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Seismic Interpretation of Growth Fault and Salt Diapirism in Qianjiang Sag, Jianghan Basin, Southeastern China

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Abstract: Qianjiang depression is one of the most faulted lacustrine depressions in Southeastern China. This study considered the main faulting influencing the different sedimentary rocks, the causes of this faulting and the relationship of faulting to salt diapirism. To satisfy our research needs, we used 3D seismic data, where 4 seismic section profiles were chosen. Northeastward salt domes aligning along the depression center showed evidence of active diapirism and a normal growth fault has been continually active at least since, the middle Eocene. This steep fault extended deeply to a strong reflection event that may represent the base of the salt layer. We inferred that faulting is caused by basinward flow of salt from the deep part of the depression into domes, there by creating a great difference in hydrostatic pressure between the upthrown (uplifted area) and the downthrown (depression area) sides of the fault and by removing support for the over lying block of sedimentary rocks.

Key words: Lacustrine, sedimentary rocks, diapirism, salt domes, growth fault, hydrostatic pressure

INTRODUCTION

Qianjiang depression is one of the most lacustrine petroliferous depressions in Eastern China, with an area of 2500 km^2 (Chen, 2003a). The Northeast trending fault limiting the depression both in North and South by Qianbei fault and Ton Haikou fault, respectively, gave depression the special elongated angled 135°E wedge shape (Fig. 1). The wedge shape (steep North Slope and gentle South slope) allowed great thickness of salt-bearing strata and oil-source rocks to accumulate (Chen *et al*., 2007). The maximum thickness of salt is 1800 m. The Qianbei fault which bounds much of the northern part of Qianjiang depression is the most developed and extends for >120 km^2 (Fang, 2002).

Several geologic studies have been done in the area among them; Holly *et al*. (1989) reported that oil and gas fields; Kenneth *et al*. (1996) has studied the petroleum systems; followed by the research of Kliti *et al*. (1998) about the molecular isotopic characterization of hydrocarbon biomarkers in Paleocene-Eocene evaporitic lacustrine source rock (Fang, 2006). Treated the hydrocarbon exploration significance of intersalt sediments; where Chen (2003b) reported that the classification of sequence Stratigraphy. Fang (2006) research, covered the main controlling factors and exploration direction of subtle oil reservoirs, as well as the discussion of magnetic enhancement caused by hydrocarbon migration in the Mawangmiao oilfield (Qing *et al*., 2006).

Although, those researches have so far been done, but no such tectonic work has yet been done in the proposed site. In this study, we attempt to determine the main faulting affecting the area, the causes of this faulting and the relationship of faulting to salt diapirism.

Geological setting: Jianghan basin is located in the southern part of Hubei province (Southeastern China), with an area of 28.000 km^2. It is a Mesozoic to Cenozoic basin that developed after the Yanshanian structural movement into multiple faults (Northeast trending fault and Northwest trending fault), 4 swells and 6 sags, among these sags Qianjiang sag (our study area) is the most important salty sediments, specially structured oilfield in the basin (Fang, 2002).

Qianjiang depression is located in the central part of Jianghan basin, limited in the north by Qianbei fault, in the south by Ton Haikou fault, in the northeast part by

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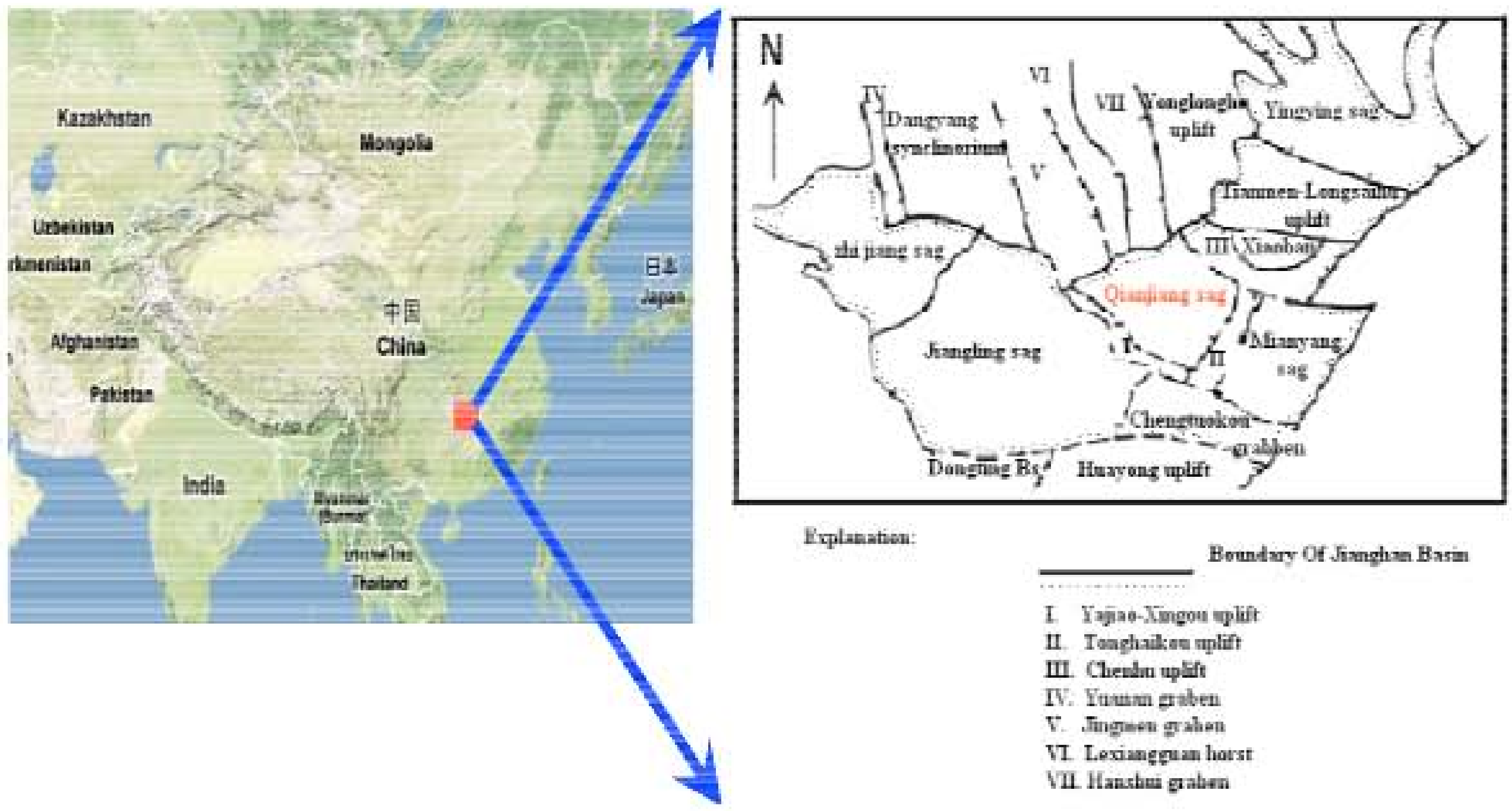
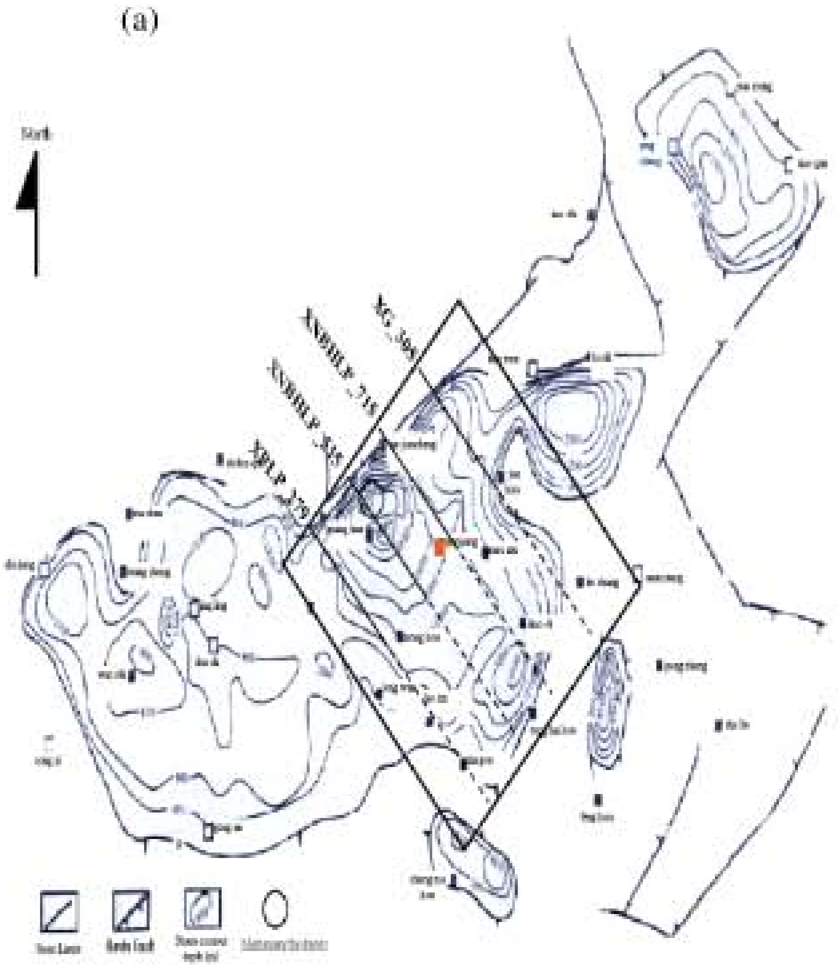


Fig. 1: Geographic settings of the study area (a) sketch of structural division of Jianghan basin (b) and emphasizing Qianjiang depression (red color)

(a)



(b)

Table 1. Stratigraphic Column of Jianghan Basin.

Stratigraphic Sequence						Lithologic Character	Thickness (m)	A*	B	C
System	Series		Formation	Member						
Quaternary	Holocene Pleistocene		Plain			Grey clay, silt, fine-grained sand, gravel beds	50-150			
Neogene	Pliocene Miocene		Guanghuasi			Mottled mudstone with intercalated sandstone and conglomerate	300-900			
Eogene	Oligocene	Upper and Middle	Jinghezhen			Dark-gray mudstone and siltstone with intercalated oil shale and glauberite-bearing mudstone	0-1000			
		Lower	Qianjiang	1	Upper	Referred to as "mud-gypsum layer": consists of gray to dark-gray mudstone, gypsum-mudstone, oil shale with interbedded salt	120-450	II	II	II
					Middle	Intercalation of gray mudstone and siltstone				
					Lower	Intercalation of gypsum, salt, sandstone and mudstone, with some oolitic marlite				
	Eocene	Upper		2		Consists of 20 rhythmic units, each composed of salt, gypsum-mudstone, glauberite mudstone, oil-bearing mudstone, marlite; occasionally, silty fine-grained sandstone occurs at the bottoms of the units	110-700			
				3	Upper	Gray to dark-gray mudstone, siltstone and oolitic marlite; three rhythmic units and two salses of mudstone	150-640			
					Lower	Consists of 10 rhythmic units, each composed of dark-gray mudstone, gypsum-mudstone and salt, with some silty fine-grained sandstone				
				4	Upper	Gray and dark gray mudstone, glauberite-mudstone, salt, oil-bearing mudstone and silty fine-grained sandstone	100-700			
					Lower	Gray and dark-gray mudstone, glauberite-mudstone, salt, oil-bearing mudstone	175-2218			
		Middle	Jingsha			Brown-purple-red mudstone, gypsum-bearing mudstone and siltstone	600-1000			
		Lower	Xingouzui			Purple-red and gray-green mudstone, mud-gypsum, gypsum-bearing siltstone, oil-bearing mudstone	600-2000	I		
	Paleocene		Shashi			Dark-gray and brown-red mudstone, gypsum, gypsum-bearing mudstone, siltstone	200-1900		I	I
Cretaceous	Upper					Brown-purple-red mudstone, mud-gypsum, salt, siltstone, gypsum, red sandy mudstone with intercalated conglomerate	1200-2800			
	Lower									

* A: Oil-bearing rock series B: Salt-bearing rock series C: Cycle of sedimentation

Fig. 2: Qianjiang depression (black square) sediments thickness (a) Stratigraphic column of Jianghan basin (b) emphasizing Qianjiang sag stratigraphy (blue line)

Chenhu uplift and in the Southwest part by Jiangling depression (Holly *et al*., 1989) (Fig. 1). It was formed between early Cretaceous and Oligocene time by 2 sets of structural lines (early Cretaceous to early Eocene time set and middle Eocene to Oligocene time set); every set underwent a development process from faulted-depression to depression stage (Owoyemi and Brian, 2006). Particularly, from late Eocene to Oligocene time (2nd set), the northeast trending faults were best developed under the influence of the westward plunging of the pacific plate, the Qianbei fault moved violently and many other faults, which were also activated at that time helped to determine the faulted-depression nature of the sag (Gerald, 2007).

Stratigraphy: Basically, it is a stratigraphically complex unit formed of deltaic and mostly lacustrine deposits, thus, the stratigraphic sequence shows apparent rhythmic characteristics that reflect alternating fresh and saline water depositional environments (Chen, 2003b). Cyclothems composed either of intercalations of mudstones and salt or mudstones and sandstones and salt were formed (Chen *et al*., 2007), consequently created a series of complete combinations of source, reservoir and cap rocks throughout the depression (Fig. 2).

Qianjiang depression is controlled by Qianbei fault in the North part and Tong Haikou fault in the South part.

It is a succession of sediment supply for a long time, which occurred between late Eocene to lower Oligocene time, where the sediments in the north part are deeper about 4000 m than in the South part ounces about 1600-2000 m (Fig. 2). The sedimentation rate is fast (0.32 mm) can be reached every year (Holly *et al*., 1989).

Qianjiang Sag can be divided into for members (Q^1, Q^2, Q^3 and Q^{4up} and Q^{4low}). Respectively, Q^1-Q^2 belong to the shallow lake sediments where some places were buried deeply, but generally the bottom is shallow, thus, the transformation conditions of organic matter is not available (Glenn, 1984). Q^3-$Q^{4up, low}$ was deeply buried, the thickness is very big and transformation conditions of organic matter are favorable. Thus, they are the main source rocks in the depression (Sangree and Widmier, 1971).

MATERIALS AND METHODS

To examine the tectonic structure that effects the Qianjiang depression, we consider 4 adjacent multichannel seismic lines (average spacing of 4 km): XG_305, XNBHLP_715, XNBHLP_515 and XPLP_279 (Fig. 2). These 4 profiles cross the peripheral parts and the central part of the sag. We consider also 2 well logs, which are available: Guang 4-11, which crosses the profile XNBHLP_515 and Zhang 25, which crosses the profile XG_305. Published surface geologic maps and reports, which used in the structural analysis include the 1:2,000,000 and 1:500,000 geologic map of Hubei province, which provided regional outcrop patterns for faults, salts domes and bed orientations.

RESULTS AND DISCUSSION

Seismic profile XG_305: Profile XG_305 shows an incomplete crossing of the peripheral northeast of depression. It is presented in Fig. 3a and its interpretation is shown in Fig. 3b. We interpret that an angular unconformity giving fall to diffractions, dips to the

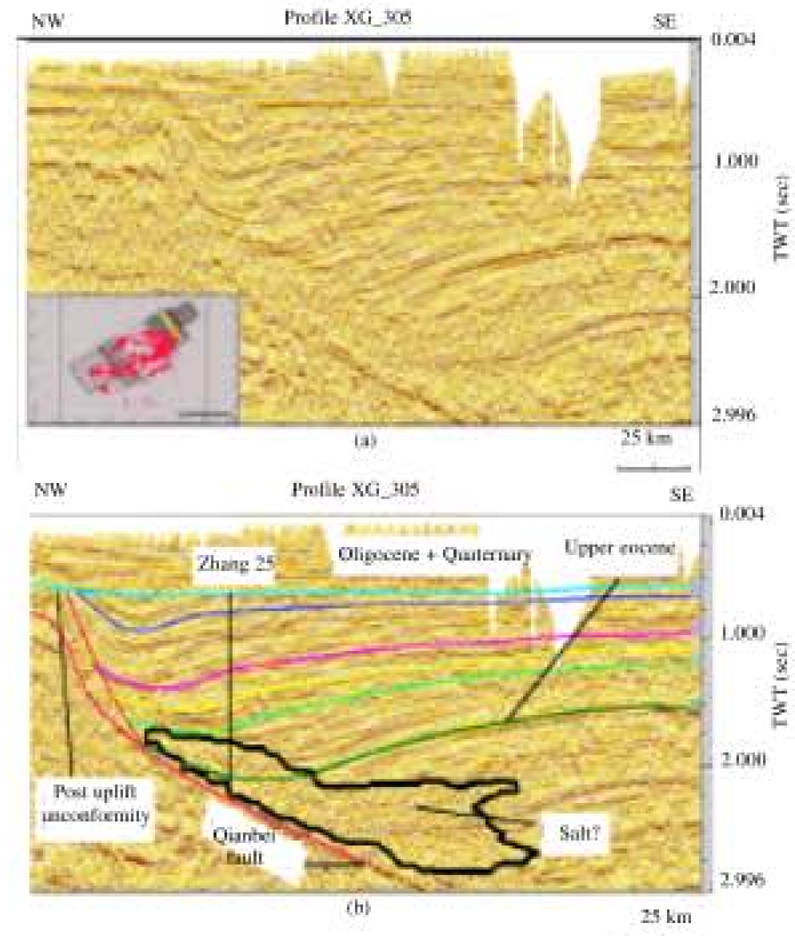


Fig. 3: Seismic line XG_305 that crosses the northeast part of Qianjiang depression. Profile location is shown in the base-map (A: down left corner). All data were collected by Jianghan oilfield company SYNOPEC. TWT indicates 2 way time in seconds and it's the same in all coming profiles

Southeast on the left side of the profile segment and extends up a set of very strong incline-subhorizontal reflections at 0.7 and 2 sec (Michael, 1985).

The unconformity is considered to be a post uplift unconformity and the strong subhorizontal reflections are considered to arise from salt and may be also arise from sandstone and mudstone as well logs indicates (Holly *et al*., 1989). The post uplift unconformity originally was defined as forming by short erosion during the thermal uplift and extension stage of the basin in early middle Eocene (Owoyemi and Brian, 2006).

One fault is indicated in Fig. 3, located on the left part of the profile, which called Qianbei fault. This fault is observable in many profiles and its near-surface location is mapped in Fig. 1. Fault throw increases fairly smoothly as depth increases, indicating that the fault was active during sediment deposition. We believe that the fault should be termed a growth fault (Ocamb, 1961; Fran and George, 1961; Janok and Russel, 2001; Brita *et al*., 2003; Nigro and Renda, 2004; Freddy *et al*., 2005; Fabrizio, 2008) because, it shows evidence of movement during the deposition. An equivalent term is contemporaneous fault, defined by Hardin and Hardin (1961).

Our stratigraphic estimates are not sufficiently developed in this area to make a throw versus age plot (Vail, 1987). However, assuming that the long

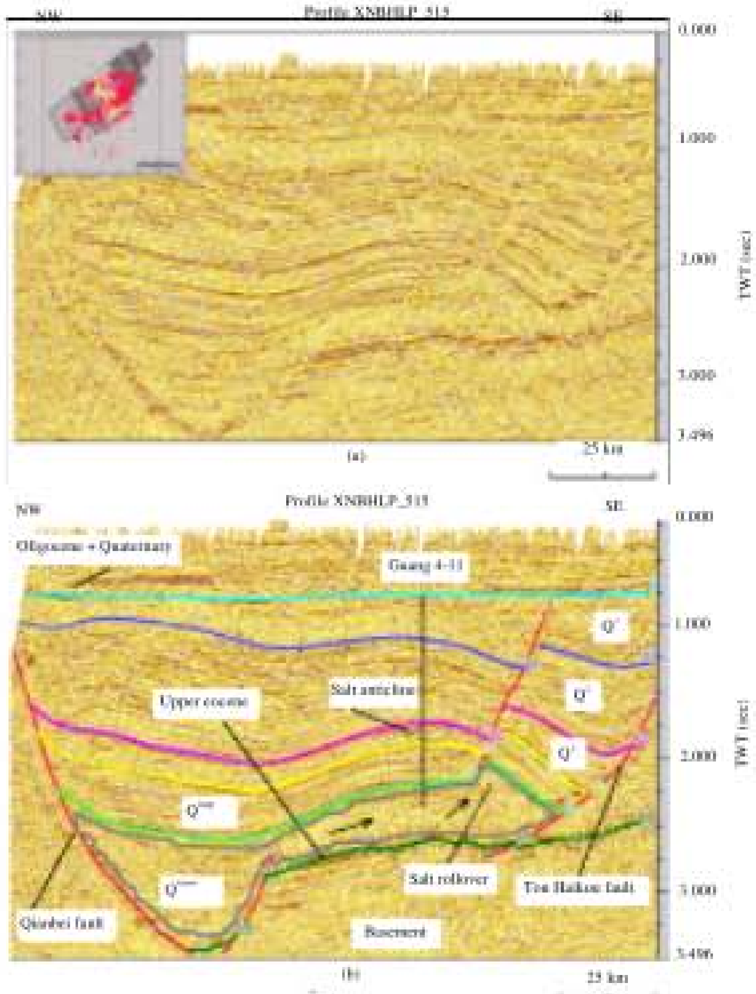


Fig. 4: Seismic profile XNBHLP_515 crosses the central part of Qianjiang sag. Profile location is shown in the base-map (A: up left corner). Beneath well guang 4-11 presented the salt anticline in its early stage, located between Q^{4up} and basement. The salt movement in the profile is from the left to the right

term-sedimentation rate vary greatly rapid at 0.6-1.5 sec and greatly constant at 1.5-2.8 sec (towards the left of the profile). Throw is observed to increase downward at least as deep as horizon referred to the bottom of the early late eocene, where the salt is inferred to be of middle eocene. Thus, the fault has been active at least since the end of middle Eocene and probably earlier.

The fault seems to continue lightly steep to the inferred salt layer, it is curved flatten into bedding, has associated antithetic fault and wedge shaped sediment package (Morley, 2002). Thus and to be more precise, it is a basement involved listric normal fault, which we believed that is the main mechanism of extension in back-arc faulted depression (Tingguang and Peter, 2001). In the same time, salt was deposited as a result of continual, rapid and subsidence of the depression due to the broadly distributed saline lake environment.

Seismic profile XNBHLP_515: The profile XNBHLP_515 crosses the near-central part of Qianjiang sag. Also, shows 4 normal faults where the major fault and a small fault is on the left side of the profile and 2 faults on the right part (Fig. 4). Almost all faults dip towards the center of the depression. The major fault (Qianbei fault) has completely changed from what it was being in the profile XG_305. In here, it doesn't show any associated antithetic faults, nor wedge shaped sediments neither listric shape fault plane, but all what we can see is a planar normal fault, which dip steeply towards the inferred salt layer (Brita *et al*., 2003). Whereas, the right part of the profile shows a typical listric normal fault (from 1.5-2.7 sec), dipping to the northwest and presenting a typical reverse drag of the hanging wall block and a wedge shaped syn-fault sediment package (Ocamb, 1961).

Major fault throw is observed to increase downward at least as deep as horizon referred beneath the bottom of early late eocene time (middle eocene) and where the salt is inferred to be beneath the early late eocene, while the other faults throw increases downward as the horizon referred to the bottom of early late eocene. Thus, we consider that Qianbei fault has been active probably since, the middle Eocene time until nowadays because, it influences the formations of Oligocene and Quaternary time, while the other faults have been activated since, the beginning of late Eocene and stop activation in the end of late Eocene age.

An eastward to upward diapiric salt in its early stage of formation is presented just in the Qianjiang 4 strata (Q^{4low}) of early late Eocene, which is more clearly in Fig. 4 (Jennifer and Katherine, 2005). We interpret that due to salts plasticity and low density among the surrounding layers (sandstone and mudstone), salt moved upward and through the faults, forming two existing salt structure: a salt anticline and salt rollover.

Seismic profile XNBHLP_715: Unlike other profiles, the profile XNBHLP_715 crosses the deep central part of Qianjiang depression and which is the most important one as oil and gas capture reserves. The profile also displays a main planar growth fault to the northwest dipping southeast towards the sag and presenting a steep throw, 2 small faults in the middle center of the sag dipping northwest and showing a moderate to steep throw and additional fault to the southeast (Fig. 5). As in previous cases shown, the basinward dipping faults are thought to terminate at depth in a salt layer, while in this profile it's a well developed salt anticline.

The Qianjiang formation Q^{4low} is basically composed of salt with intercalated mudstone. The well Guang 4-11 shows that salt and mud reach a thickness of 1265 and 332 m, respectively, both together accounting for 72% of the total thickness of penetrated rocks (Holly *et al*., 1989). The other strata in the well are mudstone and mud-bearing gypsum with excellent plasticity. From Q^{4up} the sequence is basically made up of relatively hard sandstone and mudstone that contain beds of salt that's what explains the strong reflections especially in Q^1, Q^2, Q^3 and Q^{4up}.

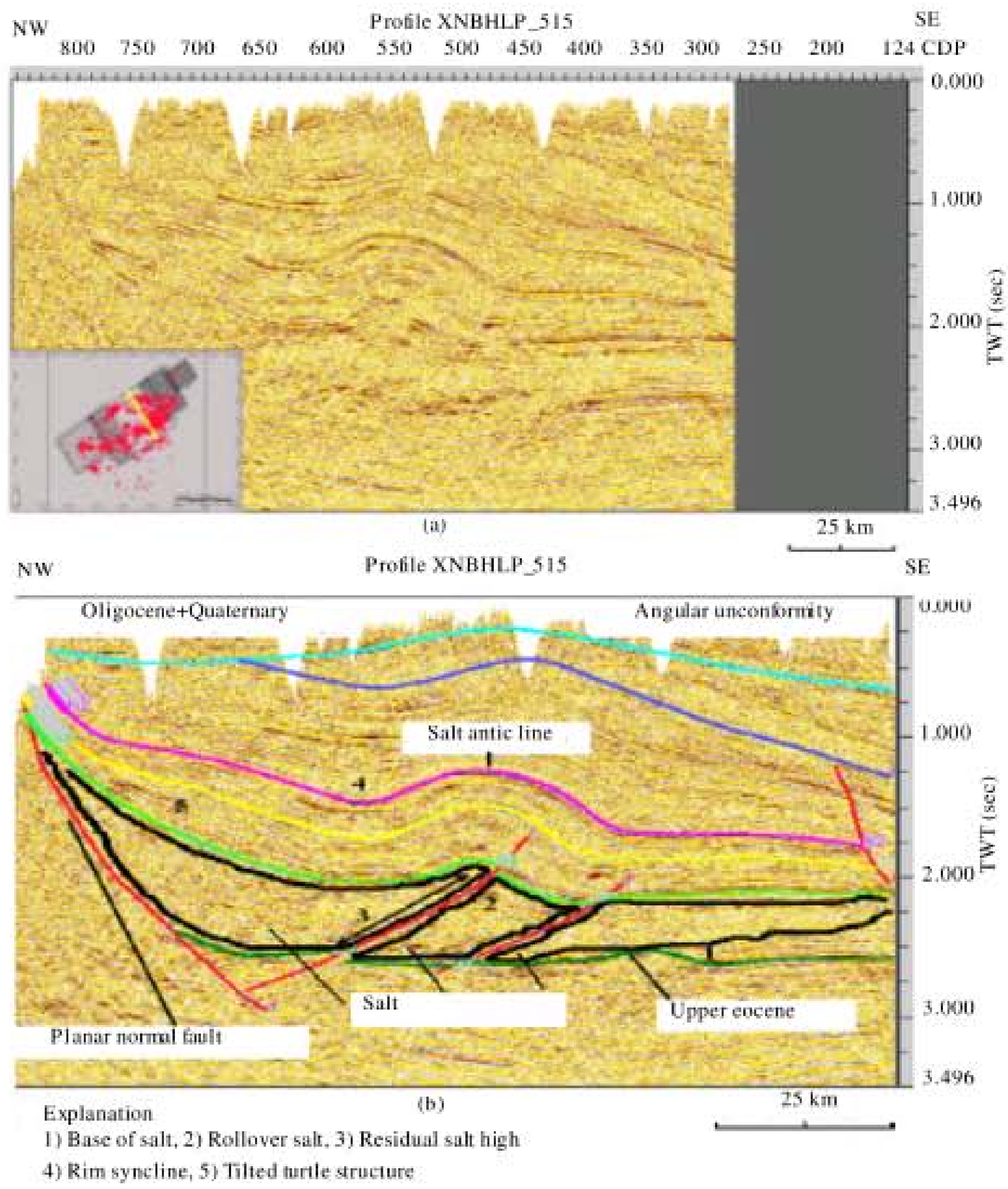


Fig. 5: Seismic profile XNBHLP_715 crosses the deep central part of Qianjiang sag. Profile location is shown in the base-map (A: down left corner). The profile shows the salt anticline late stage (late Eocene to late Oligocene)

We interpret that the movement by faults led to an alternating arrangement pattern of uplifts and depression (positive total subsidence) and a considerable difference in thickness of deposits existed between the upthrown and downthrown sides of the faults. Thus, vertical difference between uplifted and depressed areas produced an appreciable difference in hydrostatic pressure, which caused the salt to flow plastically uptoward the upthrown sides of faults and the higher parts of structures forming a salt anticline and a salt rollover (Fig. 5b).

The development of salt anticline, in reverse enhanced the movement of faults and brought about the continental subsidence of the depression and an increase in water depth. Such environment was favorable for organic matter to be deposited, preserved and transformed (Yuri *et al*., 2003). We believed that salt anticlines are paleo-uplifts, thus, oil and gas migrated towards them and form oil and gas pools (Bruno, 2005). The adjacent layers affected by salt anticline, so, we consider that the salt anticline was developed during the long period between (late Eocene and latest Oligocene).

Seismic profile XPLP_279: Far away from the lake environment, the profile XNPLP_279 crosses the southwest part of the sag (Fig. 2), where like the other profiles, it also shows several faults. From the left to the right of the profile (Fig. 6), a series of Horst and Graben are wholly distributed where the main major faults are listric normal faults almost dip towards the northwest. Faults show a special Y shape which is characterized by a Graben structure in the center of the Y (between the 2 faults forming the Y shape and which are in fact a listric normal fault and probably a reverse fault) and 2 Horsts structures apart the 2 faults (Schultz-Ela, 2003; Michael and Martin, 2006).

Qianbei fault's activity has changed (right side of the profile), actually it has a listric to planar fault plane, with total absence of antithetic fault, whereas the sediments package have no special shape and not much thicker as

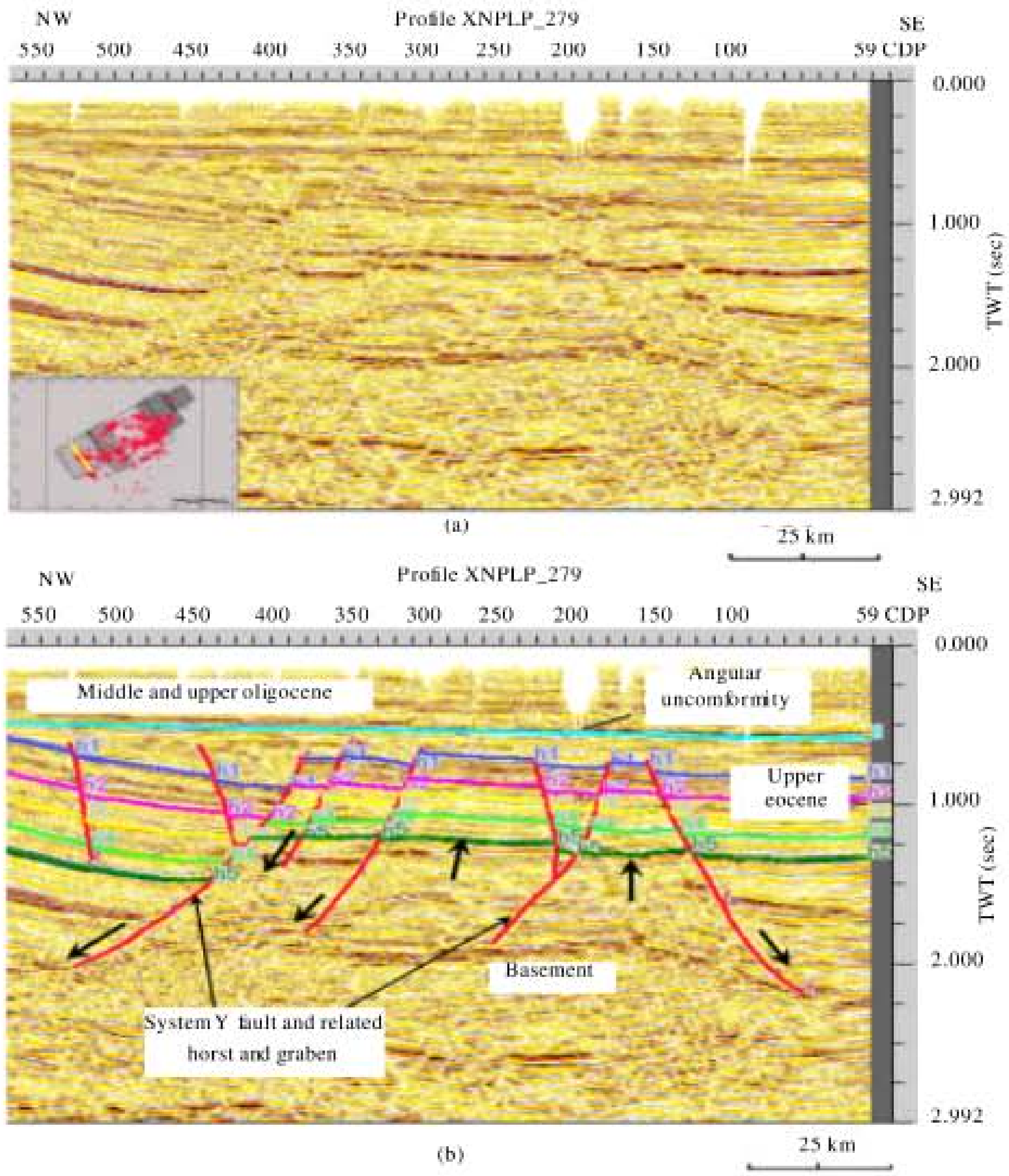


Fig. 6: Seismic profile XNPLP_279 crossing the southwest part of Qianjiang sag, represents faults in Y shape limiting the horst and graben structures. Absence of any kind of salt structures. Towards the left of the profile (profile continuation) the area becomes lightly stable and has no tectonic movements

they were in the above profiles (especially, in the center of the depression). No salt structures are shown in the profile, but only some thin layers intercalated with mudstone and sandstone. We infer that the salt was concentrated just near the deepest part of the depression, where the greatest thickness of salt was deposited due to the deep and subsided center (Fig. 7).

Relationship between growth fault and diapirs: The multichannel profiles indicate that the main fault breaking the strata on the North side of the deep Qianjiang depression is a growth fault (Koledoye *et al*., 2000). By our estimates of stratigraphic horizons, we see increasing offsets back to at least the middle Eocene. We consider that the faults throw exist at 0.6 sec below lake water level. Any fault showing effects so close to the sea floor in an area of deposition must be considered active.

Our detailed surveys show that diapirism is presently active because salt anticline deforms the lake floor in an area of active sedimentation. For example, Fig. 5 shows a strike line through anticline that offset the post uplift unconformity just northwest of the profile XNBHLP_715.

The location of the main growth fault and the salt diapirs clearly are related to the morphology of the Qianjiang depression. We suggest that salt was deposited in the deepest part of Qianjiang depression and that it was loaded by sediments during middle Eocene and probably earlier and began to flow basinward and migrate into rising anticline and salt rollover (Holly *et al*., 1989; Chen *et al*., 2007).

The location of anticline was probably controlled by a shallowing of basement and movement by fault (due to the basin stretching during rift stage evolution), which creates a considerable difference in thickness and hydrostatic pressure, that's probably caused the salt to begin to flow upward the upthrown sides of the faults.

Removal of a salt volume resulted in subsidence of the block of sedimentary strata above the area of the original salt depositing pan (Fig. 8). In addition, rapid subsidence of that block caused a fracture in the

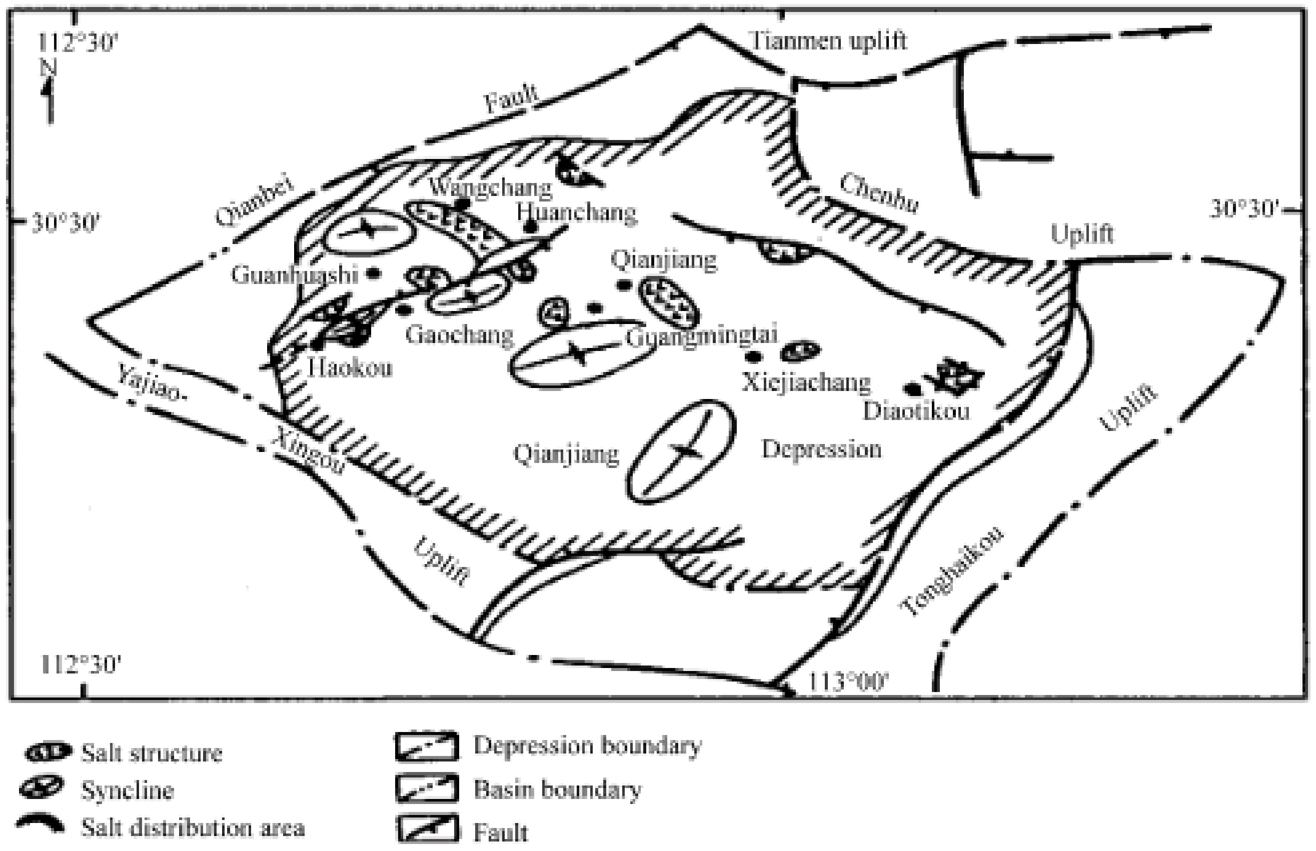


Fig. 7: Distribution of salt structures in the Qianjiang depression

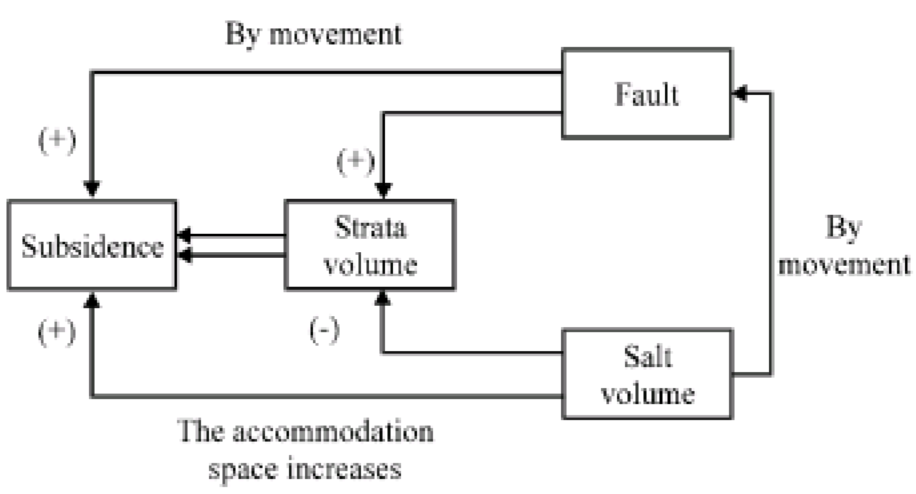


Fig. 8: Relationship between growth fault and salt diapirism

sedimentary strata and because the flow of salt continued for a long period (and still continues); the fault was active through this period (middle eocene). Thus, the growth fault formed because of continual removal of support from a major block of strata by salt flow. Such a volume transfer requires that the volume lost in subsidence of the block of strata in the Qianjiang depression must be equal to the volume of salt removed, which is represented mainly by the volume in the domes (Fig. 8).

CONCLUSION

Qianjiang depression is a wedge elongated (2500 km^2) shaped sag in Jianghan basin, southeastern China, where a group of northeastward salt structures is aligned along the center of the sag.

Normal faults follow the basinward side of the Qianjiang depression. It is a growth fault as is shown by a pattern of throws increasing as depth increases. The fault generally continues steeply down to salt level in the sag. At one location, the faults steepens at depth may have reverse faults (Y shaped fault) associated with it that were created by this steepening of the fault plane.

The growth fault probably resulted from the appreciable difference of hydrostatic pressure between the uplifted and dowlifted area and from the removal of supports as salt flowed into the anticline from the deep part of the sag. Thus, transfer of volume from the deep sag resulted in subsidence of a block of strata as the anticline roses.

The growth faulting and related flow of salt probably began in middle Eocene time as is indicated by increasing offset in deep strata (basement).

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