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RESEARCH PAPER

Slope belt types and hydrocarbon migration and accumulation mechanisms in rift basins

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Abstract: Based on the classification of slope belts in rift basins, this paper discusses hydrocarbon accumulation characteristics and accumulation mechanisms for different slopes. The slopes in the Jizhong and Huanghua depressions in the Bohai Bay Basin are classified into five types: flexure slope break, gentle platform slope, wide terrace faulted slope, narrow-steep terrace faulted slope and tilting slope in terms of pre-Tertiary sedimentation, tectonic activities, occurrence and geometric configuration. Each individual slope shows various hydrocarbon accumulation characteristics and enrichment extent caused by different accumulation mechanisms. The flexure slope break is characteristic of the terrace fault type of hydrocarbon accumulation with the highest level of hydrocarbon enrichment. In contrast, gentle platform slope, wide terrace faulted slope and narrow-steep terrace faulted slope are characterized by medium enrichment with a near-source linear shape, far-source stair shape and fault zone multiple hydrocarbon accumulations separately. However, the tilting slope shows relatively low hydrocarbon enrichment. The main hydrocarbon accumulation controlling factors include nose structure, sandstone development degree, sand body with favorable petrophysical properties and juxtaposition thickness. Nose structures control hydrocarbon convergence directions, sandstone development degree controls lateral hydrocarbon migration, sand bodies control lateral hydrocarbon diversion, and juxtaposition thickness controls vertical hydrocarbon migration.

Key words: rift basin; slope belt; hydrocarbon migration; migration pathway system; hydrocarbon accumulation characteristics; Bohai Bay basin; Jizhong Depression; Huanghua Depression

Introduction

Most sags in rift basins are asymmetric "half graben-like structures" with the fault on one side and onlapping on the other, and can be subdivided into the trough region and slope belt with the latter making up about 50% of a sag area and is one of the major directions of hydrocarbon migration. In the 12th World Petroleum Congress in 1987, it was proposed for the first time that the composite hydrocarbon accumulation slope belt has a high hydrocarbon potential. In the 1990s, the exploration in the slope belts in the Bohai Bay Basin achieved major breakthroughs, successively finding many structural oil and gas pools (fields) mainly in fault nose and fault block traps in the western slope of the Liaohe Depression, the southern slope of the Dongying Sag in the Jiyang Depression, the Wen'an slope and Lixian slope in the Jizhong Depression, etc., with total in place reserves of about 15×10^8 t[1]. The slope belts have conditions for forming structural oil and gas pools, and also have favorable conditions for forming nonstructural oil and gas pools (stratigraphic, lithologic and structural-lithologic etc.); particularly, the latter have become the major targets for discovering large-scale reserves in the re-exploration program in oil-rich sags[2–3]. The end and edge of the migration pathway systems, which are composed of sandbodies, faults and unconformities, are usually the major directions of hydrocarbon migration[4]. Slope-break belts, nose structures and lithologic pinchout belts on slopes are the favorable sites for hydrocarbon accumulation[5–7]. These findings have effectively guided hydrocarbon exploration in slope belts, but different types of slope belts differ widely in hydrocarbon enrichment degree. Based on subsidence, strength of tectonic activity and occurrence of slope belts, the types of slope belts have been re-classified once again, by analyzing hydrocarbon accumulation differences in various slope belts, the relationships between hydrocarbon migration and accumulation mechanisms and accumulation features have been investigated in

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this study, in the hope to further improve the theory of hydrocarbon accumulation in the slope belts.

1. Classification of slope belt types

The slope belt in a rift basin largely refers to the transition zone from the deep sag to the uplift. They mainly take the forms of onlapping and eroded monoclinal zones between the slopes and uplifts, with edges often tilting and eroded in later period, and the eroded belts in various widths covered by younger deposits[8]. There are numerous studies on the classification of slope belt types, for instance, Wang Haichao et al.[1] classified slope belts into three types (successive type, concave slope type and platform slope type) according to their stratigraphic stacking patterns, and further divided the successive slope into two types (successive onlapping style and successive onlapping-eroding style); Li Pilong[9] divided slope belts into three types (broad type, narrow-steep type and binary type) according to their form and structural features.

Based on the study results of previous researchers[8–12], we have analyzed the slope belts in several sags in the Jizhong Depression and Huanghua Depression in the Bohai Bay Basin, and classified them into five types (bending slope-break type, gentle platform-slope type, broad fault-terrace type, narrow-steep fault-terrace type, and tilting type) (Table 1), according to the faulting intensity and slope occurrence.

2. Hydrocarbon accumulation in various slope belts

The slope belt is the major direction of long-term hydrocarbon migration and accumulation in rifts, with various hydrocarbon enriching mechanisms and hydrocarbon pool types. The different forming mechanisms of various types of slope belts determine that different types of slope belts differ in oil and gas accumulation characteristics too.

2.1. Bending slope-break slope

One of the typical bending slope-break slopes is the Qibei slope in the Qikou Sag, with hydrocarbon accumulation characteristics of slope-break terrace and highest hydrocarbon enriching degree (Figs. 1 and 2). Situated in the central-west in the Qikou Sag, 58 km long, 14–25 km wide, with an area of about 1 000 km^2, the slope is an east-dipping large slope bound by two large-scale regional faults on the Kongdian Uplift dipping to the main Qikou Sag in the Huanghua Depression. Its formation was controlled jointly by three tectonic activities: gradual rise of the ancient uplift, continuous subsiding of the sag, and successive development of the boundary faults. As the boundary faults had weaker activity, the subsiding profile formed had a small slope gradient and the potential energy difference between the provenance and the water catchment area was small, so deposits of braided river delta front facies with relatively finer grains were developed on the gentle slope at the high position of the bending slope-break belt, and deposits of distal slump turbidite facies were developed at the low position of the slope-break belt. Controlled by both tectonic framework and sandbody distribution, there are mainly lithologic hydrocarbon pools with updip pinchout trap style in the high position of the slope-break belt, and lithologic hydrocarbon pools with updip pinchout trap style and sand lens in the trough area.

The Qibei slope is one of the most important enriching positions for lithological oil and gas pools in the Qikou Sag[13]; the Qibei sub-sag and the major Qikou Sag are both important hydrocarbon generation regions, with plentiful hydrocarbon resources. Hydrocarbons migrated and accumulated along slope belts in three ways (proximal, inside source and lateral, proximal and vertical), forming two types (self-sourcing reservoir, adjacent-charging reservoir) of oil and gas pools; moreover, hydrocarbons can be vertically adjusted by some faults in the slope belt to form oil and gas pools of lower-source and upper-reservoir stacking pattern. Finally, hydrocarbons can accumulate within the source rock or the proximal regions in deeper sags of the slope, and in distal regions in higher locations of the slope, forming a hydrocarbon distribution pattern of slope-wide oil-bearing and composite accumulation. The slope-break zone with a higher slope gradient changes has a higher hydrocarbon enriching degree.

Currently, the Paleogene in the Qibei slope hosts 1.8×10^8 t proved in place oil reserves and 84.31×10^8 m^3 proved in place gas reserves; while the oil and gas pools controlled by bending slope-break belt contain 1.3×10^8 t of proved in place oil reserves and 84.31×10^8 m^3 of proved in place gas reserves, accounting for 72.2% and 100% of the total proved in place oil and gas reserves of the slope, respectively. Most of the oil and gas pools have lithological type styles, oil pools are mainly confined to the 1st member of Paleogene Shahejie Formation (Es1) and the Dongying Formation (Ed), while gas pools are mainly distributed in the 2nd (Es2) and 3rd (Es3) members of the Shahejie Formation.

The oil and gas pools in this slope have accumulation features of "two-episode charging, differential accumulation, oil in higher position and gas in lower position"[11]. At the end of the deposition of the Dongying Formation, most of the 3rd member of the Shahejie Formation (Es3) was at hydrocarbon generation peak, leading to the first episode of oil and gas charging that was dominated by oil. During the deposition of the Neogene Minghuazhen Formation (Nm), most source rocks in Es3 entered gas generation threshold, giving rise to the second episode of oil and gas charging that was dominated by gas, that was the major hydrocarbon accumulation period for oil and gas pools in the Qibei slope[14].

2.2. Gentle platform slope

One of the typical gentle platform-slope type slopes is the Lixian slope in the western Raoyang Sag of the Jizhong Depression, where the hydrocarbon accumulation is characterized by proximal hydrocarbon accumulation in "line" style, and higher hydrocarbon enriching degree (Fig. 3). The Lixian slope is a NE-striking Paleogene-Neogene slope that was uplifted in the west and dips to the east, with a formation dip