Lacustrine Deep-water Sequence Stratigraphy and Prediction Model of Gravity Flow Deposits: A Case Study of Shahejie Formation in Dongying Depression, Bohai Bay Basin, China

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Lacustrine gravity flow deposits are becoming the significant hydrocarbon reservoir in China with the application of new concepts such as sandy debris flow and new deep-water depositional theories. At the same time, prediction of gravity flow sedimentary elements is so difficult in lacustrine basins due to small-scale geometry of sandstone, rapid transformation in flow types and sedimentary elements. Sequence stratigraphic study became the key way to better understand the distribution of deep-water deposits in Eocene middle of 3rd member of Shahejie formation ($E_2s_3^z$) in Dong-Xin area, Dongying depression, Bohai Bay basin.

Predictive model of lacustrine gravity flow deposits was studied in this study. First, high frequency sequence stratigraphy and shoreline trajectory changes were identified by seismic and well logging data. Then, flow mechanism or deposition origin of each sedimentary cycle was interpreted with core, thin-section and grain-size data. Finally, origin and type of architectural element and their distribution in sequence stratigraphic framework were discussed for predictive model.

First, $E_2s_3^z$ was interpreted as one 3rd sequences deposited during the falling period of 2nd-level base level after the maximum flooding period in $E_2s_3^x$. As a result, HST became the remarkable system tract with nine periods of regression or parasequence sets (PSSs), but TST was very thin including one PSSs only. Besides, the PSSs in HST may be divided into rising normal regression, stable normal regression and forced regression according to shoreline trajectory features.
Seven gravity flow deposits, i.e. turbidite, sandy debrite, muddy debrite, mud flow, sandy slump, muddy slump and slide, were identified by introduction of new concepts such as sandy/muddy debrite, sandy/muddy slump in 38 cored wells. Statistics showed that sandy debrite is the most common one with the ratio of 52% of all sedimentary cycles and the most important one with the largest average thickness of 1.04m each cycle. Liquefied flow has not been studied as one type of gravity flow in this study because it is not always an independent flow but the follow-up reformation process after deposition in debrite or turbidite.
Two sedimentary systems, channeled subaqueous fan and non-channeled slope deposit, were recognized by seismic attributes, logging curves and sedimentary mechanism analyses based on core and grain size data.

Deep-water deposition in lake such as Bohai Bay basin should be simpler than that in marine basin for missing of bottom flow and internal wave and internal tidal. But it is still difficult to predict because of small-scale basin and sedimentary units. Relationships analyses among flow mechanism, type and size of depositional elements with the change of base level and shoreline trajectory are helpful to build up a predictive sedimentary model for seismic attributes interpretation and deep-water hydrocarbon exploration.

This study showed that (1) sandy debrite but not turbidite was the most important type of sandstone for hydrocarbon reservoir. (2) Type and ratio of dominated gravity flow change regularly from sandy debris flow, turbidity current, slump to sandy debrits flow with base level change. (3) Channeled subaqueous fan developed mainly in LST and late HST, and tongue-shape small-size debrite dominated non-channeled slope deposit developed in TST and early HST.

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Formation of High Quality Reservoir in Tight Sandstone in Upper Paleozoic of Ordos Basin，China

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Gas reservoir of Upper Paleozoic of Ordos Basin generally has the characteristics of large area, multi-layers and low abundance, reservoir properties generally being low porosity and permeability, however, there are still some blocks concentrated with high, greater abundant gas reserves. The Upper Paleozoic gas reservoir is mainly controlled by the distribution of relatively high-quality reservoir such as Yulin and Sulige large gas fields whose main producing formation of Shanxi Group 2 (Shan 2 Group) and Xiashihezi Group 8(He 8 Group) with permeability over 0. 5 × 10^{-3}μm^2 have Hundreds of billions of cells in the reserves.
According to the sand type, physical properties, particle compositions and particle size, matrix compositions and content and other factors, the main natural gas exploration strata Shan 2 Group and He 8 Group was conducted comprehensive assessment. there are four categories in the deferent areas of Ordos Basin, which are Ⅰ$_A$, Ⅰ$_B$, Ⅱ, Ⅲ from good to bad in turn(Figure 1).
After discussed the controlling mechanism of Ⅰ$_A$, Ⅰ$_B$ class of high-quality reservoirs in Upper Paleozoic of Ordos Basin from depositional environment, diagenesis and tectonic, the following understandings are achieved:
① sedimentary sources control the distribution of Lithofacies. Yulin and Sulige large gas fields whose main producing formation of Shan 2 Group and He 8 Group belong to depositional system controlled by the west sedimentary source of Hangjinqi, where quartz sandstone or quartz sandstone is widely distributed. Because it has single detrital components, mainly quartz, silica component, the late realability under pressure, diagenesis obvious transformation of the original pores, which become pure quartz sandstone rocks tight sandstone gas in the "sweet spot" (Figure 2).
②palaeogeomorphology controls the overall distribution of sedimentary facies. In Shan 2 Group of the eastern Ordos Basin, high-energy fluvial system controlled by the local ancient landscape, the distribution of main river phase with coarse sand is consistent with low palaeogeomorphology Distribution. Exploration results also confirm that Yulin and Zizhou gas fields are located in the strong water power along the distribution of the direction of the main river.
③ post-dissolution of the reservoir by organic acids plays an important role in holes and is the key factor for sandstone occurrence of relatively high quality reservoir under deep, high-evolutionary conditions (depth 3500 m below the rate of organic matter, vitrinite reflectance of 1.5% ~ 4%) . In addition, diagenetic micro-fractures on improving the physical properties of the reservoir plays a more important role.
④ tectonic plays two roles for the reservoir. First, the source area uplift makes continuously increasing sediment supplies, morever, sedimentary sand particle size, thickness and size distribution was significantly increased. Second, the tectonic movement controls the maximum burial depth of different tectonic units in the basin. The eastern region of Ordos basin has been in a tilt with maximum depth being less than 3000m, compaction is relatively weak, more primary porosity has been saved, so physical properties of reservoir is better (Figure 3).
The main controlling factors of relatively good quality reservoir ("sweet point") in tight sandstone are systematically analyzed and the distribution of relatively good quality reservoir are revealed in the study. It has a forward-looking guidance to find the same type of "sweet"area in the exploration of this kind of basin.

Key words: tight sandstone, sweet point, controlling factors, distribution, Ordos Basin.

Architecture characteristics and fine-grained sedimentary model in lacustrine sand bank reservoirs

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Lacustrine sand bank deposits with high net-to-gross sand ratios are commonly attractive reservoirs, yet internal lithologic heterogeneities, particularly the presence of low-permeability mudstone deposits, significantly complicate the development of such units. Previous work has focused on measuring the scale and distribution of sand bank deposits in outcrop analogs; however, because of extreme differences in scale, gritty consistence, grain size, and geologic history, the results of these studies are difficult to apply with confidence to a wide range of lacustrine sand bank reservoirs. Based on work in modern lakes (Qinghai Lake, Qinghai and Daihai Lake, Inner Mongolia) and ancient lacustrine sand bank deposits (Shahejie Formation, Paleogene, Bohai Bay Basin), we deal with the identification marks, spatial distribution and hierarchical system of internal architecture of sand bank, and finally propose a process-based conceptual model for understanding and predicting the distribution and geometries of fine-grained (mudstone) intervals in lacustrine sand bank deposits. This model is an idealized depositional unit composed of three hierarchies sandy deposits (compound sand bank, individual bank, inner accretion of individual bank) and five fine-grained lithofacies (semideep or deep lake facies mudstone, surface heterolithic strata, behind bank mud, retention mud-gravel, and interbank inclined mud).

Sandy deposits:

- compound sand bank (the fifth-order architecture unit)
- individual bank (the fourth-order architecture unit)
- inner accretion of individual bank (the third-order architecture unit)

Mudstone deposits:

- semideep or deep lake facies mudstone (the fifth-order architecture interface)
- surface heterolithic strata caused by deleveling (the fourth-order interface)
- behind bank mud (the fourth-order architecture interface)
- retention mud-gravel drawn by storm (the fourth-order interface)
- muddy interlayer deposited low wave energy (the third-order interface)

With 6 recognition marks of individual bank including the sedimentary characteristics, logs and number of interlayer summarized from sand bank reservoir, we divide bank into several sand bodies (individual bank), and analyze the mudstone (the fourth-order architecture interface) dimension between them. The further research is to define the distribution in space of the third-order architecture interface through anatomizing modern sand banks. We find that the muddy interlayers with thickness about 0.1~1m are nearly horizontal close lakeshore and inclined in low angle towards the center of the lake (the inclination is about 2°~5°), and the scale proportional to sand bank dimensions, including thickness, cross-shore width, and along-shore length.

Within lacustrine sand bank deposits, extrinsic depositional factors, such as wave energy, available accommodation, and tectonic movement, produce different sand bank stacking or migrating arrangements, preserving fine-grained lithofacies in different, relative proportions. Each lithofacies is found in a different region in an individual sand bank. The relative position and distribution pattern of each lithofacies reflects the order of deposition in a sand bank, and we can also predict the scale and morphology of sand bank rely on that. This conceptual model provides an approach to reservoir characterization that deductively constrains the dimensions and distribution of fine-grained barriers to flow and may help account for the inherent variability in lacustrine sand bank deposits.

Discussion on Deposition-Diagenesis Genetic Mechanism and hot issues of Tight Sandstone Reservoir

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Tight sandstone gas and shale gas are currently two major unconventional hydrocarbon resources, which will be the significant resources for replacing conventional oil and gas in next 10 to 30 years. No matter from the understanding of geological property, or the technology of exploration and development, the former one has more reality than the later one in the next 10 years. However, accurate prediction of favorable reservoir space has become a bottleneck for current tight sandstone gas exploration and development. Clarifying the deposition-diagenesis genetic mechanism of tight sandstone reservoir is the key to solve this problem. According to the research on the typical tight sandstone gas fields in China and data analysis abroad, tight sandstone generally deposited under weak hydrodynamic stability and relatively slow depositional rate that much developed in coal-bearing (thin bed interbedded) strata of the transitional environments or deltas. Hence, these depositional mechanisms facilitate the requirement of forming tight sandstone. Continuous compaction during early diagenetic stage was the main process for their tight nature. The complex burial history under low geothermal gradients which were caused by multi-cycle movements of basin is the sufficient condition for forming tight sandstone reservoirs. Therefore, abnormal pressure zones in multi-cycle pre-Tertiary basins with low geothermal are the favorable area for exploring tight sandstone gas. The sandstones with thin interbedded coal-bearing strata in delta front are primary exploration and development intervals. Heterogeneity characteristics of tight sandstone should play a role on reservoir exploring and evaluating. The microscopic pore structure change on the effect of permeability, irreducible water saturation and abnormal pressure data should be studied for evaluating pay reservoirs property.

Evolution and Distribution of Sedimentary Facies of the Upper Fourth Member of Shahejie Formation of Bonan-luojia Area in Zhanhua Sag

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Continental fault basins have multi-directional sources of sediment supply and multi-type distribution of sedimentary facies. Due to their special fault-development and tectonic pattern the topography includes depressions and embossments distributed alternately. Multi-type rocks including sandstone, mudstone, conglomerate, carbonatite, salt-gypsum and mixed sedimentary rocks were deposited in the Bonan-luojia area in Zhanhua sag. The source of sediment supply, relative slope, transport distance, water depth and fault dominant planar sedimentary distribution are typical of a continental fault basin. Results of sequence stratigraphy, sedimentary petrology and sedimentary dynamics reveal the evolution and distribution of sedimentary facies of the upper fourth members of the Shahejie Formation (can be divided to three system tracts from the bottom) of Bonan-luojia area in Zhanhua sag, integrating seismic data, logging, well-logs, statistics of particle sizes and core data. Main studied processes include: a) ascertaining source direction through data statistics of particle size, composition of lithic fragments, heavy mineral, etc.; b) recognizing sedimentary microfacies through observation of core and log data; c) determination of a sedimentary model through petrographic analysis of east-west and north-south well profiles; d) resolving planar distribution characteristics of depositional elements through isopachous maps of sandstones and isopleth maps of sandstone content; e) reconstruction of lake level fluctuations and sequence evolution through sedimentary analysis.

The uppermost fourth member of Shahejie Formation is a third-order depositional sequence unit which includes lowstand system tract (LST), transgressive system tract (TST) and highstand system tract (HST), but is lack of falling-stage systems tract (FSST). Corresponding parasequence sets are weak retrogradation of sand-mudstone, aggradation of sand-mudstone and aggradation-progradation of mudstone-gypsum rock. From the lower to the upper fourth member of the Shahejie Formation, the red sediments indicative of a dry environment become gray indicating more humid conditions and thus rising lake level. Lake-level initially ended at Bonan fault, accompanied with the development of fault on the initial depositional stage and subsequently extended to the south of the Chenjiazhuang salient in later period of depositional stage of the fourth member of Shahejie Formation. The LST ending at the Bonan fault was composed of sediments of a fan delta front which was from east and northeast source direction. TST and HST distributed around the whole study area. TST group was composed of beach bar in midwest area and sediments of fan delta front which was from east, northeast, south, southeast source direction. HST was composed of gentle slope fan delta and lacustrine carbonates in the south and southeast, thick mudstone-gypsum unit in the center and a thick glutenite in the steep north slope.

Depositional history of the Upper Oligocene strata in the Baiyun Sag, northern South China Sea margin

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The depositional system of the Upper Oligocene strata (25.5Ma to 23.8Ma, referred hereafter as ZHSQ6) in the Baiyun sag, along the northern South China Sea margin, has caused intensive interest but is as yet little known. Using conventional cores, 3-D seismic data and amplitude attribute slice maps over approximately 2500 km^2, nine seismic facies were incorporated into five major depositional environments or systems, from shelf margins to continental slope. These nine seismic facies are identified based on the internal configuration and texture, external shape and termination relationships of the seismic reflections. Depositional systems include delta, clinoform, mixed carbonate-siliciclastic system, deep-marine system and restricted platform. Clinoforms are characteristiced by sigmoidal and oblique tangential foreset geometries reflections. Representative seismic reflections of mass transport deposits (MTDs), channel-levee complex and lobes are identified in deep-marine systems. ZHSQ6 is mainly located in the clastic environment, whereas mixed carbonate- siliciclastic deposits, controlled by tectonic events of the Dongsha uplift, developed in the northern study area. Moreover, carbonate platform deposited in the southeast regionally. ZHSQ6 is controlled by sediment flux, shelf width and gradient and relative sea-level behavior. Lowstand systems and forced regressive tracts consist mainly of shelf-margin deltas, gullies and channel- levee complexes. Highstand systems tracts, in contrast, contain mid shelf deltas, longshore drifts, mixed carbonate-siliciclastic systems and MTDs. A long-lived sand-rich delta lacks the thick coeval prodeltaic shales, which is characterized by progradational clinoforms. Results from the current study indicate that shelf margin delta and longshore drift, together with the slope-fan reservoirs, represent the most favorable reservoirs for drilling. Our results therefore are great significance for hydrocarbon exploration along the northern South China Sea margin.

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Keywords: the Northern South China Sea margin, Late Oligocene, depositional system, depositional history

Deepwater Depositional Architecture and Evolution of the Northeast Bay of Bengal (Offshore Northwest Myanmar)

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Since the discovery of the Pliocene turbidites and the commercial Shwe gas field in offshore northwest Myanmar in 2004, the northeast Bay of Bengal has attracted extensive attention of petroleum geologists. In our research high-resolution 2-D and 3-D seismic data, acquired by CNPC from 2008 to 2013 in offshore northwest Myanmar, were analyzed to study the depositional architecture, evolution and reservoir potential of the northeast Bay of Bengal.

The analysis of seismic facies and seismic attributes indicates that the Miocene– Pleistocene deepwater architectural elements in the study area mainly include canyons, confined channel complexes, aggradational channel-levee complexes, individual channels, depositional lobes (i.e. sheet sands), mass-transport complexes, and hemipelagic drape complexes, which range in character from slope facies to basin-floor facies. Furthermore, confined channel complexes can be subdivided into entrenched channel complexes and offset stacked channel complexes according to their inner structure. And individual channels can also be subdivided into straight channels and sinuous channels according to their outer morphology. These architectural features reflect a combination of active (sediment input from channel systems) and relatively passive (slope failures and slumps) sediment supply systems in the study area.

The investigation of depositional evolution suggests that the northeast Bay of Bengal experienced rapid progradation during the Miocene-Early Pliocene and gradual retrogradation during the Early Pliocene-Pleistocene. During the Miocene-Early Pliocene, deepwater architectural elements changed from hemipelagic drape complexes to confined channel complexes, channel-levee complexes, and sheets because of rapid progradation of the sediments. And then, these elements gradually evolved into smaller channel complexes, channel-levee systems, and hemipelagic drape complexes during the Early Pliocene-Pleistocene because of gradual retrogradation of the sediments.

Exploration results in adjacent blocks indicate that main reservoirs of the discoveries are the Pliocene depositional lobes (sheet sands) and channel-levee-overbank sediments. In our study area, the analytic results of seismic facies, seismic attributes and acoustic impedance inversion indicate that channel complexes, depositional lobes and individual channels are probably sand-rich facies. And probable sandy levees are also recognized. Controlled by the depositional evolution, the Early Pliocene channel complexes and depositional lobes have the best reservoir potential in the study area.

Late Cenozoic tectonic deformation in the northeastern Tibetan Plateau: evidence from sedimentology of the Yangqu basin

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Over the past two decades, studies on uplift and tectonic deformation processes of the northeastern Tibetan Plateau have become a hot topic. A series of tectonic deformation and mountain building occurred in the northeastern Tibetan Plateau, responding to the far–field effects of the India–Asia collision at ca. 50–55 Ma. The deformation is characterized by a number of large intracontinental basins including the Qaidam, Qinghai Lake, Gonghe–Guide and Longzhong basins, exhibitting a unique basin–range geomorphology. However, the timing of deformation and uplift, which are crucial to understanding the machanics of how and when the plateau has grown in time, are still under debate. Some studies suggest that the uplift occurred in the Pliocene–Quaternary. Others indicate that the timing of uplift is much earlier, in the middle and the late Miocene. Accordingly, the late Cenozoic tectonic deformation history is rather complicated in the northeastern Tibetan Plateau.

As a part of the “basin–range” coupling hypothesis, the temporal evolution of the Yangqu Basin (located in the southern margin of the Gonghe Basin) directly reflects the formation and development of the northeastern Tibetan Plateau.

Magnetostratigraphy provides an age of ~20–7 Ma for the sedimentary rocks in the Yangqu Basin. In our study, syntectonic growth strata, sedimentary accumulation rates, and changes in paleocurrents of late Cenozoic sediments within the Yangqu Basin provide new insights into the timing and character of the tectonic deformation in the northeastern Tibetan plateau.

In the early stages of basin formation, the accumulation rate is near 333 m/Myr, accompanied by the intermittent conglomerates deposition, is a consequence of activity on the eastern Kunlun fault. Furthermore, the angular unconformity and N–to–NNW oriented paleocurrents observed in lower section indicate the prominent uplift of the eastern Kunlun Shan at ~20 Ma.

Using field observations and magnetostratigraphic results, we realize that the growth strata formed at ~16 Ma, with a change of strata dip angles from averagely 35° to 20°, when the paleocurrents changed from N–to–NNW to S–to–SSE and accumulation rates increased to 147 m/Myr. Considering this, we infer that the Ela Shan, located approximately 60 km west of our study area, has experienced rapid uplift, erosion, and subsequently provided material sources for the Yangqu basin.

Strata dip angles become gentler after 12 Ma, turning to 0° by ~7 Ma at the top of the section, accompanied by a change in paleocurrent from S–to–SSE to N–to–NNE. Furthermore, these strata exhibit significant acceleration in accumulation rates as well as coarsening upwards, suggesting that sediments exposed along the Yangqu section were subjected to synsedimentary deformation. This closely relates to the emergence of the Gonghe Nan Shan at 12–7 Ma.

Based on our results together with tectonic deformation data in the northeastern Tibetan Plateau archived by other authors, we suggest that the northeastern Tibetan Plateau has undergone at least three phases of protracted tectonic deformation during the late Cenozoic: at ~20 Ma, 17–15 Ma, and 12–7 Ma.

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Characteristics and forming mechanisms of soft sediment deformation structures—Examples from the Pearl River Mouth Basin, South China Sea

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Soft sediment deformation structures (SSDS) in the Pearl River Mouth Basin in the north of the South China Sea were studied using cores and seismic data. They include deformed cross-bedding, large-scale folds, load structures, water-escape structures, clastic dykes, vertical fractures seen in cores, and sandstone injectite volcanoes, polygon faults, mud diapir volcanoes and gas chimneys seen in seismics. Deformed cross-bedding, faults and vertical fractures prevail in the delta plain, and load structures, large-scale folds, columnar structures, and clastic dykes occur in the front of the shelf margin delta. Mound and wing-like intrusions show a strong amplitude reflection in seismic profiles. Vague, large mud diapers in combination with polygon faults and gas chimneys are surrounded by bright areas in the seismic lines.

In an experimental setup the forming mechanisms of SSDS in the study area were studied, using a set of devices with 16 accessories. 8 experiment runs examined the influence of the three main variables important for the structures formed during fluidization: (i) the thickness of the overlying coarse sediment layer; (ii) the configuration of the inlet pipes; and (iii) slope angle. A thin overlying layer and a large water supply were liable to form sand volcanoes.

The process of SSDS formation shows five stages: (i) fluids start to flow, pressure increases with no obvious change in the strata; (ii) As the fluid pressure increases, the effective stress becomes tensile enough to cause failure beneath the uppermost sealing layer, forming an isolated water-filled laccolith in the contact surface; (iii) the void increases in volume; (iv) the effective stress become tensile enough to produce a conical network of barren hydraulic fractures in the top of the sealing layer; (v) the overpressure gradient becomes high enough to fluidize the lowermost sand, which fills fractures and the laccolith, and extrudes at surface. Overpressure appears the most important condition for the formation of SSDS. In the experiments, compaction disequilibrium, tectonic compression, hydrocarbon generation and hydrocarbon cracking, hydrothermal pressurization, and diagenetic reactions worked together to produce overpressure in the sedimentary basins.

Five SSDS subtypes were identified from vertical slices made after the sediment had been frozen. The statistical data show that the average deformed area was 1%, with a maximum of 5.58% in the horizon, and those values in vertical were 7.72% and 29.59%, respectively. These statistical parameters are comparable to those measured from the cores. And their shapes are much similar. So the simulated results can be good references.

The SSDS found in the Huizhou-Xijiang Sag and the Baiyun Sag have a different geological background. Thus the controlling factors may be different. The forming mechanisms in the Zhu I Depression might be wave-tide action and tectonic movements, while the overpressure in the Baiyun Sag could be the result of the combined influence of differential compaction, tectonic movements and hydrocarbons injected by tectonic movements. Triggering by earthquakes, moreover seems an important element.

The significance of SSDS for oil and gas in the Pearl River Mouth Basin was analysed by studying the actual drilling and seismic reflection characteristics. Sand injcetites in the study area may be favourable reservoirs, and gas chimney, mud diaper and polygon faults could be subsidiary for the structural faults for the migration of oil and gas but they also may lead to escape.

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