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Maturity Modeling in Bai Yun Depression and Pan Yu Low Uplift, South China Sea

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Abstract: One-dimensional basin modeling that simulated burial, maturation and generation histories for five wells was carried out. Transient heat flow model in the Petromod 7.1 software was chosen to model the thermal histories of the individual wells (1, 2, 3, 4 and 5). They were selected on the basis of suitability for thermal modeling using Petromod 7.1. The maturity modeling of the preserved stratigraphy calibrated against vitrinite reflectance R_o and T_{max} demand the palaeo-heat fluxes ranging from 56.6 to 66.75 mW m^{-2}. The results indicated that the measured maturity data in five wells were in agreement with a transient heat flow model. The modeled results indicated a good match of the simulated maturity data (vitrinite reflectance R_o and T_{max}) with the measured data in all wells. The result also showed that the maximum paleo-temperatures were attained by the three source beds (Wen Chang, En Ping and Zhu Hai Formations respectively from bottom to top) in Bai Yun depression and Pan Yun Low Uplift during Early Miocene. The Eocene source rocks started to expel hydrocarbons during Early Miocene to Present.

Key words: Maturity modeling, heat flow, Bai Yun depression, Pan Yu Low uplift, South China Sea, Rock-Eval T_{max}, Vitrinite reflectance R_o

INTRODUCTION

The South China Sea is bounded to the north by China mainland, to the south by the Palawan Trough and to west by the Manilla Trench. Current exploration is focused on four major sedimentary basins-The southwest Taiwan basin, the Pearl River mouth Basin, the Beibu Gulf Basin and the Yingge Sea Basin (Tang, 1980; Li, 1984) as shown in Fig. 1.

Bai Yun unit and Pan Yu Low uplift are located within Zhu-2 depression (since PRMB consists of three sub-basins, Zhu-1, Zhu-2 and Zhu-3), the southernmost of the sub-basins (Fig. 2).

The South China Sea was formed by oceanic spreading along a WSW-ENE axis during the Oligo-Miocene in the eastern part of the basin (Briais *et al.*, 1993; Lu *et al.*, 1987; Taylor and Hayes, 1980). The origin of the extensional forces is controversial. Extension in the area is believed to have commenced in Late Cretaceous-Early Paleocene (Schülter *et al.*, 1996) and seems to take advantage of the location of pre-existing Andean-type arc, located above a north-dipping subduction zone along the south coast of china (Hamilton, 1979; Jahn *et al.*, 1976). U-Pb dating of the arc volcanic and intrusive rocks exposed in Hong Kong (Davis *et al.*, 1997) indicates that magmatic activity ceased after 140 Ma, although $^{40}Ar/^{39}Ar$ ages of granites from Pearl River Mouth Basin (PRMB) also suggest that some magmatism continued into the late cretaceous-Paleocene (Daquan *et al.*, 1989).

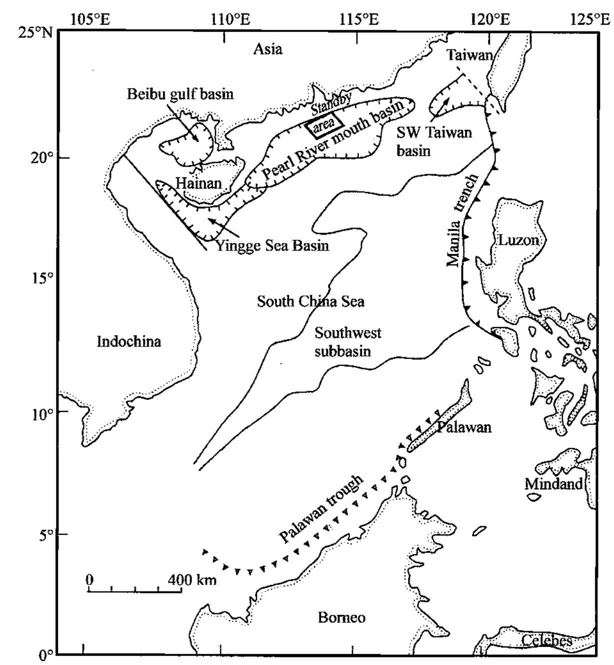

Fig. 1: Regional map of Pearl River Mouth Basin

Much of the sediment deposited on the shelf today is derived from Pearl River in the central part of the shelf, or from the Red River in the westernmost areas, although it seems likely that other larger rivers fed sediment into the sea during the Cenozoic (Clift *et al.*, 2000). Dating of sediments is well-constrained following marine

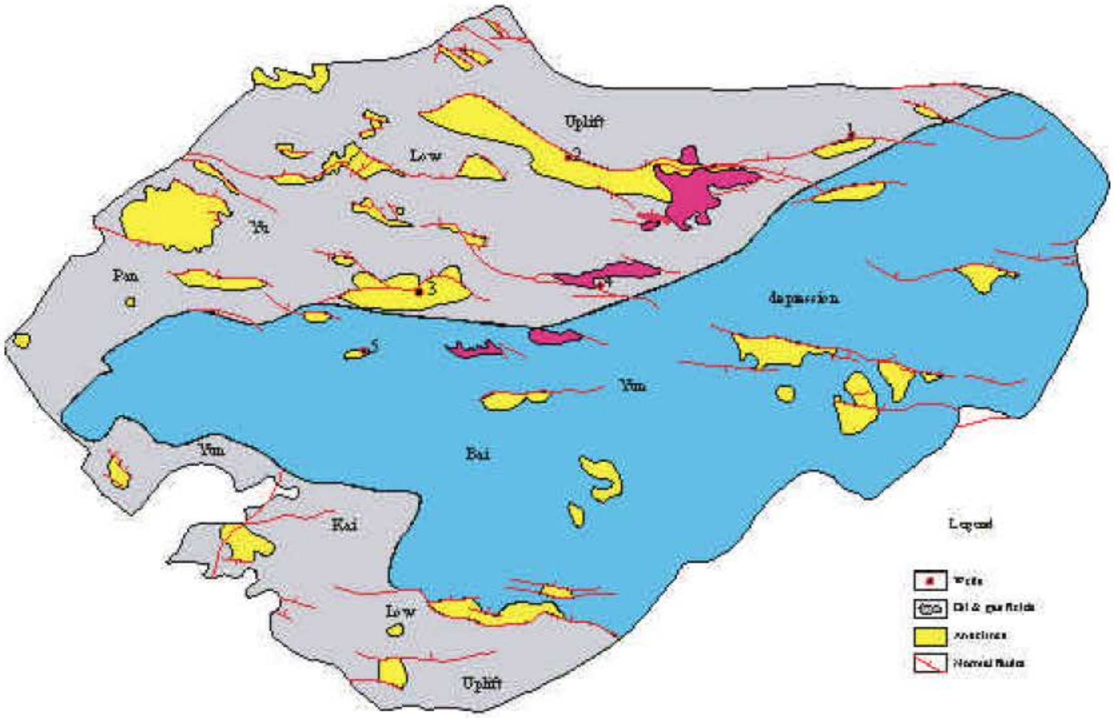

Fig. 2: Detailed map of study area

transgression in the Early Oligocene. Earlier ages within the syn-rift deposits, however, are generally determined by palynological methods, which provide a poorly defined Eocene-Oligocene age. Consequently, the start and duration of the syn-rift episode are not clearly defined.

The heat flow history of this basin is obtained by a smooth match between calculated maturity values and the measured vitrinite reflectance R_o and Rock-Eval T_{max}. The modeled maturation is obtained based on the alteration of organic matter, which is dependent on formation temperature and time (Tissot and Welte, 1984) and the Arrhenius-reactions model is used to simulate the chemical reaction that produce maturation (Larter, 1988; Burnham and Sweeney, 1989). The formation temperatures must be modeled through time, which are determined from burial depth, heat conductivity, surface temperature and heat flow data. High paleoheatflow in rift-related basins is commonly associated with rifting and sea floor spreading and the reconstruction of thermal history from vitrinite reflectance is a function of tectonic history of a basin (Allen and Allen, 1990). The evolution of Pearl River Mouth Basin is commonly to be accepted as such: (1) rifting and rapid subsidence together with slight to moderate uplift and faulting and (2) regional gravitational and thermal subsidence.

The goals of the present study are (1) to investigate the applicability of the transient heat flow thermal history to this study area, (2) to use Rock-Eval T_{max} and R_o data to evaluate thermal maturity and (3) to give detailed thermal histories of individual wells. The model presented here combines current knowledge of thermal evolution with kinetics treatment of hydrocarbon generation using the Petromod 7.1 (IES).

PEARL RIVER MOUTH BASIN STRATIGRAPHY

Nine formations have been recognized ranging from Paleogene to Quaternary in age (Fig. 3). The summary presented here was drawn from the study of Duan and Huang (1987), Wu (1988), He (1988), Feng and Zheng (1982), Wang (1982) and Zhang *et al*. (1983).

Sediments are mainly of continental and shallow marine facies. The pre-rift basement is composed of Mesozoic granites and metamorphic rocks (Roberts, 1988).

At the base of the sequence, the Shen Hu, Wen Chang and En Ping Formations are thought to be terrestrial. Fossils including spores and pollen are rare. The Shen Hu Formation is dominated by red or mottled sandy conglomerates of fluvial fan facies, associated with igneous and volcanoclastics debris. The Wen Chang Formation consists of grey to black lacustrine mudstones, with thin sandstones and siltstones. In contrast, the En Ping Formation is dominated by floodplain and stream sandstones with some swamp and lacustrine mudstones. Paleowater depths range between 0 and 20 m (Wang *et al*., 1985).

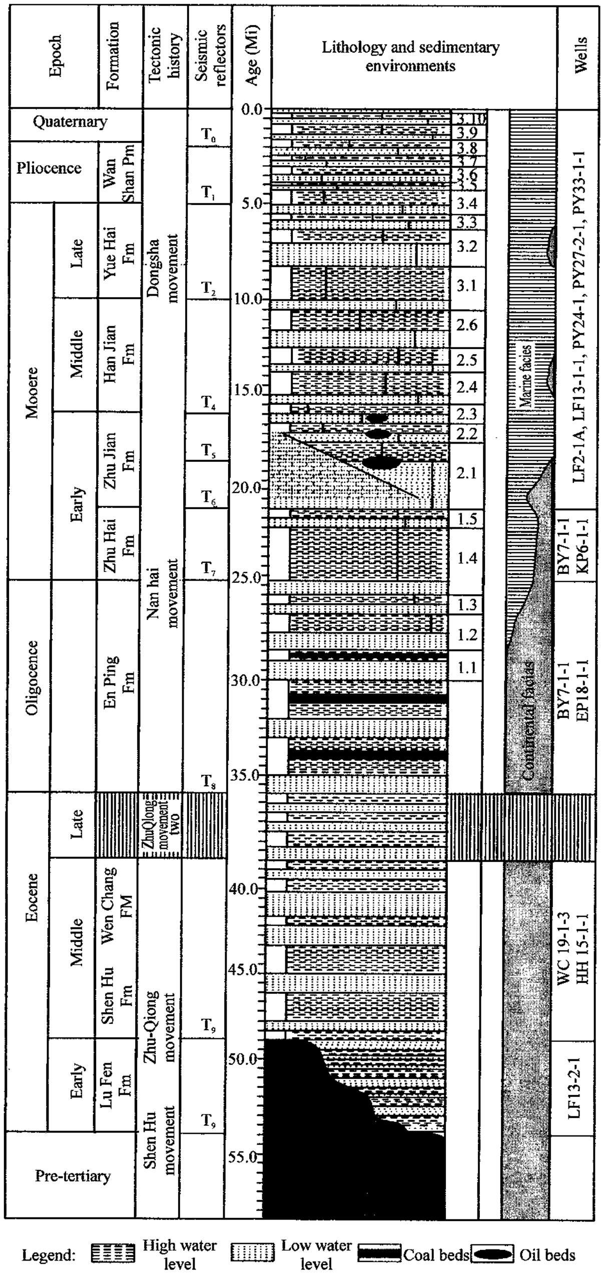

Fig. 3: Bai Yun depression and Pan Yu Low Uplift stratigraphic column

The upper Oligocene Zhu Hai Formation comprises a sequence of grey gravelly sandstones and grey silty mudstones. Spores and pollen are abundant, but foraminifera are absent (Duan, 1985).

The Lower Miocene Zhu Jiang Formation consists of brownish-grey silty mudstones, sandstone and conglomerate. Foraminifera occur in a few layers, but are poorly preserved. This formation was deposited in a shallow marine, inner shelf environment and comparison with modern foraminifera suggests a water depth of 0-50 m (Wu, 1988).

MATERIALS AND METHODS

Data analysis: All the data and samples were provided by the China National Offshore Oil Company, Guangzhou (CNOOC). Part of the data was obtained from a number of geological composite log, seismic section and reports supplied.

There are mainly three source rock formations in Pan Yu Low uplift and Bai Yun depression: Eocene Wen Chang, Eocene-Oligocene En Ping and Oligocene Zhu Hai. The Miocene Zhu Jiang Formation has also a capacity of producing hydrocarbons (Su, 1987). The Wen Chang Formation is not penetrated by any well in this study. Many other geochemical data were supplied and were used in this study.

In addition from other geochemical data available Zhu Hai limestones subfacies may also be regarded as a good source rock with a high content of organic matter and oil generation potential.

The burial histories at the five wells have been compiled by means of biostratigraphical analyses carried out by CNOOC, Guangzhou. The present studies have been supported by lithostratigraphical correlations to wells within the vicinity. The reliability of the data presented is considered fair to good. Here the magnitude of original deposition and subsequent erosion must be regarded as uncertain, since it is based on approximation.

The porosity data are based on petrophysical log readings, mainly the acoustic sonic, supplemented by few sample measurements from several wells. The reliability of the absolute porosity values are considered to be fair and the porosity trends are considered to be reliable.

The temperature measurements at the five wells (1, 2, 3, 4 and 5) are probably within 2-4°C of the true formation temperature. The temperatures have been corrected, but the accuracy is unknown.

Based on the earlier statements temperatures measurements are also fairly reliable .Core chips, cuttings and sidewall samples were analyzed for vitrinite reflectance (Ro) data. The Ro data quality is rated fair in all wells under study.

Stratigraphic data (depths, lithologies, ages etc.,) were obtained from seismic and well data, biostratigraphic data and many other reports.

The two erosions were modeled here in the burial histories. The amount of eroded thickness due to the two regional erosions is estimated on the basis of what is observed in nearby correlatable wells since no exposure is found and hence the amount of erosion involved is

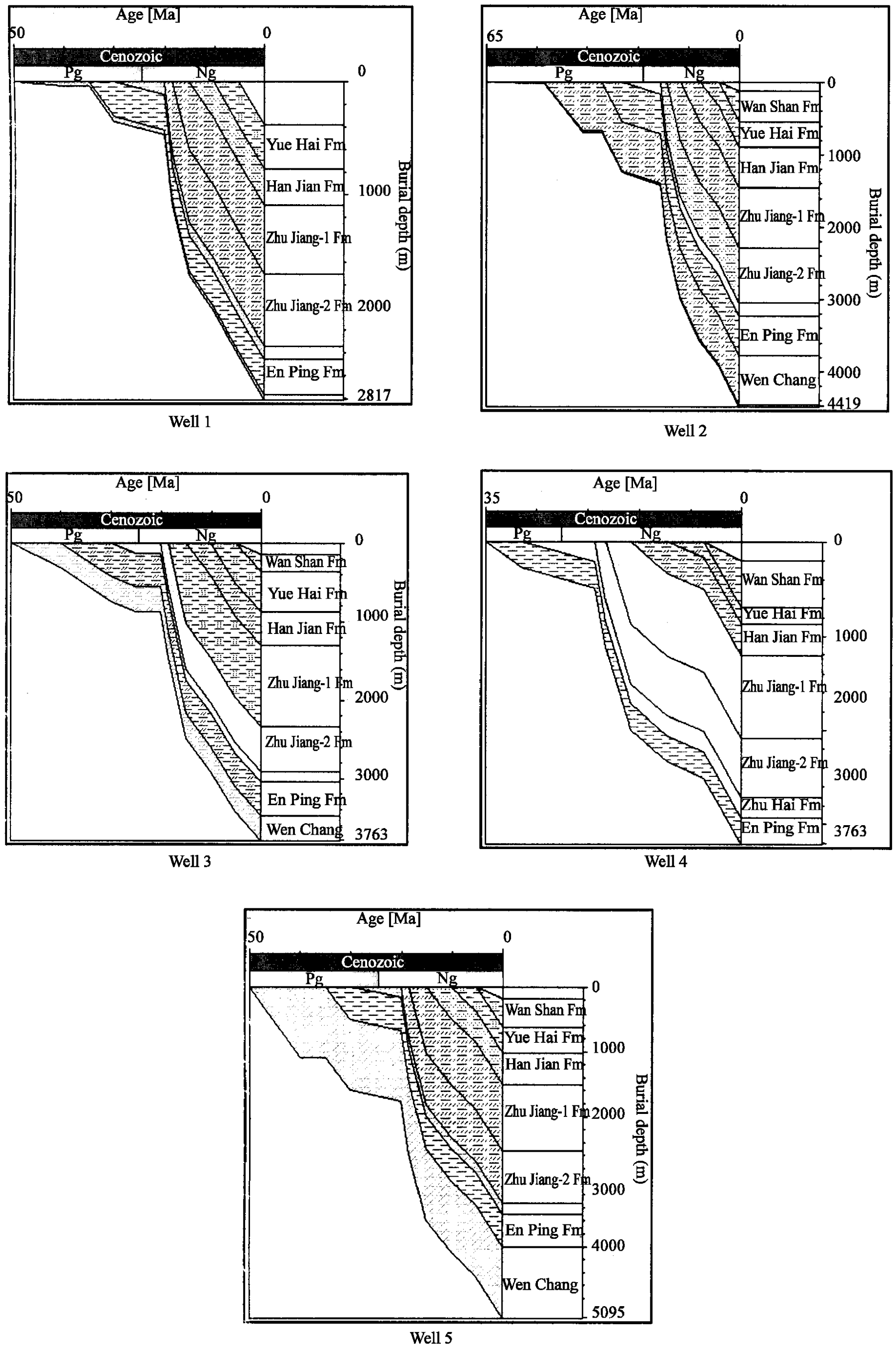

Fig. 4: Burial histories at different wells

difficult to establish. Four different geologic scenarios of burial histories have been examined by trial-and-error comparisons between measured and calculated Ro values.

Input modeling parameters: The Petromod 7.1 can simulate the burial, generation, expulsion and accumulation of oil and gas (three phase fluid flow). The modeling is divided into three categories: geological, generation and migration.

The geological modeling is responsible for the reconstruction of burial and compaction of sediments, tectonics and hydraulic fracturing, fluid flow and heat flow. The compaction is calculated based on effective stress laws and fluid flow conditions which are governed by Darcy's Law. Pressure increase is achieved either by sediments loading, fluid expansion or hydrocarbon generation. Tectonics fracturing is calculated by simplified stain analysis and hydraulic fracturing is predicted based on pore pressure distribution. Convective and conductive heat flow creates the temperatures distribution in the section.

Generation modeling is responsible for the calculation of maturation of organic matter and generation of oil and gas. A first order kinetics reaction model is applied for these calculations and multiple parallel reactions are specially used for generation.

Migration modeling is responsible for the calculation of expulsion, secondary migration, PVT conditions (dissolution of fluid) and sealing (accumulation). The expulsion and secondary migration is calculated based on Darcy's Law using the relative permeability concept.

The Petromod 7.1 software package is applied to reconstruct numerically the burial, thermal and maturation histories for five wells selected based on their suitability to be using in this software.

The burial and thermal history reconstructions took into account processes such as (1) sedimentation and consolidation of porous rocks with variable rate, (2) erosion or interruption in sedimentation, (3) change of thermo physical characteristics with lithogoly, depth and temperature of rocks and (4) and matrix heat conductivities on temperature. Temperatures in the sedimentary section calculated as function of depth are used to estimate the maturation level of the organic matter. The kinetic model of vitrinite maturation (Sweeny and Burham, 1990) is the method for maturity estimation.

In all five reconstructions, three main criteria for model validity were adopted (1) the measured values of vitrinite reflectance must be close to those calculated, as shown in Fig. 6, (2) the measured values of temperatures must be close to those calculated as in Fig. 5, (3) variations in tectonic subsidence of the basement, computed by removing of surface load, must be close to the subsidence determined from variations in density distribution in the basement column, as in Fig. 4.

Changes in thermal state and rock densities during heating and stretching of the lithosphere, intrusions and hydrothermal activity are also analyzed in the IES Petromod 7.1 basin modeling software.

The input parameters for the model include the present-day sedimentary cross section, lithology percentages of each rock unit if available and petrophysical characteristics of rocks involved, maturity indicators (vitrinite reflectance (Ro) and Rock eval T_{max} (T_{max} is the temperature at the maximum S_2 (pyrolysable hydrocarbons, mg Hcg rock^{-1})) as a function of the thermal maturity (Espitalie' *et al.*, 1984; Peters, 1986; Tissot *et al.*, 1987), paleosea depth, present-day surface temperature and computed or measured heat flow, palaeo and present day tectonic setting of the Pearl River Mouth Basin. The results of model constructed are in agreement with the data of seismological published by Daquan *et al.* (1989) and thermal studies in other sag as pointed out by the work of Zhu *et al.* (1999) in Wenchang B sag.

Lithology percentages, stratigraphic data for burial history and Bottom Hole Temperatures (BHT) data from various logging equipments were also used in this study.

RESULTS AND DISCUSSION

Well one: The well one is located on the northern margin of Pan Yu Low uplift. The TOC at this well is between 0.05-2.90%. The section is therefore organically rather good. Kerogen quality as measured by pyrolysis is somewhat variable. The section is thermally immature down to about 2370 m, below which the oil-generative zone is reached. The vitrinite reflectance value at total depth (2817 m) is 0.71%. Four formation temperatures were determined from BHT measurements using Horner plot corrections. The current heat flow of 65 mW m^{-2} is calculated at this well from the formation temperatures with seafloor temperature of 15.6°C. The vitrinite reflectance profiles are shown in Fig. 6. The vitrinite reflectance (R_0) data matched well with the present heat flow and the seabed temperature. This modeled result suggests that R_0 values can be used to evaluate the thermal maturity trend in this well.

Many oil and gas shows were encountered in this well as reported in mud logs. The En Ping and Zhu Hai Formations are regarded as the two source units in this well. However, from TOC values of the samples, it can be seen that En Ping Formation is having much higher values, which can be interpreted as the main source rock in the section. The oil generation started in this well at around 15 Ma and reached its peak at present, generation and expulsion are actually going on with little oil and dry gas as shown in Fig. 7. From the thermal modeling, using the current heat flow (projected back into the past), it is seen that, the simulated R_0 values follow in a fair to good trend the measured values. Temperature curve shows also a good fitting despite the fact that we have four temperature measurements from DST data as shown in Fig 5.

Well two: The well two is also located on the northern margin of Pan Yu Low uplift. The TOC at this well is between 0.14-1.65%. This section is organically rather fair. Kerogen quality as measured by pyrolysis is somewhat variable due to varied source of organic matter. It is

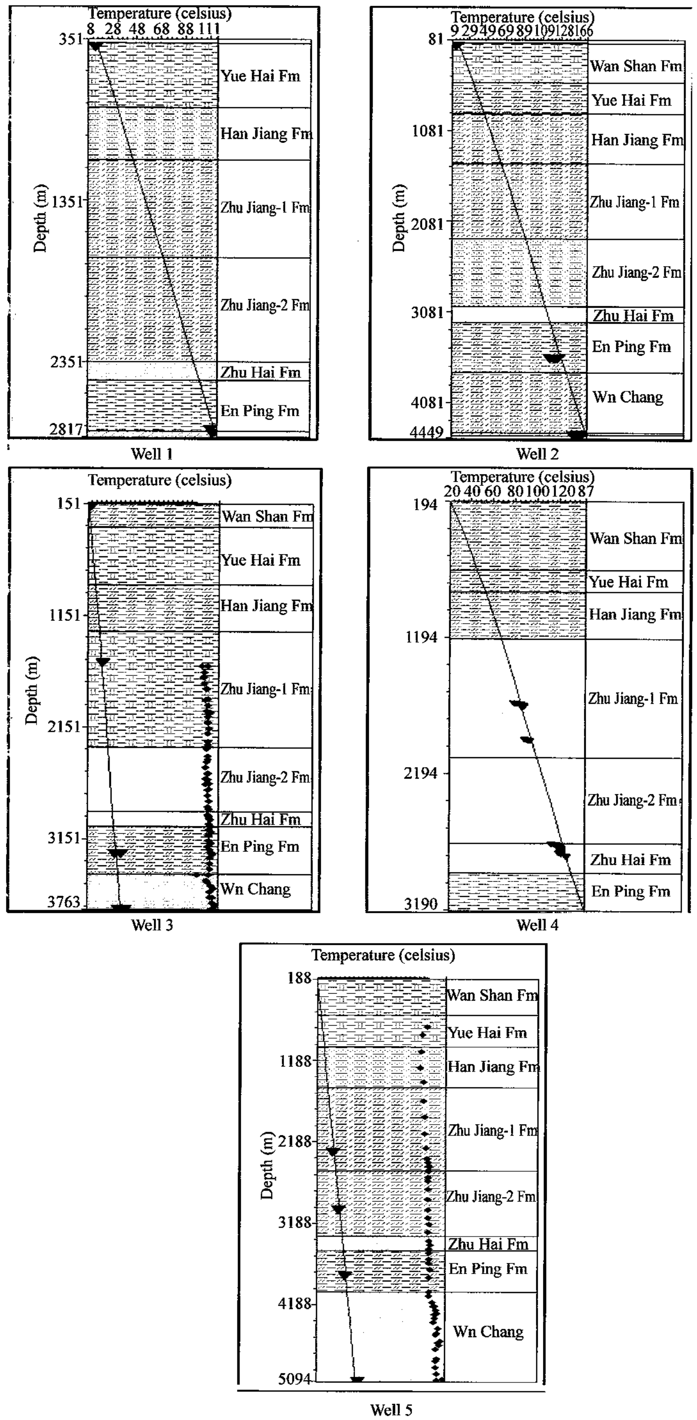

Fig. 5: Simulated temperature modeling matches with measured BHT and T_{max} at 1-5 wells

thermally immature down to about 2700 m, below which the oil-generative zone is reached. Six formation temperatures were determined from BHT measurements using Horner plot corrections. The current heat flow of 56.00 mW m^{-2} is calculated at this well from the formation temperatures with seafloor temperature of 15°C. The vitrinite reflectance profiles are shown in Fig. 6. The vitrinite reflectance (R_o) data can be matched with the

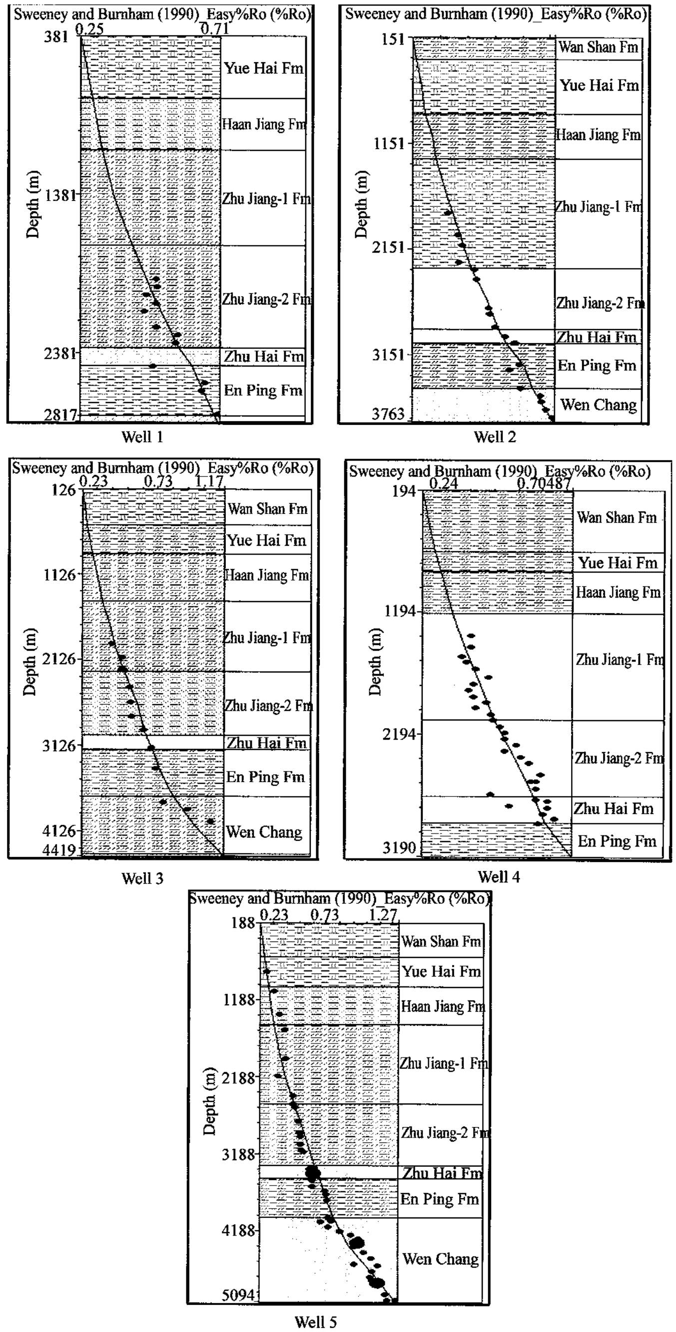

Fig. 6: Simulated Ro modeling matches with measured Ro data at 1-5 wells

present heat flow and the seabed temperature. This modeled result suggests that both R_o values can be used to evaluate the thermal maturity trend in this well.

The oil generation started in this well at around 17 Ma and reached its peak at present, generation and expulsion are actually going on with little oil and dry gas as shown in Fig. 7. From the thermal modeling, using the current heat flow (projected back into the past), it is seen that, the simulated R_o values follow in a fair to good trend the measured values. Temperature curve shows also a good fitting as shown in Fig. 5.

Well three: The well three is located on the margins of Bai Yun depression on a faulted anticlinal structure. The TOC at this well ranges between 0.1-1.97%. Kerogen quality as measured by pyrolysis is somewhat variable as

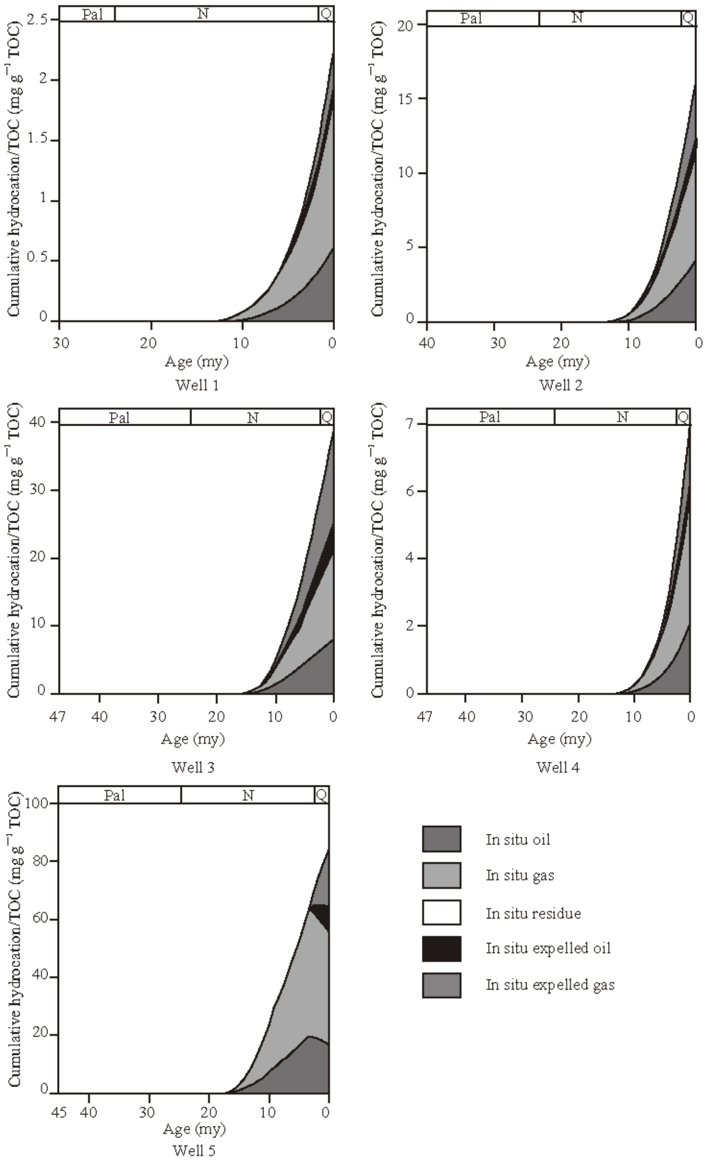

Fig. 7: Generation histories at 1-5 wells

well. The section is thermally immature down to about 3200 m, below which the oil-generative zone is reached. Vitrinite reflectance value at total depth (3724.5) is 0.73% indicating the onset of oil generation. In this well, five formation temperatures were derived from horner-plot corrections and a seafloor temperature is 20°C. The calculated current heat flow is 58.00 mW m^{-2}. From R_o values and T_{max} data, it can be seen that both support moderate thermal maturity. The best match so far obtained between the valid maturity data (T_{max} and R_o) and calculated maturity curve was obtained from transient heat flow model as shown in Fig. 6. In this well also, both R_o and T_{max} data can be matched with the present heat flow and seabed temperature. This modeled result suggests too, that both R_o and T_{max} values can be used to evaluate the thermal maturity trend in this well.

The onset of oil generation started around 14 Ma and actively generating hydrocarbon as shown in Fig. 7. The maturity curve of simulated R_o values shows a good fitting. The calculated temperature values give a good matching with the measured temperature values as shown in the Fig. 5.

Well four: Well four is located on the margins of Bai Yun depression. The TOC at this well is between 0.05-2.90%. The section is thermally immature down to about 2370 m, below which the oil-generative zone is reached. Vitrinite reflectance value at total depth is 0.71%. Eleven formation temperatures were determined from BHT measurements using Horner plot corrections. The current heat flow of 66.75 mW m^{-2} is calculated at this well from the formation temperatures with seafloor temperature of 15.6°C. The vitrinite reflectance profiles are shown in Fig. 6. The vitrinite reflectance R_0 data can be matched with the present heat flow and the seabed temperature. This modeled result suggests that R_0 values can be used to evaluate the thermal maturity trend in this well.

The oil generation started in this well at around 12 Ma and reached its peak at present, generation and expulsion are actually going on as shown in Fig. 7. From the thermal modeling, using the current heat flow (projected back into the past), it is seen that, the simulated R_0 values follow in a fair to good trend the measured values. Temperature curve shows also a good match as shown in Fig. 5.

Well five: Well five is located on margins of Bai Yun depression. The TOC at this well is between 0.94-38.65%. This section is therefore organically rather very good. Kerogen quality as measured by pyrolysis is variable. The section is thermally immature down to about 2900 m, below which the oil-generative zone is reached. Vitrinite reflectance value at total depth (5094.5) is 1.40%. Four formation temperatures were determined from BHT measurements using Horner plot corrections.

The current heat flow of 60 mW m^{-2} is calculated at this well from the formation temperatures with seafloor temperature of 15°C. The vitrinite reflectance values and T_{max} profiles are shown in Fig. 6. Both R_0 and T_{max} data can be matched with the present heat flow and the seabed temperature. This modeled result suggests that both R_0 and T_{max} values can be used to evaluate the thermal maturity trend in this well .The oil generation started in this well at around 19 Ma and generation and expulsion are actually going on, as shown in Fig. 5. From the thermal modeling, using the current heat flow, it is seen that, the simulated R_0 values follow in a fair to good trend the measured values.

CONCLUSIONS

The model presented in the present study simulates satisfactorily the thermal maturity data (R_0 and T_{max}) trends for the five wells under our study. The Cenozoic post-rifting thermal subsidence phase is satisfactorily supported by the modeling results using constant heat flows of 56.6 to 66.75 mW m^{-2} from about 50 Ma to the present-day in all wells. Possible errors in the modeled palaeoheatflow may be related to the conceptual model for this study such as single thermal event and also uncertainties from the measured maturity data, formation temperatures, palaeo-seafloor temperatures, erosional thicknesses and hiatus times from input data. Another problem touches upon the paleosea depths. The variations in these depths are not known with sufficient accuracy. These problems can be reduced if only working with stratigraphic sequences consisting with shelf-depth deposits and not with sediments deposited in deeper water. Fortunately in our cases, we work with shelf-depth deposits.

Modelling using Petrodmod 7.1 (IES) shows that the maximum paleotemperatures were attained in the source rocks (Zhu Hai, En Ping and Wen Chang Formations respectively from top to bottom) units by burial in the north of Bai Yun depression and at the margins of Pan Yu Low Uplift during late Oligocene. The T_{max} data give a good relationship with the R_0 data. Our study indicates that T_{max} are reliable and can be used to evaluate thermal maturity unlike in previous studies in the same area .High attractiveness is observed for the northeast margins of Pan Yu Low Uplift, where generation and migration of hydrocarbons (Early Miocene to Present) postdated trap formation (Early Oligocene to Early Miocene). The active source rock started expelling their hydrocarbons about 12-19 Ma (from the five wells) and the generation is still on at present in most of the areas.

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