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The Subsidence of Cenozoic Formations in Nanpu Sag (Bohaiwan Basin)

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Abstract: The study of subsidence as geologic process is very important to understand oil migration and its occurrence in some basin areas. The subsidence rate and rapid deposition, sediment compaction and occurrence of overpressured zones are linked to one another in extensional faulted basins. The presence of locally high subsided and overpressured areas in Nanpu sag is related to the rapid sedimentation followed by depositional compaction and tectonic activities. The subsidence study consists of geohistorical analysis, which required the correction of sediment compaction and paleobathymetric depth determination through paleontologic studies and sea level changes. The subsidence of any stratigraphic horizon or any geological formation is caused by tectonics movements and the sediments and water loads, which led sediments to subside and compact. The subsidence analysis is useful for understanding regional tectonic history, the history of sea-level changes and thermal history of basin, which in turn, is essential for hydrocarbon studies. The subsidence analysis is very important key in sedimentary basin modeling in sense that sedimentary bodies are key recording information that allow making up good geologic appraisal, in the aim to understand the process of generation, migration and hydrocarbon accumulation. The subsidence analysis in Nanpu Sag shows that the highly subsided areas were controlled by structurally faulted zones, which coincided to the depocenters, where most of oil fields have been discovered.

Key words: Subsidence rate, depositional compaction, sea level changes, paleobathymetric depth, depocenters, oil fields

INTRODUCTION

Nanpu Sag is located in the North part of Huanhua Super Depression in Bohaiwan Basin (Fig. 1). Nanpu Sag was formed during the development of extensional normal faults with NNE-NEE trend (Fig. 2), caused by episodic rifting. This sub-basin was filled continuously by terrestrial and lacustrine sediments during Cenozoic, but the deposition and subsidence rates varied episodically through this time. Depending on the Cenozoic time, the Bohaiwan Basin, particularly Nanpu sag had undergone a subsidence with variable magnitude. This variability was linked to the variable geological conditions through time in which this depositional environment was involved. The more influenceable factors in this evolution were: the rapid deposition of continental and lacustrine materials, dictated by episodic rifting in Bohaiwan Basin during Cenozoic, as well as the lake level changes and the effect of global tectonic. The goal of geohistory analysis is to produce a graphical representation of the vertical movement of a stratigraphic horizon in a sedimentary basin as an indicator of subsidence and uplift history in the basin since the horizon was deposited[1].

The sedimentary basin history is linked to the water mass filling as well as its sedimentary mode filling. While subsidence rate calculation, the error of water depth is not tolerable even it's difficult to obtain in many cases and the sea/lake level changes must be considered in subsidence analysis, as well as sediment compaction and paleobathymetric depth. In this study, the Sedimentary Basin Software under EBM was used to simulate the basin subsidence of Nanpu Sag. The tertiary formations in Nanpu Sag were considered. These were Shahejie formation (Es_1, Es_2 and Es_3), Dongying formation (Ed_1, Ed_2 and Ed_3), Guantao group (Ng) and Minghuazheng group (Nm).

COLLECTION OF DATA TYPE

To evaluate subsidence rate of given formation, the decompaction (bacstripping techniques) of all stratigraphic units (layers) (Fig. 3), that it encompasses should be done. For this reason the depositional order of each stratigraphic sequence or lithological assemblage must be defined through core log study, facies analysis, paleobathymetric depths determination (Fig. 4) and seismic profile interpretations. The physical properties of sedimentary rocks under normal compaction were considered, Table 1.

The paleobathymetric depth is determined through sedimentary facies analysis and thorough study of paleontological groups etc. In general, the following

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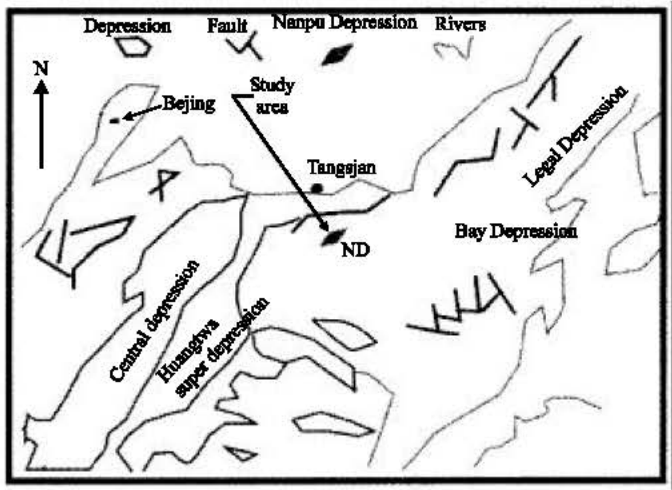

Fig. 1: Nanpu location map in Bohaiwan Basin North-Eastern China

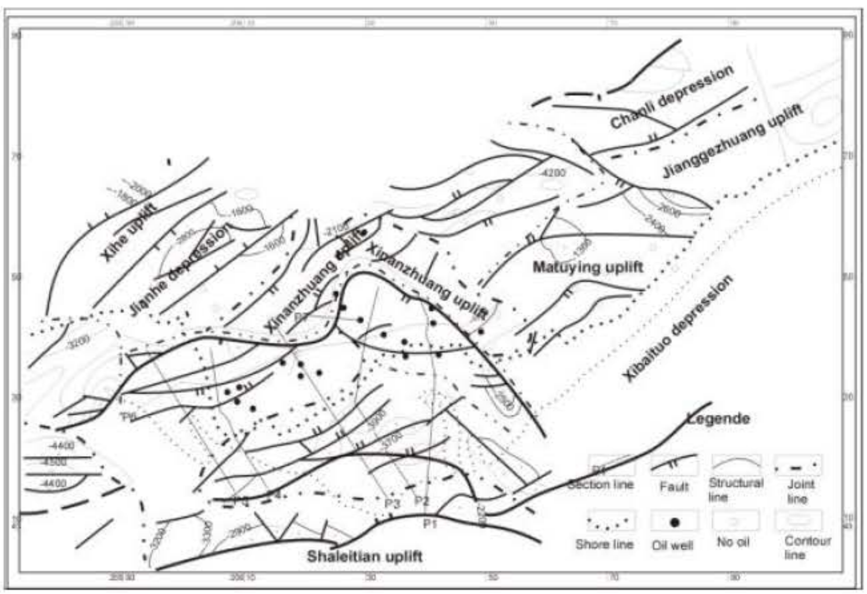

Fig. 2: Paleogeographic and structural map of Nanpu Sag and some oil prospects

Table 1: Characteristics of different sedimentary rocks under normal compaction

Lithology	Compaction coefficient (C) km^{-1}	Facial porosity φ (%)	Density (ρ) kg m^{-3}
Mudstone	0.51	0.63	2720
Sandy clay	0.39	0.56	2680
Sandstone	0.27	0.49	2650
Conglomerate	0.22	0.46	2640
Limestone	0.71	0.70	2710

parameters were considered in Nanpu Sag: the fluvial facies and alluvium have 0 m of bathymetric depth; costal under water fan ~5 m; shallow lake facies 5~20 m; deep lake facies 20~100 m and more. The fan delta is generally developed in vicinity depth no more than 30 m. Fourteen seismic section lines had been traced through Nanpu Sag, among which 11 in NS direction and 3 in EW, (Fig. 4). The thorough study of different stratigraphic units allows us define 9 formations including Quaternary deposit (Q), Minghuazheng (Mn), Guangtao(Mg), Dongying Ed(Ed_3, Ed_2 and Ed_1), Es(Es_3, Es_2 and Es_1). More than 2000 data values were used, including 339 in seismic sections. The compaction coefficient, the porosity and grain size were taken as standard parameters (Table 1).

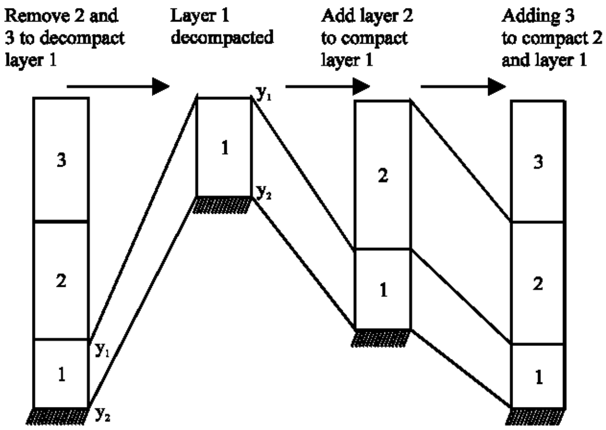

Fig. 3: Technique of layer decompaction

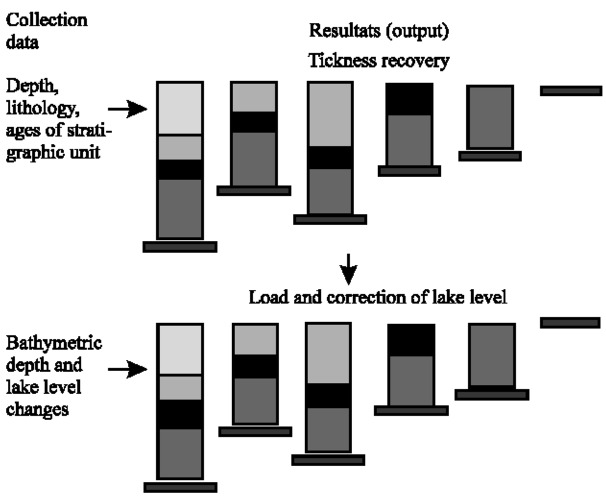

Fig. 4: Correction of lake level change and thickness recovery

SPATIAL DISTRIBUTION OF SUBSIDENCE THROUGH NANPU SAG

The subsidence of a sedimentary basin consists of two components: (i) initial fault-controlled subsidence, which depends upon the rate at which crust and lithospheric mantle are thinned and (ii) a slower phase of thermal subsidence, which decays exponentially with time as a result of cooling. McKenzie proposed a mechanism for this observed plate subsidence by invoking instantaneous lithosphere extension, which assumes that the subsiding basin remains in local isostatic equilibrium throughout its development. The procedure of backstripping was developed to remove the effect of sediment loading in order to isolate tectonic subsidence, allowing subsidence histories to be modeled[3-5]. This backstripping method has become a standard technique since it allows direct comparison between the subsidence histories of any extensional sedimentary basin irrespective of the sedimentary fill.

Subsidence rate of shahejie formation (Es): The shahejie formation consists of 3 members, namely Es_3, Es_2 and Es_1. The main subsidence zone of the Es_3 member is located in frontiers between baigezhuang and Gaoliu faults, where the subsidence rate is estimated to be in range of 50-380 m Ma^{-1}. The center of this subsidence is located between seismic profiles No. 11 and No. 13 with a maximum of 380 m Ma^{-1} near Baigezhuang fault. This relative position to the major tectonic accidents shows that the centre of the subsidence is controlled by these two faults. The contour lines of this subsidence form an irregular ellipse along Baigezhuang fault. The subsidence zone of the second member of shahejie (Es_2) is also located in frontiers of Baigezhuang and Gaoliu with a large scope of subsidence rate values (20~790 m Ma^{-1}), in difference of Es_3, its subsidence zone forms an elliptic body in EW direction and has been influenced by compressional movements than extentional, which were NS trend and in difference of Es_3 and Es_2, the first member (Es_1) shows significant subsidence in two areas: The first area is again between Baigezhuang and Gaoliu and the second subsidence area is located in Beibao field oil near fault (Fig. 5).

The general analysis of subsidence shows that some subsided areas are far from main faults and we suggest that they were controlled by others factors like expansion, thinning and crustal basin cooling that characterized basement of rifting and extensional basin.

Subsidence rate of dongying group (Ed): The subsidence research of Dongying formation shows a renewal of tectonic activities with a maximum of 1200 m Ma^{-1}. During Dongying depositional period the subsidence zones were widely distributed through Nanpu sag, the contour lines on the map shows a dense and complex network and there are numerous centers (Fig. 6) of subsidence: 950 m Ma^{-1} in North of Liuzan field oil near Gaoliu faulted zone; Some subsidence rate values of 900 m Ma^{-1} were determined in Jh1-1 in East part of Gaoliu faulted zone; 540 m Ma^{-1} in North of Beibao field oil in B22-1 etc, this irregular distribution of subsidence rate point out of the non uniformity of basin basement of Nanpu and difference in tectonic subsidence through space and time. For example Ed_3 was more affected by tectonic subsidence than Ed_2 and Ed_2 in turn was subjected to the subsidence than Ed_1. They had, respectively, a maximum of 1200 m Ma^{-1}, 490 m Ma^{-1} and 410 m Ma^{-1}. That pointed out the decreasing of subsidence.

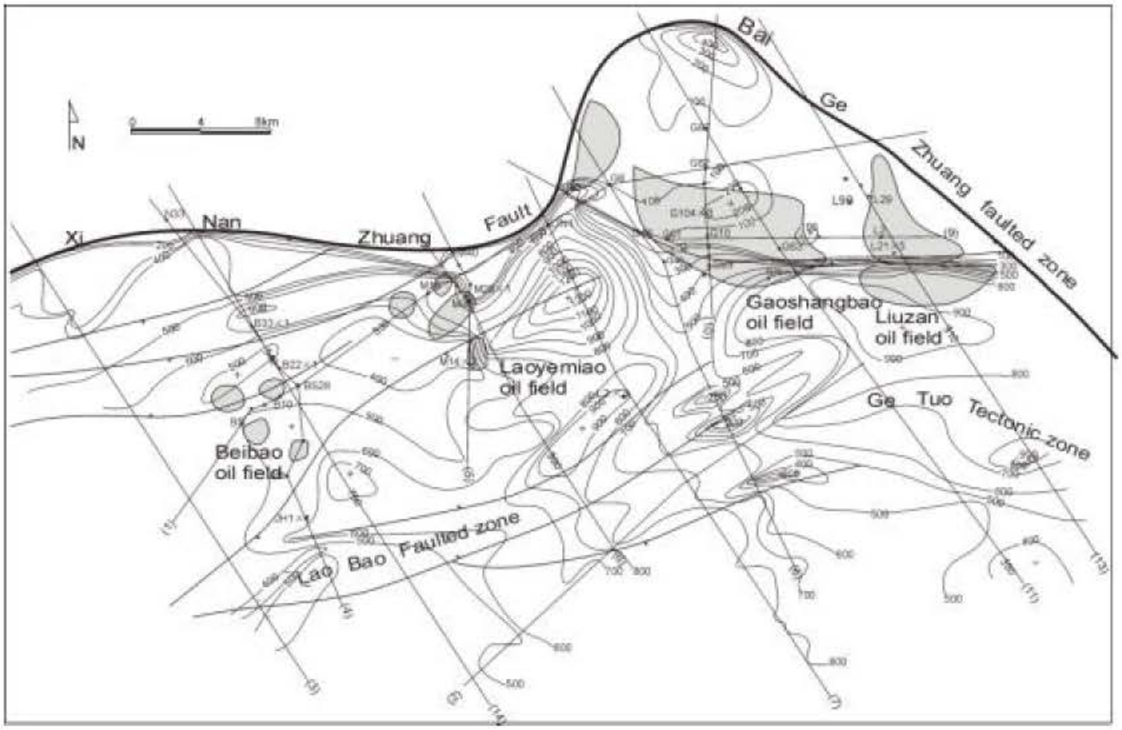

Fig. 5: Isopleths map of Es (Shahejie formation) subsidence rate in Nanpu Sag

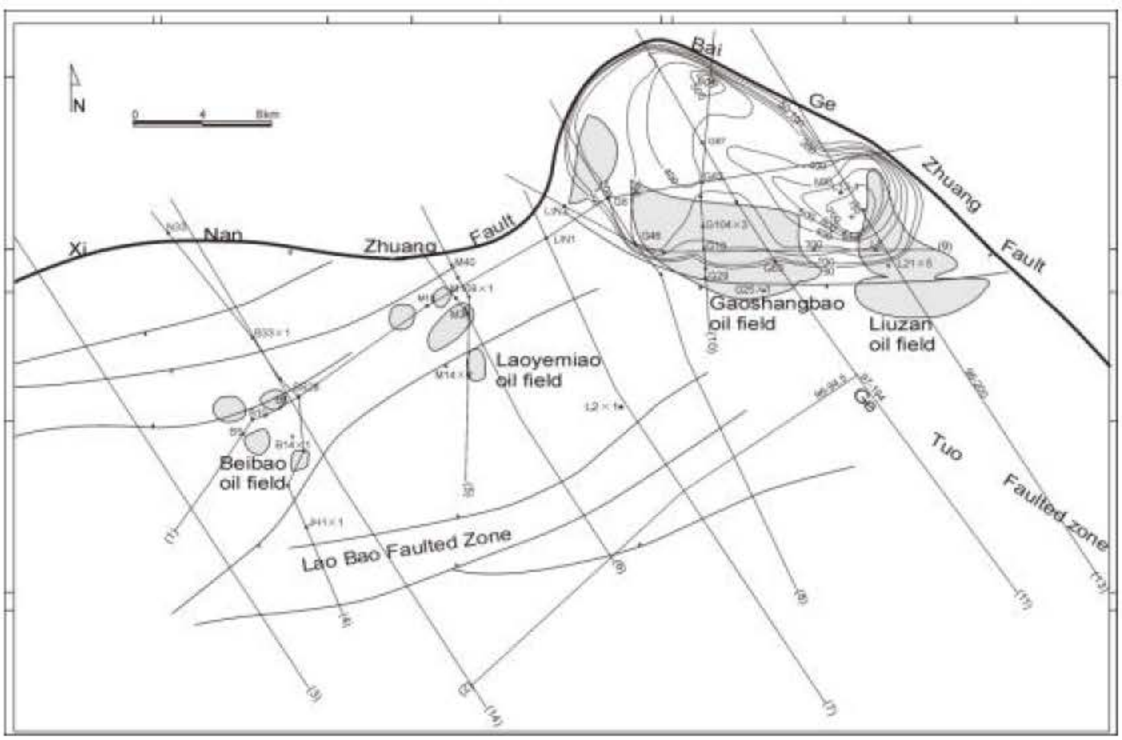

Fig. 6: Isopleths map of Ed (Dongying formation) subsidence rate in Nanpu Sag

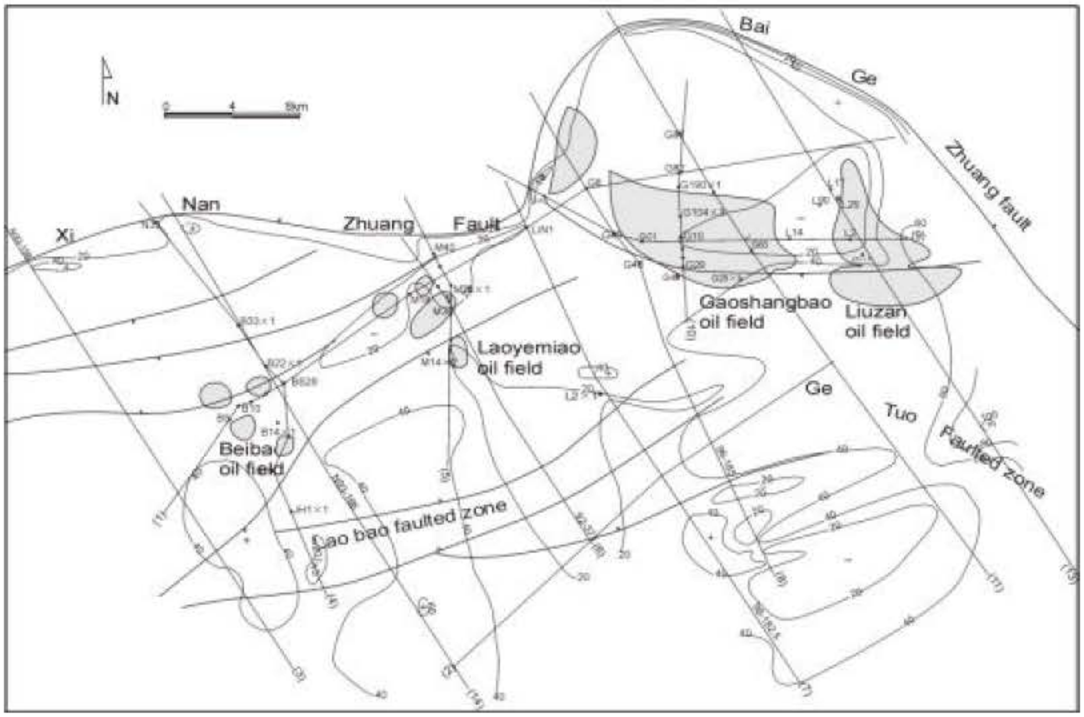

Fig. 7: Isopleths map of Guantao(Ng) Group subsidence rate in Nanpu Sag

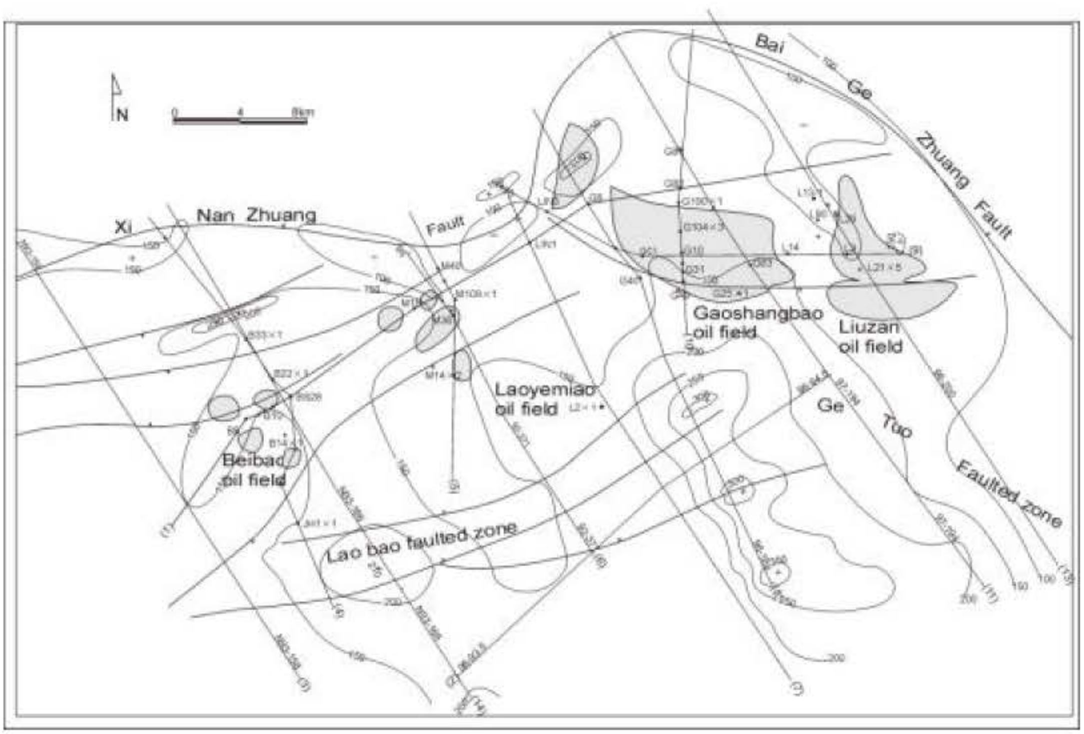

Fig. 8: Isopleths map of Minghuazheng Group (Nm) subsidence rate in Nanpu Sag

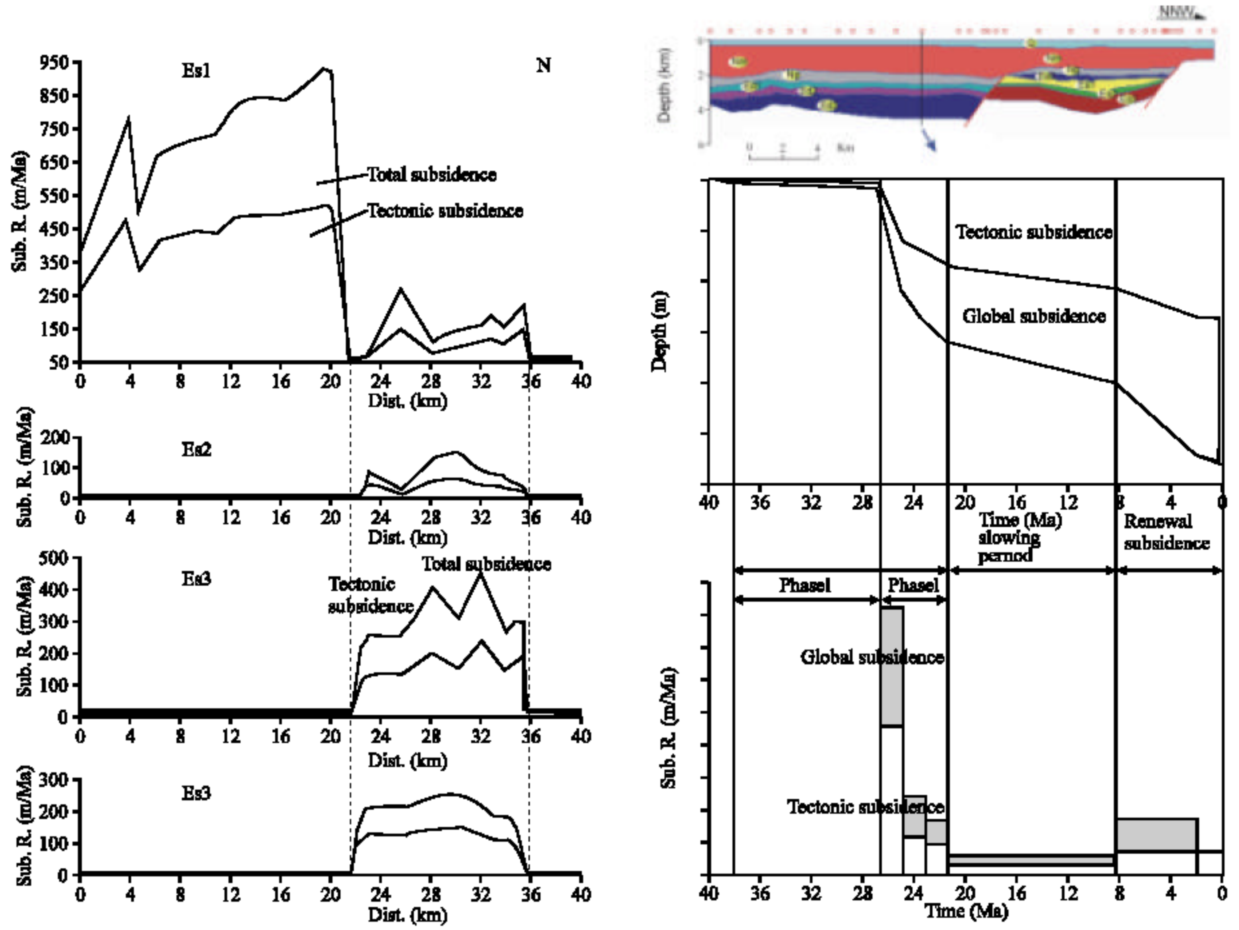

Fig. 9: Vertical evolution of subsidence rate through time and space along profile seismic No 11 (right) and No 13 (left) of tertiay formations in Nanpu Sag

Subsidence rate from Guantao to Minghuazheng depositional periods: After Dongying period (Ed), the subsidence continued weakening till the end of Minghuazheng formation, during which it was decreased to 100 m Ma^{-1}, approximately. After Guantao period, the entrance of Minghuazeng period saw a revival and increasing of subsidence rate, which reached 350 m Ma^{-1} in certain localities (Fig. 7 and 8). The main lesson of the subsidence analysis of Nanpu Sag shows that, this region has undergone episodically tectonic movements during Cenozoic Era and that subsidence reached its climax during Dongying depositional period (Fig. 9). Other remark is the high frequency of subsidence centers occurrence between Gaoliu and Baigezhuang faults from Es_3 to Es_2 depositional periods and its displacement from north to south from Shahejie (Es) to Minhuazheng (Nm) formation. The main controlling subsidence rate factors during Es_3-Es_2 were the fault activities and this is independent of regional subsidence that affected Es_1. During Ed_1 to Nm, the whole basin was affected by combined action of faults and regional subsidence. The highest subsidence rate value is due to the tectonic subsidence and lowest by regional one.

Subsidence evolution in nanpu sag: The use of backstripping techniques have been used to estimate the vertical evolution of subsidence in Nanpu sag. The seismic profiles had been chosen in this study to show this evolution through Nanpu Sag. After a synthetic analysis of subsidence curves, we divided the Cenozoic rifting and subsidence evolution in three phases: Synrift period of Shahejie and Dongying depositions from 42~23.3 Ma postrifting period of deposition of Guantao spanning from 23.3~9 Ma and 9 Ma~ nowadays which corresponds to the period of deposition of Minghuazheng to Quaternary deposits. The observation of temporal and spatial subsidence evolution curves through Nanpu sag shows different characteristics. The abrupt subsidence curve changes occurred during rifting phase and the gentle subsidence curve changes indicated the beginning of still period and the deepening of basin during which it received an important quantity of clastics and lacustrine sediments (Fig. 9).

These curves show that the high subsidence rate intervened during the second period of rifting and does not correspond to the tectonic or fracturing period. During the dislocation of basin basement, the subsidence rate is not important. Later phase of rifting corresponded of the deposition of the Dongying formation 23.3~9 Ma (Fig. 9), during which the global subsidence rate took pace on tectonic subsidence (>1000 m Ma^{-1}), however the tectonic subsidence rate was about equal to ½ of global subsidence at the end of Ed deposition, e.g. Ed_1. This analysis of basin subsidence shows that the main controlling factor of subsidence is tectonic during the first period, however it became progressively secondary relative to the global subsidence process.

The subsidence analysis of Nanpu sag, coupling with facies analysis indicating the distributions of facies types, can favorably help to hunt hydrocarbon in this interesting depositional lacustrine and continental environment, where the estimates of total Cenozoic sediments thickness reached 8000 m in depocenter. The high thickness of lacustrine sediments and high local subsidence rate in Nanpu Sag (more 300 m Ma^{-1}) may be an advantage in hydrocarbon exploration.

CONCLUSIONS

The rapid deposition and burial process of sediments followed by thermal compaction due to the subsidence of basin crustal, were the main causes of the occurrence of normally pressured sedimentary rocks layers in Nanpu. Sediment compaction is mostly a mechanical process resulting in the reduction of porosity by increases in vertical stress due to loading on the sedimentary pile. Lateral deformation is commonly ignored and many workers have followed the numerical approach[6,7] where the fluid flow and heat flow domains are restricted to a vertical cross section which grows with sedimentation. This mechanism is the main cause which increases fluid pressure potential in the basin. When the rate of deposition is important, there is an important sediment accumulation that provide thick but non compacted layers overlying compacted previous deposit, this led to the pressure disequilibrium state in the basin if the underlying formation (or layer) were fine grained rich organic sedimentary rock (source rocks), the overlying formation can be a good petroleum reservoir, where the hydrocarbon may be migrate because of the differential pressure. This condition is quite possible in Nanpu sag, where geohistory of lacustrine environment is favorable in development of rocks reservoir, source rocks, geothermal gradient and abnormal pressure. The subsidence phenomena in which results the compaction of rock should be thoroughly considered to determine the oil route migration and their deposition in reservoir rocks, for this reason, we suggest that, the more important part in oil prospection is geohistoric study of the basin, because the oil can not be generating if:

- The deposited sediment in a given basin does not contain organic matter.
- The depositional rate is not enough to preserve OM.
- The geothermic gradient is not in range to generate oil
- The fluid potential is not enough to made oil migrate from source rocks to carrier rocks and from carrier rocks to residence of oil-pool forming or traps.

Even the basin analysis is an integrated study; we suggest that the subsidence process of stratigraphic units is very important oil exploration. Subsidence value reflects the dynamic evolution of basin or a given geologic formation. The matter of prospecting is how oil forms? How is migrating? And how is accumulating in residence traps. A rapid subsidence rate creates favorable conditions of organic matter preservation. Pressure and geothermal gradient values are crucial in oil generation, the migrations of hydrocarbons is a matter of many factors, where compaction of source rocks may play an important role in primary and secondary migration. The illustration of this idea can be seen in Nanpu Sag, where the main oil- fields were formed in response to sediments compaction followed by important fluid pressure. The accurate geohistorical study, namely subsidence rate analysis may lead people to find new petroleum pools in Nanpu sag.

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