steeper due to lateral compression. The remaining positions are mainly affected by the lower salt structure and syndeposition.

2. Construct segmented features

The Zhongqiu-Dongqiu area has been squeezed by the South Tianshan Mountains for a long time[16], and the structural style is complex and changeable. The coupling of geological factors such as paleo-uplift, syntectonic sedimentation, and the number, nature and thickness of gypsum salt layers lead to differences in structural changes on the salt. As the main controlling factor, the gypsum salt layer plays an important role in the structural deformation on the salt. Therefore, based on the distribution range and property differences of the gypsum salt layer, three typical seismic framework sections in the Zhongqiu-Dongqiu area were selected for fine structural analysis.

2.1 Structural section analysis of single salt-rich gypsum salt layer $E_{1-2}km$ salt rock

Fig.4 shows that the section is mainly affected by the gypsum-salt layer of the $E_{1-2}km$.Gypsum-salt rock has the characteristics of strong plasticity and easy flow. The gypsum salt layer of the $E_{1-2}km$ extends far from south to north, with large morphological changes and obvious thickness fluctuations. It is used as a boundary to divide the upper salt layer and the lower salt layer. The upper salt layer develops a fault detachment fold, and F1 breaks up and breaks through the upper combination stratum until it is exposed to the surface. The fault distance is large, the dip angle is high, and it is hidden in the gypsum salt layer downward. The gypsum salt layer in the north is strongly squeezed by the South Tianshan Mountains and cannot continue to flow. It accumulates here to form a salt ridge, breaks through the stratum, and the fault acts as a plugging effect, forming a slope-flat fault-slip anticline. The gypsum salt layer of the N_1j has weak decoupling characteristics of layered detachment, and the overall performance is the characteristics of sandstone layer, which flows along the layer above the $E_{2-3}s$. Due to the traction effect near the fault, the syndepositional phenomenon is caused by different deposition rates. The thickness of the Neogene strata is about 550 m on both sides and about 1250 m in the middle, showing a spatial thickness change trend from the middle thickness to the thinning on both sides. The thickness of the gypsum salt layer of the N_1j is larger than that of the $E_{1-2}km$, but it has little effect on the supra-salt structure.

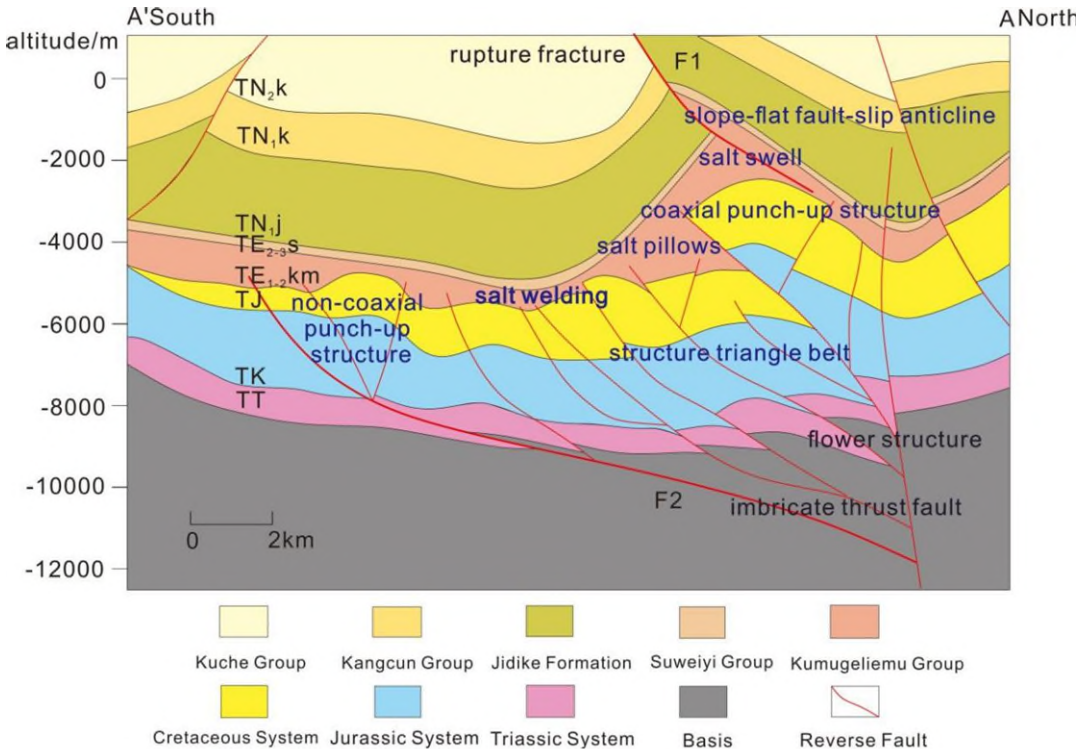


Fig. 4. Geological Cross-Section of Zhongqiu Litage - Dongqiu Litage Section-L1228

2.2 Structural section analysis of double salt layer

In the control section of the double salt layer, The thickness of the gypsum salt layer of the $E_{1-2}km$ gradually decreases from south to north, and the thickness of the gypsum salt layer of the N_1j gradually increases from north to south, and the thickness trend is mainly north-south differentiation. The northern part of the study area is mainly controlled by the gypsum-salt layer of the $E_{1-2}km$. The high-angle lateral extrusion produces a recoil fault F3, which makes the overlying strata bend as an anticline. At the top of the anticline, the fault F1 is formed due to extrusion. The combination forms an oil source channel, which connects the Cretaceous Bashijiqike Formation reservoir, goes straight to the surface, and affects the surface morphology. There may be small oil and gas seedlings ; the southern part is dominated by the gypsum salt layer of the N_1j. On the basis of the main fault F4, it forms a thrust structure together with the reverse secondary fault to maintain the balance of the deep strata. From south to north, a series of fault-bend folds are formed on the top of the Paleogene strata. The fault distance is small but the extrusion strength is large. The two sets of gypsum-salt layers are inconsistent in extrusion deformation. The thickness of the gypsum-salt layer of the $E_{1-2}km$ is affected by the adjustment of the sub-salt structure, and the plastic flow characteristics are obvious, forming a variety of salt-related structures such as salt pillows and salt piercing. The overall thickness of the N_1j gypsum-salt layer is relatively uniform, mainly in

the form of broad and gentle anticlines.

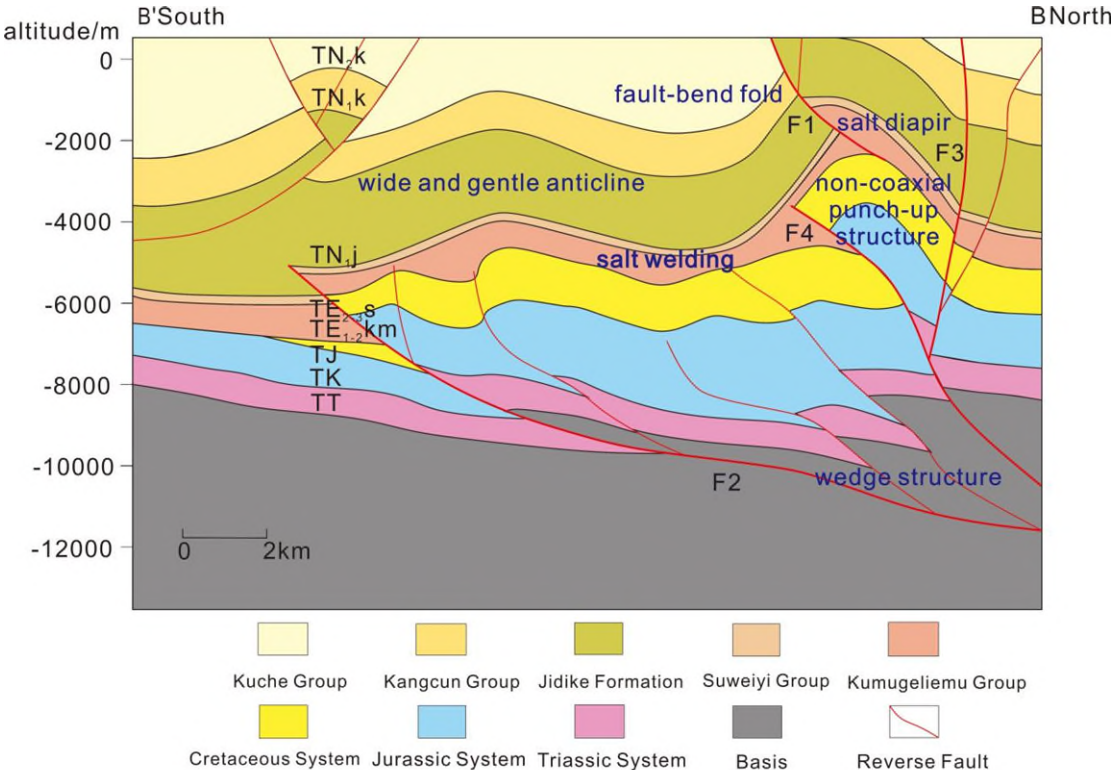


Fig. 5. Geological Cross-Section of Zhongqiu Litage - Dongqiu Litage Section-L1660

2.3 Structural section analysis of gypsum salt rock in single salt-rich N1j

In the single salt-rich N_1j gypsum-salt rock control section ,the $E_{1-2}km$ has basically no plastic rheology and becomes a dry rock layer. Only a set of non-dry salt layers of N_1j gypsum-salt rock develops large-scale plastic deformation. The F4 developed in the south died out in the gypsum salt layer of the N_1j. The salt nappe structure was formed in the hanging wall, and the small anticline was formed in the footwall, and the thrust was also produced near the surface. The thrust fault F1 was developed in the north and did not rush out of the surface. The small non-coaxial anticline appeared in the hanging wall of F1, and the footwall of F1 was a south-dipping monoclinic stratum. Compared with the profile A-A ', the Paleogene strata form a thrust imbricate fan structure, no longer only develop reverse adjustment faults and small secondary faults, and the fault amplitude increases, showing that the hanging wall of the reverse fault rises, the footwall drops, the fault distance becomes larger, and the faults are terminated in the gypsum salt layer of the N_1j. The thickness of the gypsum salt layer in the N_1j is thinning from south to north, and the morphology of the upper and lower salt strata is basically the same. The main reason is that the F2 runs through the Neogene and Paleogene strata, and the lateral extrusion pressure is dispersed.

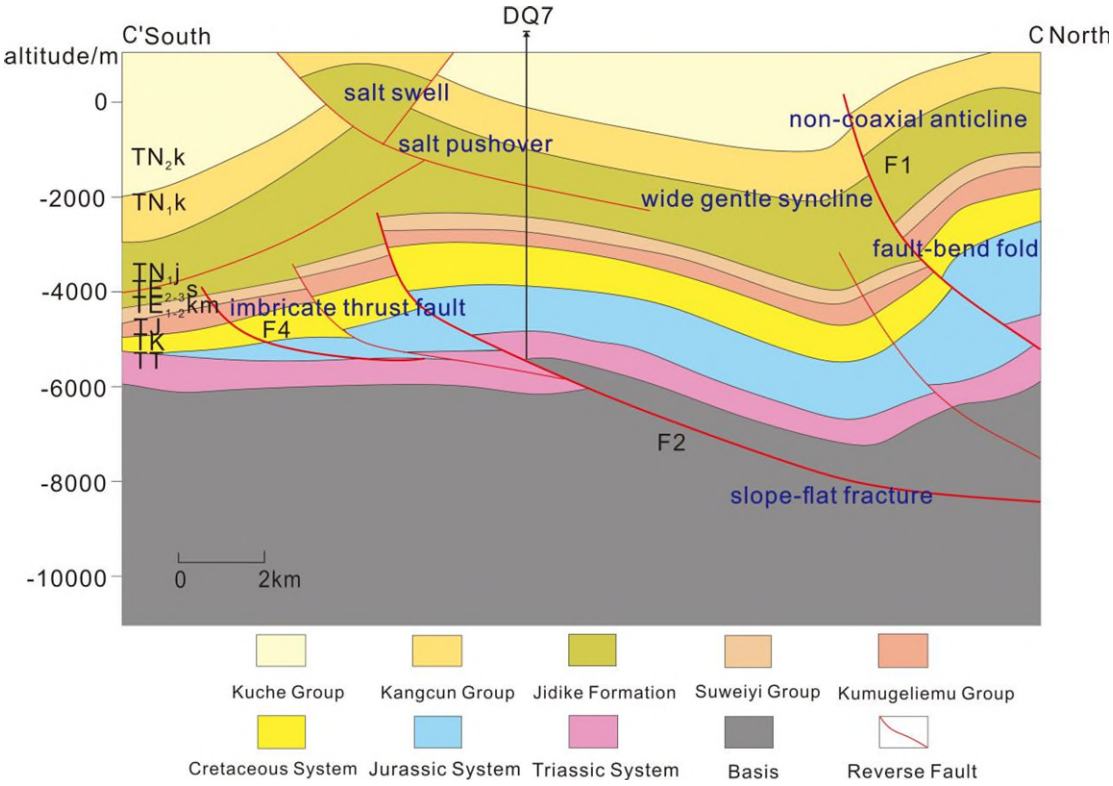


Fig. 6. Geological Cross-Section of Zhongqiu Litage - Dongqiu Litage Section-L2560

3 Experimental Design

3.1 Experimental Model Design

The experimental design of double salt layer paleo-uplift sand body is shown in Fig.7. Relying on the "Basin Structural Modeling Laboratory of Karamay Campus of China University of Petroleum (Beijing)".The size of the sandbox experimental area is limited to 600 mm long, 600 mm wide and 200 mm high. The electric drive push rod acts as the extrusion stress to push the extrusion edge forward and realize the extrusion effect.The extrusion rate is always kept at 0.03 mm / s during the experimental process. The experimental extrusion shrinkage is 45 %, accounting for 60 cm * 0.45 = 27 cm of the total length of the experiment. The camera on both sides and the PIV particle monitoring system on the top are used for data acquisition at an interval of 30 s,so as to facilitate the comparative analysis. The design of the model experiment focuses on laying a double salt layer. On the west side of the model, it is mainly $E_{1-2}km$ gypsum salt layer. The paleo-uplift angle is about 9 degrees, and the distribution range is 350 mm from west to east. On the east side of the model, it is mainly N_1j gypsum salt layer. The paleo-uplift angle is about 7 degrees, and the distribution range is 450 mm from east to west. The two sets of gypsum salt layers are only paved with a certain range and the rest is filled with sandstone. When the gypsum salt rock is laid, it is thick from the east and west sides and thins to the middle. The overall

geometry of the two sets of gypsum salt rock is a nearly conical shape wedged into each other.

3.2 Model Design Purpose and Parameter Selection

The purpose of this study is to take the double salt layer and its overlying strata in the study area as the main research object, to explore the deformation characteristics and genetic mechanism of the upper combination structure in the study area of the double salt lake area-single salt lake area-salt lake transition zone. It provides a theoretical basis for the exploration and deployment of the upper combination structural traps in the study area.

The physical simulation experiment material of the sand box is selected as follows. The bottom of the sand box is mixed with a variety of quartz sand, consolidated with water, and the part of the paleo-uplift at the bottom of the sand box is simulated. The Jurassic strata overlying the paleo-uplift use micro-glass beads to simulate the development of decollement structures in coal-bearing strata. The white quartz sand is used to simulate the actual sand layer, and the first set of salt layer is the gypsum salt layer of the $E_{1-2}km$. The rich paste 20 % content of sand-doped silica gel is mixed with 20 % quartz sand and 80 % content of 700000 molecular weight silica gel. The preparation method is as follows. According to the length, width and height of the gypsum salt rock layer laid by the experimental model, the volume of the silica gel is calculated. The volume of the two sets of gypsum salt layers is 60cm*60cm*0.3cm/2=540cm^3, 60cm*60cm*0.7cm/2=1260cm^3 and the calculation is divided by 2 is the simulated conical volume, which is approximately half of the rectangle. Wedge each other.Then through the high-precision counting scale as the intermediary conversion, it is convenient to calculate the volume of 50cm*36.5cm*1cm=1825cm^3.It is necessary to take out the volume of 540cm^3/1825cm^3=30% , 1260cm^3/1825cm^3=69%, silica gel mixed with 20 % sand, silica gel: and is 8:2,910g silica gel needs sand 910g / 8 * 2 = 227.5g, and then mixed up to obtain a silica gel mixed with 20 % of 700,000 molecular weight, with a height of 3mm. The second set of salt layer is the gypsum salt layer of N_1j, and the salt content is more pure 700,000 molecular weight silica gel. The height is 7mm, and a set of white sandstone is used in the middle of $E_{2-3}s$. The uppermost is the white sandstone used in the Neogene N_1k and N_2k. During the experiment, a thin layer of blue sand 1mm is used as a marker layer between the strata.The geometric similarity ratio between the formation thickness and the actual formation thickness in this experimental model is 1 : 50000, which is equivalent to the actual 500m of the model 1cm.

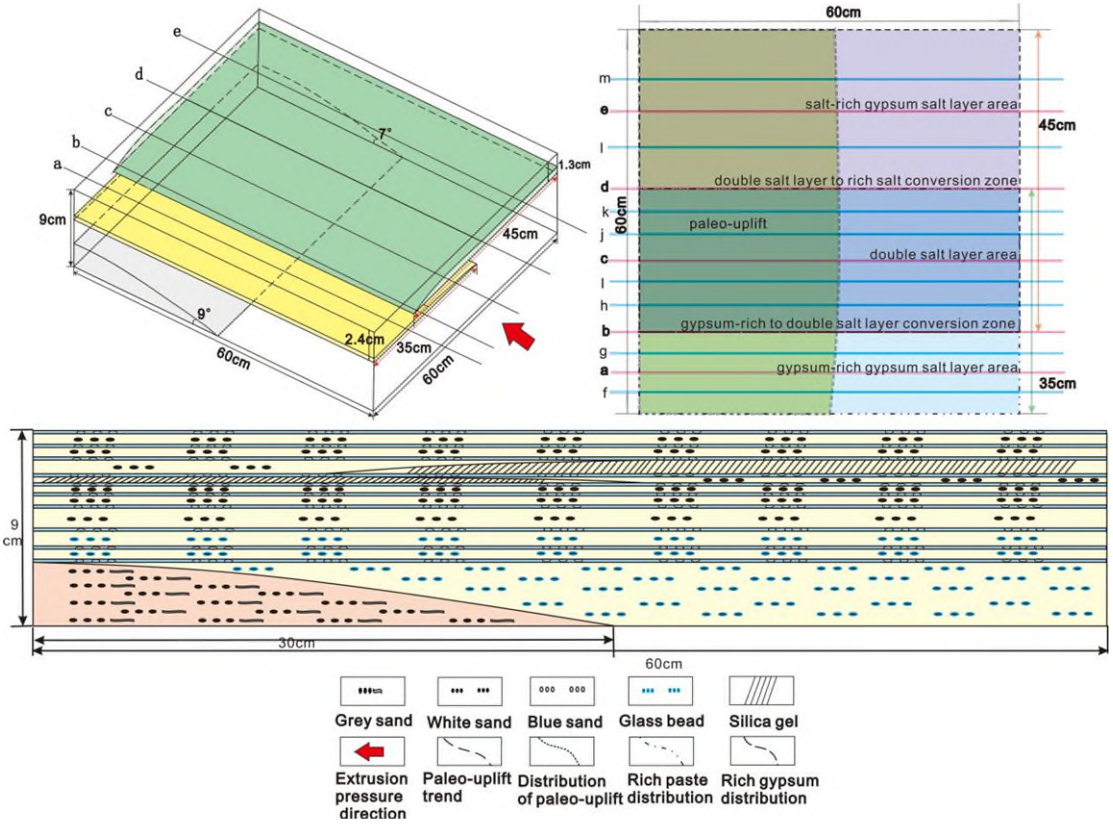


Fig. 7. Experimental Design Diagram of Double Salt Layer Ancient Uplift Sand Body

3.3 Model Experiment Results

The experiment stopped the compression when the compression reduction was 45%, so as to observe the typical structural deformation characteristics of the paste and salt layer. Five typical slices were selected to conduct a fine structural analysis of the paste and salt layer:

Slice a is an area rich in gypsum-salt layer, which is a single gypsum-salt layer of the $E_{1-2}km$. At this time, the gypsum-salt layer is thicker, and the sub-salt structural deformation near the compression edge is a high-angle thrust fault structure. The fault F1 starts from the sub-salt basement layer and continues to extend upward. It directly cuts through the gypsum-salt layer of the $E_{1-2}km$ and all the strata above the salt, and finally breaks to the surface. In the experimental slice diagram, the thrust wedge angle of the section a structure is 29.10 °, and the extension distance of the structural thrust wedge is 19.24 cm. The amplitude of the thrust structure is 9.24 cm, which is manifested in the fact that the thrust imbricate fan has a long oblique extension distance, a large vertical superposition degree, a small interval between each fan, and a narrow fold amplitude. The overlying sub-salt structural layer on the basement is uplifted as a whole, and the combination near the extrusion end forms a large-scale faulted anticline structure. The axial direction of the faulted anticline

structure is perpendicular to the direction of the experimental extrusion stress. The strata in the core of the anticline are slightly thickened due to extrusion, and the strata on both wings show a symmetrical distribution of inclination. The anticline has a large amplitude, and a small number of secondary small faults are developed at the top. In the area far away from the extrusion end, there is no large-scale thrust structure developed, and a small recoil fault F2 with a small scale is formed, which is opposite to the main extrusion stress direction.

Slice b is a conversion zone from a single rich gypsum salt layer to a double salt layer, which is manifested in the thinning of the gypsum salt layer of the $E_{1-2}km$ and the emergence of the gypsum salt layer of the N_1j. In this section, the gypsum salt layer of the $E_{1-2}km$ is still the main gypsum salt layer, but compared with the section a, its thickness is significantly thinner, the salt content of the gypsum salt layer is slightly decreased, and the sand content is initially increased. The gypsum salt layer of the N_1j began to appear. Compared with the structural style of slice a, the sub-salt structure on the side near the extrusion end also mutated from the single high-angle thrust structure of slice a to the composite structural style of high-angle thrust and low-angle thrust. The experimental slice diagram shows that the thrust wedge of slice b is 21.20 cm longer than that of slice a, and the thrust wedge angle of the near extrusion edge structure is 26.81 °, and the thrust structure amplitude is 14.11 cm. The upper combination has obvious thinning phenomenon, which is thinner than the overall formation thickness of the combination on the slice a ; on the side far away from the extrusion end, the upper combination shows obvious synsedimentary phenomenon. The thickness and distribution of sedimentary strata are controlled by structural morphology. The strata in the anticline are thinner and the strata in the syncline are thicker. In addition, the main fault F1 in the slice continues to develop and extends directly to the surface. The strong plastic deformation of the gypsum salt layer of the $E_{1-2}km$ further forms a variety of salt-related structural styles such as salt domes, salt veins, and salt wedges. The development of these salt structures further leads to multiple fold deformations in the upper composite structure. The fold amplitude is different and the shape is complex. At the same time, the prototype of the imbricate structure begins to appear. The fault arrangement direction of the imbricate structure is basically consistent with the direction of the compressive stress. The fault dip angle is relatively slow, and the imbricate fan is hidden downward in the gypsum salt layer, which lays the foundation for the subsequent development of the imbricate structure in the double salt layer area.

Slice c is a double salt layer area and enters the double salt layer superposition area. The two sets of gypsum salt layers work synergistically. Under the continuous action of lateral compressive stress, the two sets of gypsum salt layers form a series of typical salt structures due to plastic flow, mainly salt domes and salt pillow structures. Among them, the salt dome structure is a dome structure formed by the upward uplift of the gypsum salt layer under the action of compressive stress, which is mainly developed in the low-angle cap rock slip zone and the high-angle basement involved in the middle of the thrust zone. The salt pillow structure is mainly distributed on both sides of the salt uplift structure, showing a lenticular distribution. The syntectonic sedimentation is obvious, and the thickness difference between the middle and both sides of the stratum is significant. The fault does not directly extend to the surface, forming multiple small faults. In the area far away from the extrusion end, the upper combination forms a small imbricate structure. The faults of the imbricate structure are closely arranged, the fault tendency is consistent, and parallel to the direction of the extrusion stress. On the side near the extrusion end, the upper combination is dominated by a wide and gentle syncline structure, the syncline axis is perpendicular to the direction of extrusion stress, the dip angle of the two wings is gentle, and the thickness of the syncline core is large. The experimental slice diagram shows that the extension distance of the thrust wedge of the slice c structure is 30.70 cm, the wedge angle of the thrust wedge near the extrusion edge is 26.15 °, and the range of the thrust structure is 11.90 cm. It continues to extend forward and the shape becomes larger. The development of the main F1 in this slice is obviously hindered by the double salt layer. The original continuous extension of the main F1 is bifurcated when it passes through the interface of the two sets of gypsum salt layers, forming two opposite salt rupture F2 and F3, forming a fault-controlled salt arc triangle belt. These two secondary faults extend along the interface between the two sets of gypsum salt layers and the upper combination strata, and the extension length is limited. At the same time, due to the blockage of the bifurcation of the main fault F1, a series of reverse adjustment F4 are produced in the sub-salt strata, which are opposite to the main F1.

Slice d is the transition zone from double salt layer to single salt-rich gypsum salt layer. The thickness of the gypsum salt layer of the $E_{1-2}km$ is transformed into a thin layer. The component structure is transformed into the approximate sandstone property, and the dominant gypsum salt rock detachment layer is transformed into the gypsum salt rock layer of the N_1j. Near the side of the extrusion end, the structural deformation shows obvious pushover characteristics.

Compared with the slice a, the experimental slice diagram shows that the fan body of the slice d thrust wedge extends far away, the vertical distance of the fan sheet increases, and the fold amplitude between the fans is relatively gentle. The whole shows the spatial distribution characteristics of long-distance slip oblique superposition. The wedge angle of the tectonic thrust wedge is 27.13 °, the extension distance of the tectonic thrust wedge is 30.70 cm, and the range of the thrust structure is 11.96 cm. Under the control of compressive stress, the sub-salt basement strata uplift and move forward. The fault F1 passes through the gypsum salt layer of the $E_{1-2}km$ with thinning thickness and weakened plasticity, and finally terminates at the bottom of the gypsum salt layer of the N_1j, and cannot continue to extend upward. The $E_{2-3}s$, $E_{1-2}km$ and the sub-salt strata together form a large wedge-shaped nappe. The upper combination develops a series of small faults and traction structures.The traction structure is mainly developed on both sides of the small faults.The thickness of the gypsum salt layer in the N_1j increases and the plasticity is enhanced. Its blocking effect on the fracture is significantly strengthened, which effectively blocks the upward transmission of the sub-salt structural deformation. At the same time, the plastic flow of the gypsum salt layer forms a variety of salt structures, such as salt pillows and salt uplifts, and small faults are developed at the structural highs. The overall structural deformation of the upper combination does not develop large-scale folds and thrust structures.

Slice e is a salt-rich gypsum-salt layer area, which is a single gypsum-salt layer of the N_1j, and the lithology of the $E_{1-2}km$ is mainly sandstone. The tectonic deformation on the side near the extrusion end is extremely strong. The $E_{2-3}s$, $E_{1-2}km$ sandstone and subsalt tectonic layers on the salt are formed under the continuous action of lateral compressive stress. The multi-row belt thrust imbricate structure is formed. The thrust imbricate structure is composed of a series of thrust faults with nearly parallel arrangement of fault tendencies. The distance between the imbricate fan fragments is smaller than that of the slice d. The experimental slice diagram shows that the wedge angle of the slice e structure thrust wedge is 26.47 °,the extension distance of the structural thrust wedge is 21.55 cm, and the amplitude of the impact structure is 14.57 cm. Affected by the imbricate structure, the amplitude of the thrust structure near the compression end is higher, the grade I fault that constitutes the thrust structure is more strongly wedged into the gypsum salt rock layer, the fault extension distance is farther, and the overall thrust structure is inclined. The degree of uplift and fluctuation is more intense ; on the side far away from the extrusion end, the structural deformation characteristics changed significantly. The thickness of the gypsum salt

layer in the N_1j gradually increased, the inhibition effect of fracture development was enhanced, the sub-salt structural deformation was greatly reduced, and the number of salt structures was significantly reduced. Only a small number of small salt pillow structures were developed in the local area. At the same time, the curling effect of the stratum is significantly strengthened, obvious curling deformation occurs, and even stratum reversal occurs in local areas. A series of small folds are formed in the curling area. The folds are complex in shape, small in amplitude, and mostly asymmetric. In addition, Faults at the salt rise continues to develop, and the fault extends along the top surface of the gypsum salt layer of the N_1j, and the fault dip angle is gentle.

Fig. 9 presents the quantitative analysis of thrust wedge evolution. From the gypsum-rich to salt-rich domains, the forward extension distance, wedge angle, and structural amplitude display distinct stages closely coupled with the properties and distribution of salt layers. The extension distance and structural amplitude increase with salt-layer thickness and number, peak in the double salt-layer zone, and then gradually decline. The wedge angle first decreases, reaches its minimum in the double salt-layer zone, and then increases gradually. In the double salt-layer superimposed area, the two salt layers jointly suppress fault propagation; the paleo-uplift angle decreases, and basement faults shift from vertical propagation to lateral extension. Strong syndeposition provides space for stress accommodation and facilitates fault elongation, resulting in the longest forward extension, smallest wedge angle, and largest structural amplitude. In the double to single salt-rich transition zone, the plastic flow strengthens and salt structures develop widely. The limited distribution of E_{1-2}km restricts horizontal propagation, turning the thrust wedge to vertical amplification. As the dominant factor, the salt layer governs the thrust wedge pattern, forming the overall deformation framework.

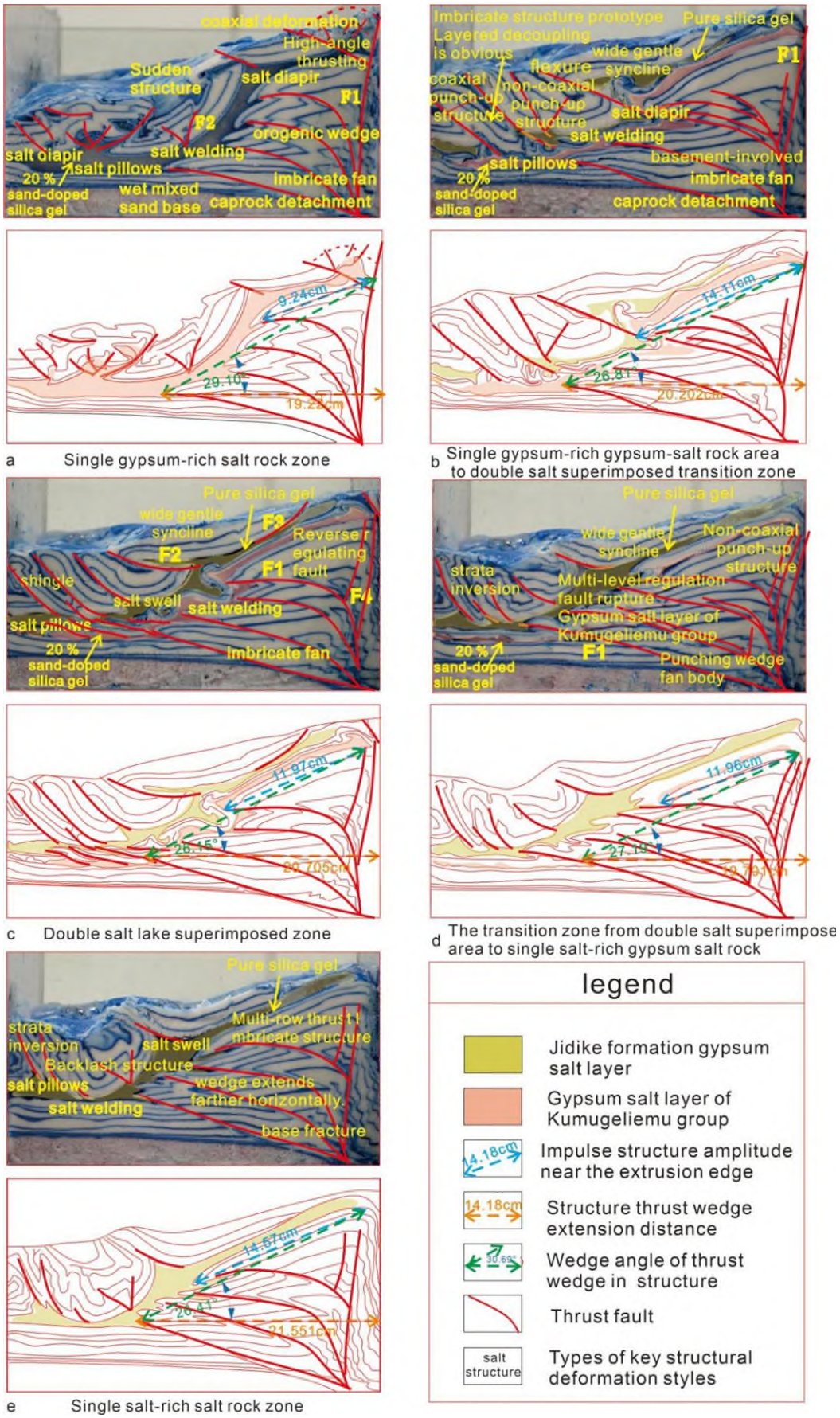


Fig. 8. Experimental Section Diagram

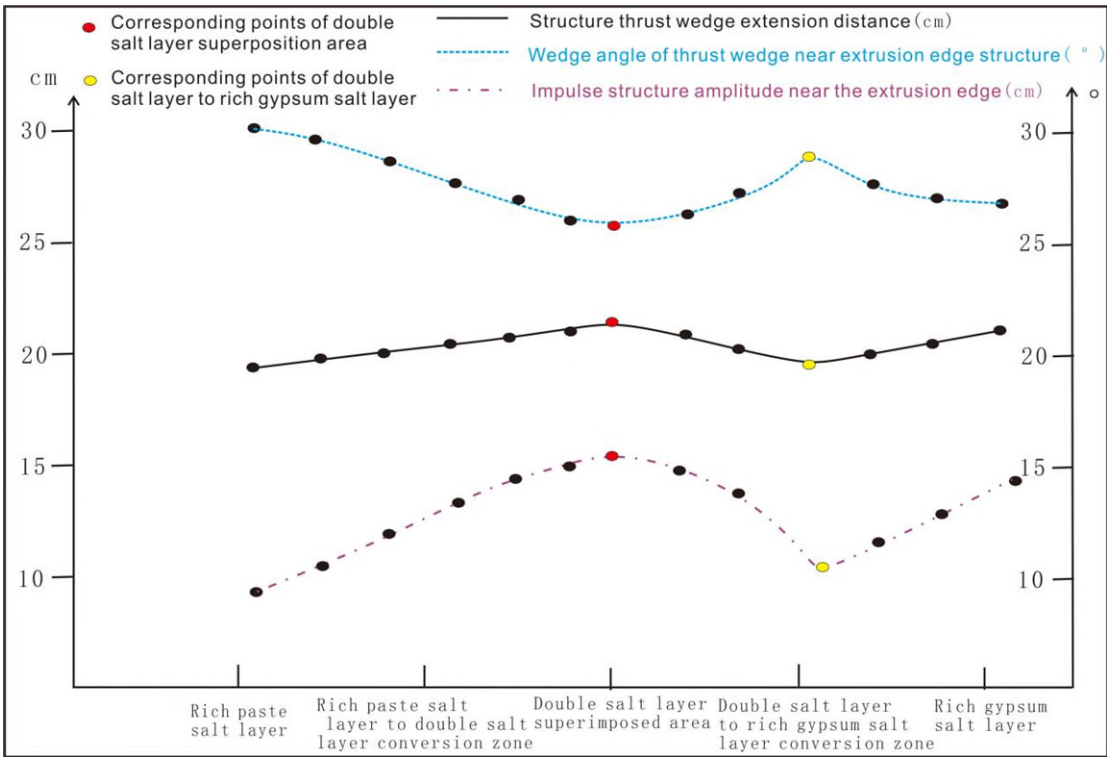


Fig. 9. Quantitative analysis diagram of the punching wedge

4. Discussion

4.1 Characteristics of structural Deformation Controlled by the properties of paste and salt layers and the Synergistic Action of double salt layers

The existence of plate-salt layers has a significant impact on the structures above and below salt. Previous studies on plate-salt rock detachment layers mainly focused on three aspects: the geometric morphology of salt structures[17], the composition of components[18], and the determination of the synergistic decoupling effect of multiple salt lakes[19]. These aspects play an important controlling role in the deformation of upper combination structures, resulting in significant zonal and stratified characteristics of structural deformation[20-21].

Combined with the experimental results of sand bodies, from the perspective of rock composition, the gypsum salt layer of the $E_{1-2}km$ is mainly composed of gypsum, with strong toughness, and the deformation is dominated by bedding detachment and vertical separation. The gypsum salt layer of the N_1j has high salt content and stronger plasticity, which is prone to large-scale plastic flow and aggregation and dispersion migration. From the perspective of salt structure geometry, in order to adapt to a variety of structural forms under the salt, the plastic flow of the overlying gypsum salt layer forms a variety of salt structures. In the double salt layer area, geological Cross-Section of Zhongqiu Litage - Dongqiu Litage

Section-L1452 shows the salt anticline, salt welding, salt pillow and salt piercing. Due to the uneven stress of the whole stratum, with the flow of the gypsum salt layer, it is easy to fracture at the top of the salt anticline and form salt piercing. For the $E_{2-3}s$, under the influence of the strong thrust of the fault under the salt, the thin layer of the $E_{1-2}km$ is broken and the oil and gas migration channel is formed. The thick layer of the N_1j acts as a caprock to seal. In the case of lateral sealing of faults and gypsum salt layer as cap rock, slope-flat fault-bend anticline traps may be formed. In the single salt layer area, the independent control of gypsum salt layer in N_1j makes the structural deformation tend to be simplified. Due to the increase of lateral compression strength and the relief stress of only single gypsum salt layer, it is urgent to find the release point of gypsum salt layer, which is easy to form high-angle fault-bend anticline, salt pillow and salt uplift structure, and the geometric shape and amplitude of salt structure are large, which proves the important control effect of salt composition on structural style.At the salt dome, with the increase of the strength of the upward thrust, the individual fault can not bear the overall pressure, forming a recoil fault, which is used to disperse the stress and make the stress field tend to be stable. At the same time, the formation of the salt dome is related to the sub-salt fault. This fault F2 is as shown in Figure 11. The geological Cross-Section of Zhongqiu Litage - Dongqiu Litage Section-L3324 breaks through part of the N_1j gypsum-salt layer. The residual stress is released in the gypsum-salt layer and rushed upward to form a salt dome. F2 itself thrusts forward to form a imbricate structure, passing through the $E_{2-3}s$ to form a slope-flat imbricate anticline trap. From the perspective of the synergistic effect of the double salt layer, in the superimposed area of the double salt layer, under the control of the synergistic effect and differential deformation of the two sets of gypsum salt layers, a complex vertical layered structure model is formed. The $E_{1-2}km$ is used as the deep gypsum salt layer, which divides the salt and the salt structure system, and controls the overall change trend of the upper salt layer ; the N_1j forms structural styles such as salt anticlines and salt nappes in the shallow layer, and its plastic flow leads to the syndepositional characteristics of ’ thick in the middle and thin on both sides ’ in the overlying strata.

In a word, the properties of gypsum-salt layer, the synergistic effect of salt structure and double salt layer play an important role in controlling the deformation of supra-salt structure. This study deepens the understanding of the spatial distribution of gypsum-salt rock and its difference in properties on the study of upper combination tectonic deformation.

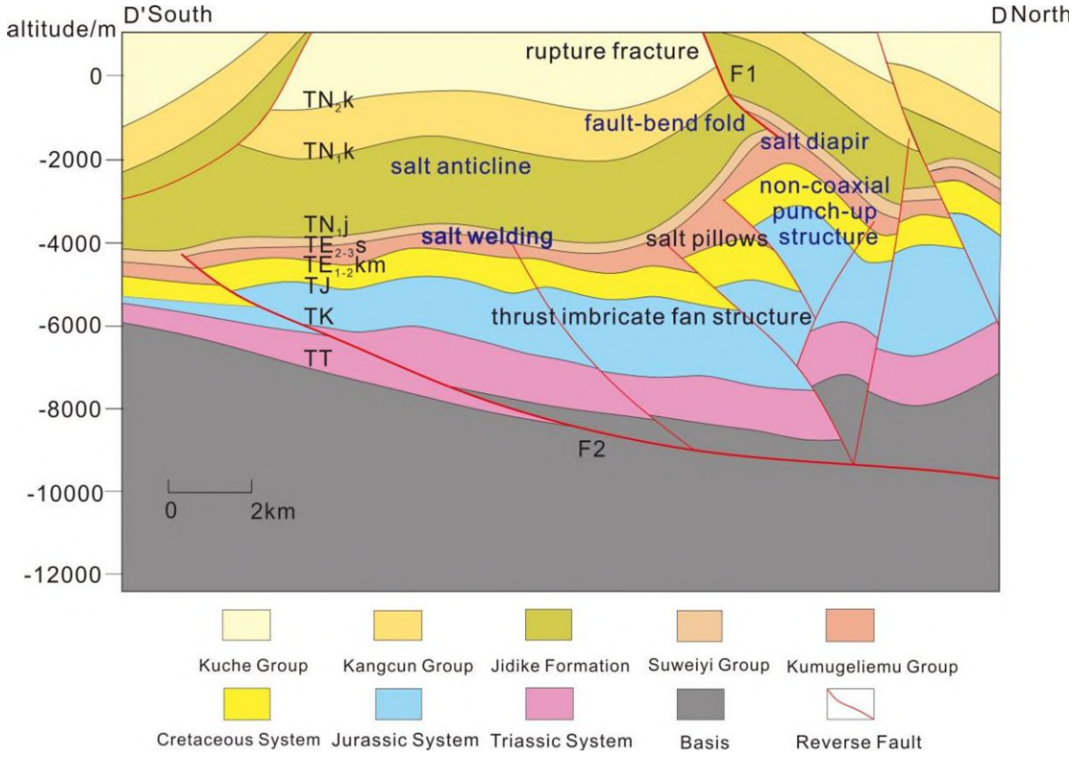


Fig. 10. Geological Cross-Section of Zhongqiu Litage - Dongqiu Litage Section-L1452

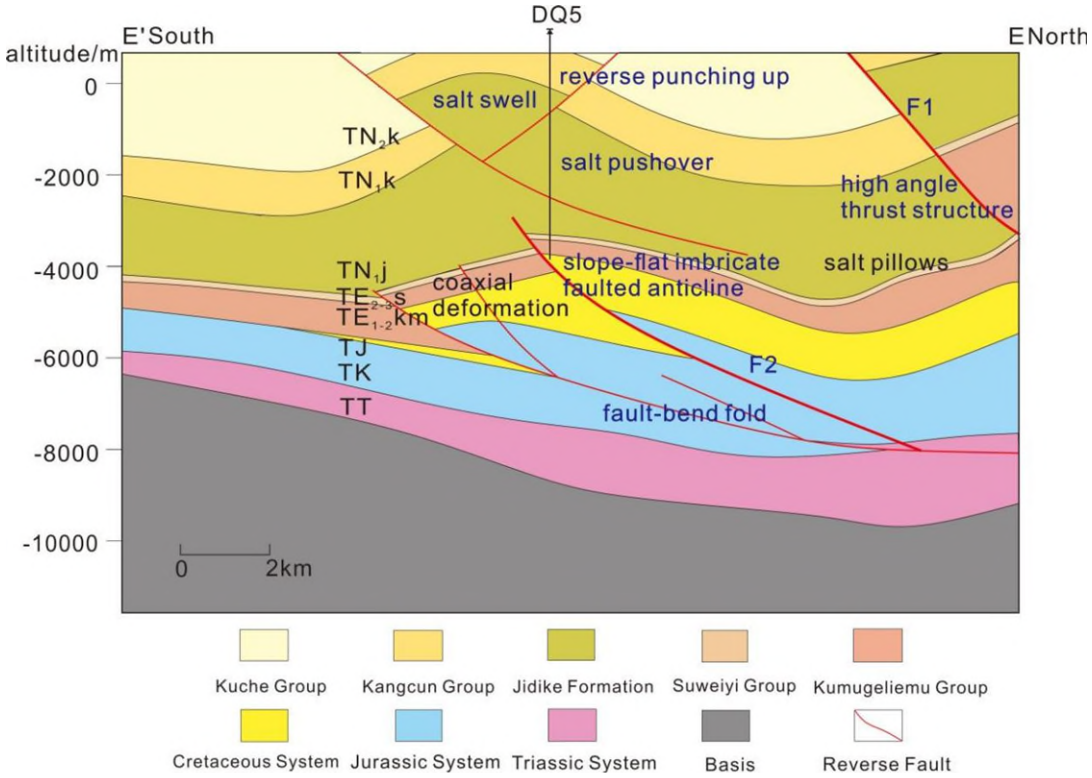


Fig. 11. Geological Cross-Section of Zhongqiu Litage - Dongqiu Litage Section-L3324

4.2 Characteristics of Tectonic Deformation under the control of tectonic sedimentation

The thickness variation trend of the salt superstructure under the

control of isomorphic sedimentation is characterized by being thinner in the middle and thicker on both sides. Based on the previous research results, it is found that isomorphic sedimentation is related to the growth activity of faults, the overlying formation pressure[22] and the plastic flow of the paste salt layer[23], and the influence of isomorphic sedimentation on the deformation of salt superstructure is also discussed[24-25].

Combined with the geological structure profile of the Zhongqiu-Dongqiu section-L2076, the gypsum salt layer of the N_1j is characterized by uniform thickness of bedding sliding in the south, forming a high-angle faulted anticline. The fault distance of F2 is smaller than that of the Zhongqiu area, and the salt uplift is formed at the high point of F2.Combined with syndeposition, it is located in the thinner part of the stratum, which is prone to fracture. The northward transition is thrust upward to form F1.Compared with the overall dip angle of Paleogene, the attitude of Neogene strata becomes larger, the thickness becomes thicker, and the deposition is more stable. The syndepositional phenomenon is obvious in the depression area, which is manifested in the thickening of the fold core and the thinning of the wing.Because the extension of fault F2 is hindered and the fault distance is reduced, under the extrusion force of South Tianshan Mountains, the force cannot be released through the fault, which often leads to long-distance lateral extension. The plastic flow characteristics of gypsum salt layer lead to the decoupling effect of slippage, resulting in a certain stress being dispersed, so that the actual stress acting on the upper combination becomes smaller. The formation deposits with the plastic flow of gypsum salt layer, forming many special salt-related structural types. The pressure difference of thick layer deposition promotes the accumulation of gypsum salt to the depression to form salt dome and salt pillow. The gypsum salt in the thin layer migrates horizontally to form a wide and slow salt anticline, which deposits rapidly at the salt welding point and deposits slowly at the salt dome, separating the overlying pressure evenly. The tectonic deformation extends far and has transitivity; under the action of sub-salt structure, gypsum salt layer and syndeposition, the structural deformation on salt is affected, and the sandstone of $E_{2-3}s$ in Paleogene has good oil and gas display in Dongqiu 8 well, with non-coaxial thrust anticline as the dominant trap. In other areas, such as the Mosuowan uplift in the hinterland of the Junggar Basin[24], it is a typical epigenetic structure. Because its main structural form is formed after the basic formation of the sedimentary cover, it is strongly reformed by the late tectonic movement, which is basically not synchronized with the sedimentation. It has the characteristics of sedimentary filling first and then extrusion uplift. The tectonic movement is strong and the distribution

range is concentrated. It is dominated by large-scale multi-high-angle imbricate thrust structure, and the fault distance is large and extends to the surface. The plastic flow of the gypsum salt layer has little effect on the structural deformation on the salt, and the shape is relatively single. Regular salt anticlines and fault-bend folds are formed in the double salt layer area. In the single salt layer area, large-scale salt pillow structure and imbricate fault anticline are developed.

In summary, syntectonic sedimentation is of great significance to the deformation of supra-salt structures. Through fault activity and the distribution of salt structures, it can more significantly reflect the structural deformation characteristics under the control of regional stress state changes and the properties of gypsum and salt layers.

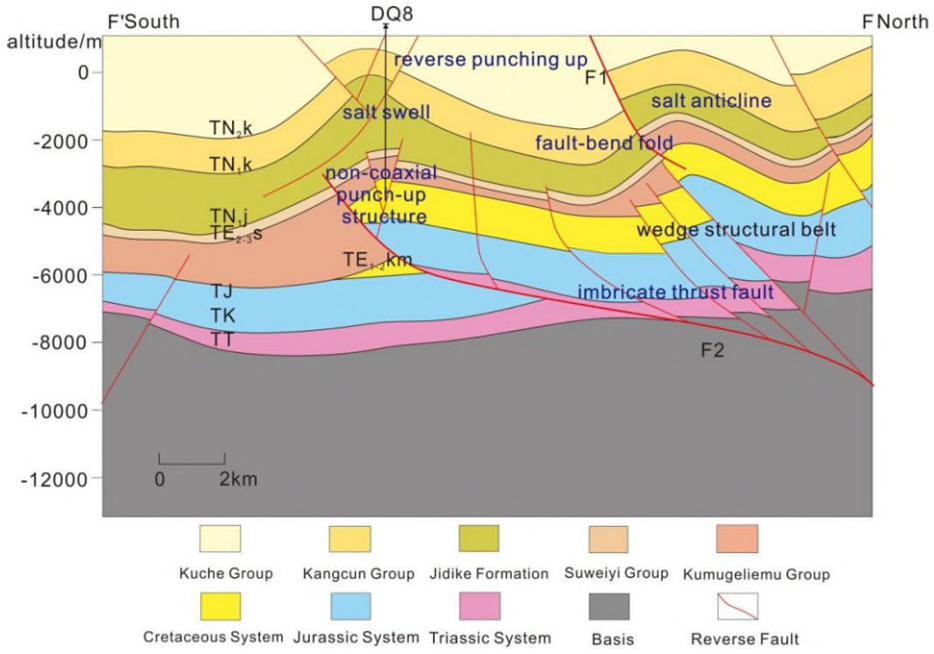


Fig. 12. Geological Cross-Section of Zhongqiu Litage - Dongqiu Litage Section-L2076

4.3 Characteristics of tectonic deformation under the control of paleo-uplift

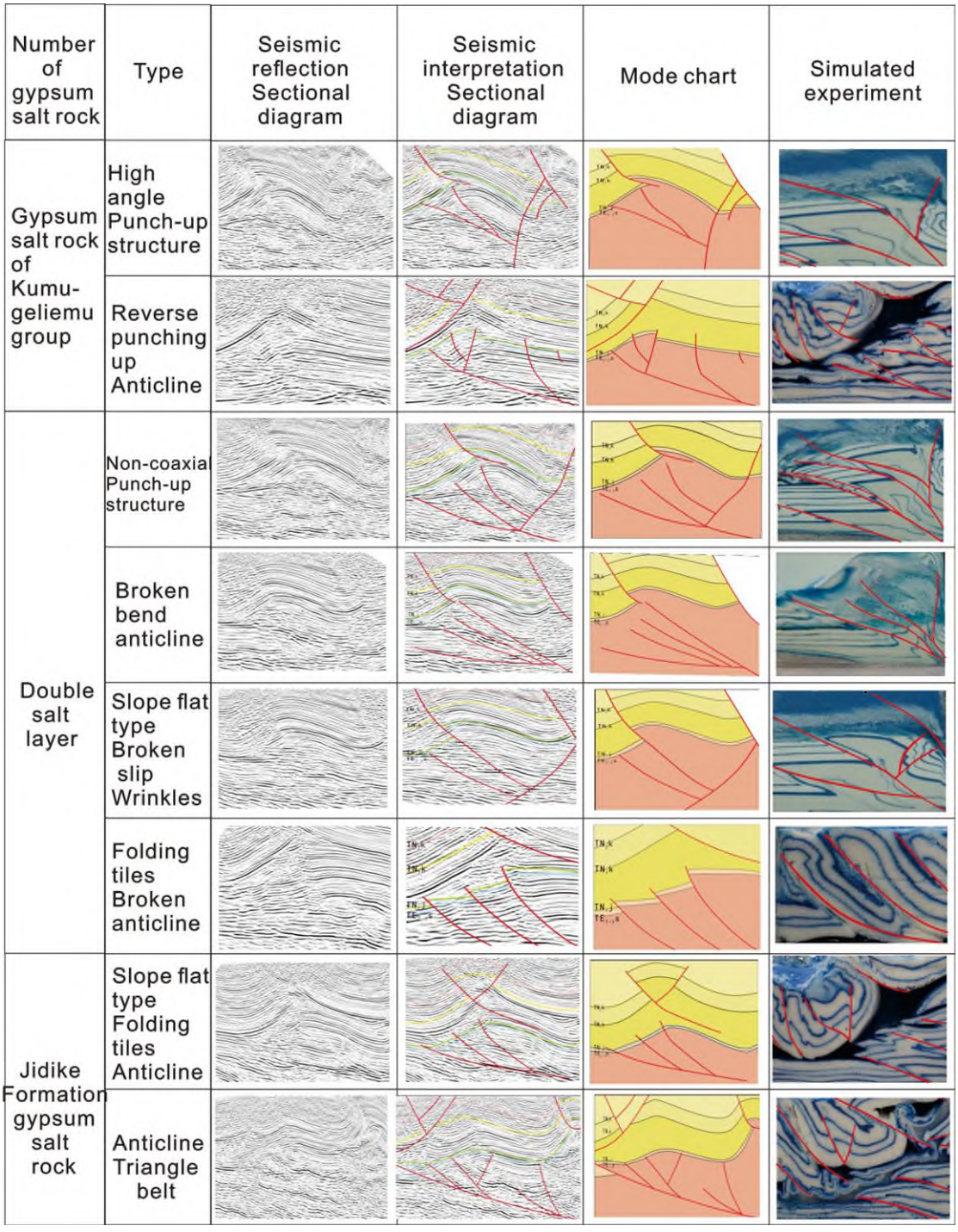
The ancient uplift is located deep within the strata. Previous studies have shown that the ancient uplift mainly affects the upper assemblage by directly influencing the structural deformation of the sub-salt strata and thereby indirectly influencing it. The distance from the orogenic belt[26], the spatial distribution pattern and angular changes[27] are important factors affecting the structural deformation of the sub-salt strata[28]. Its controlling effect is mainly reflected in the difference between the structural layout pattern and the deformation strength.

For the Zhongqiu-Dongqiu area, the experimental design of the

paleo-uplift transitions from 9 ° to 7 °. The simulation results show that the larger the angle of the paleo-uplift from west to east, the closer the extension of the sub-salt strata, and the higher the upward uprush angle, the more obvious the flow of the gypsum salt layer is blocked, and it is easy to form salt uplifts and uprush structures at the edge of the uplift. The western section of the Zhongqiu belongs to the single $E_{1-2}km$ gypsum salt layer area. Under the influence of the high-angle paleo-uplift, the sub-salt tectonic movement is strong under the action of extrusion. The gypsum salt layer of the N_1j is a super-class cap rock, and its sealing effect and the angle of the bottom paleo-uplift are large, resulting in rapid stress release. It cannot continue to transmit to the deep part of the Kuqa Depression through the thrust imbricate fan, and cannot actively adjust the stress-strain balance by adjusting the amount of fold contraction and fault distance. It can only passively adjust the stress state by developing secondary reverse adjustment faults on the main faults, and then form a large-scale distribution of large-scale thrust structures, mostly developing high-angle anticline traps.The middle section of the Zhongqiu area is a transition section from a single salt layer to a double salt layer. The angle of the paleo-uplift decreases gently. With the transformation of the gypsum salt layer, the structural deformation on the salt begins to appear imbricate structure, which is easy to develop slope-flat fault-bend anticline traps. The Zhongqiu East is a double salt layer superimposed area, the angle of the ancient uplift continues to slow down, the overall extension of the thrust wedge is far, the stress continues to release, and the imbricate anticline trap is formed at the extension end of the thrust wedge. The transition from the double salt layer to the single salt layer in the western section of the Zhongqiu formed a coordinated conversion zone ; the section from the middle of Dongqiu to the eastern section of Dongqiu is a single salt layer area. The low-angle paleo-uplift makes the deformation of the sub-salt structure weak and forms a wide and gentle anticline. The deformation of the supra-salt structure is mainly affected by the gypsum salt layer of the N_1j.Due to its strong plastic deformation and good fluidity, it is easy to form the structural form of imbricate fault anticline. The pre-existing faults at the edge of the paleo-uplift provide a weak zone for structural deformation. The compressive stress is transmitted along the pre-existing faults, resulting in fault activation and extension, forming fault-intensive zones and complex anticline triangle traps, providing channels and favorable pointing areas for oil and gas migration.

All in all, the different angles of the paleo-uplift lead to various styles of structural deformation on the salt. The study helps to describe the structural deformation on the salt, deepen the

704 understanding of the distribution of the double salt layer.



705

706 Fig. 13. Typical structural styles and dominant trap types of the
707 Zhongqiu -Dongqiu Upper combination in Kuqa Depression

708 ## 5 Conclusion

709 （1）The study area is controlled by the spatial distribution
710 differences of gypsum and salt rocks. From west to east, it is a single
711 salt-rich gypsum salt layer of the $E_{1-2}km$. High-angle thrust and fault
712 anticlines are frequently seen.The transition from a single salt-rich
713 gypsum salt layer to a double-salt layer conversion area is obvious,

and the initial appearance of shingle structures. The central double-salt layer area is characterized by the synergistic effect of salt uplift, the obstruction and dispersion of faults, and the formation of small shingle structures.Ultimately, it shifted eastward from the double-salt layer area to the single salt-rich gypsum salt layer. In the transition zone to salt-rich, the N_1j played a dominant role, and mainly developed wedge-shaped thrust bodies. In the single rich salt section of the N_1j salt layer, the development of shingle structures is more common.

（2）The properties of the plate-salt layer, along with sedimentary processes and the inclination angle of the paleouplift, are the three major controlling factors leading to the deformation of the salt superstructure.The paste salt layer contains a relatively high amount of paste and has strong toughness. Its deformation is mainly characterized by laminar slippage and vertical separation. With a higher salt content, it has stronger plasticity and is prone to large-scale plastic flow and aggregation and dispersion migration.The sedimentary action of the same structure has the deformation extension of the upper combined structure that is relatively far and has transmissibility, while the movement of the upper combined structure is intense and the distribution range is relatively concentrated, mainly characterized by large-scale multiple high-angle impulse superposition.The greater the inclination Angle of the ancient uplift, the higher the upward impulse Angle, the greater the uplift amplitude, the shorter the extension distance of the impulse wedge, and the high-angle impulse structure is dominant. The smaller the Angle, the smaller the uplift amplitude, the farther the break wedge extends, and the structure is mainly composed of multiple reverse impact laminated tile fans.

（3）The analysis of the results from structural analysis and structural physical simulation experiments shows that the double salt layer is an important factor in controlling the deformation of structures on salt and the type of traps.The types of structural traps in the upper combination of the study area can be summarized as five types of structural traps : reverse thrust anticline trap, fault-slip anticline trap, slope-flat fault-bend anticline trap, imbricate anticline trap and anticline triangle trap. The gypsum-rich salt layer area is dominated by reverse thrust anticline traps, while the transition zone from gypsum-rich salt layer to double salt layer is characterized by slope-flat fault-slip anticline and fault-slip anticline traps. In the transition area from the double salt layer to the rich gypsum salt layer, the slope-flat fault-bend anticline trap is dominant. In the rich gypsum salt layer area, the anticlinal triangle trap is commonly seen.

CRediT authorship contribution statement

Ke Xu:Writing-original draft,Writing-review and editing,Visualization, Validation, Project administration, Methodology, Inves tigation, Formal analysis, Data curation, Conceptualization.

Yongxu Mei:Writing-review ,editing,Visualization,Validatio,Project administration,Methodology,Inves tigation,Formal analysis,Data curation,Conceptualization.

Jinning Zhang:Writing-review and editing,Visualization,Validation, Project administration,Methodology,Inves tigation,Formal analysis,Data curation,Conceptualization,Funding acquisition.

Haodong Lin:Visualization,Validation,Investigation

Jiehao Su:Visualization,Validation,Investigation

Yuhuan Chen:Formal analysis,Data curation,Conceptualization.

Yan Yan:Investigation,Formal analysis.

Zeyi Wang:Conceptualization,Investigation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgment

This study was funded by the National Science and Technology Major Project of New Oil and Gas Exploration and Development Fine Description and Evaluation Technology for Deep and Ultra-Deep Clastic Rock Traps(2025ZD1402401), the National Science Foundation of China (No. 42362026), and the Key Research and Development Program of Xinjiang Uygur Autonomous Region (2024B01015).

Data availability

The authors do not have permission to share data.

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