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Hydrocarbon potential of marginal basins bounded by an island arc

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ABSTRACT

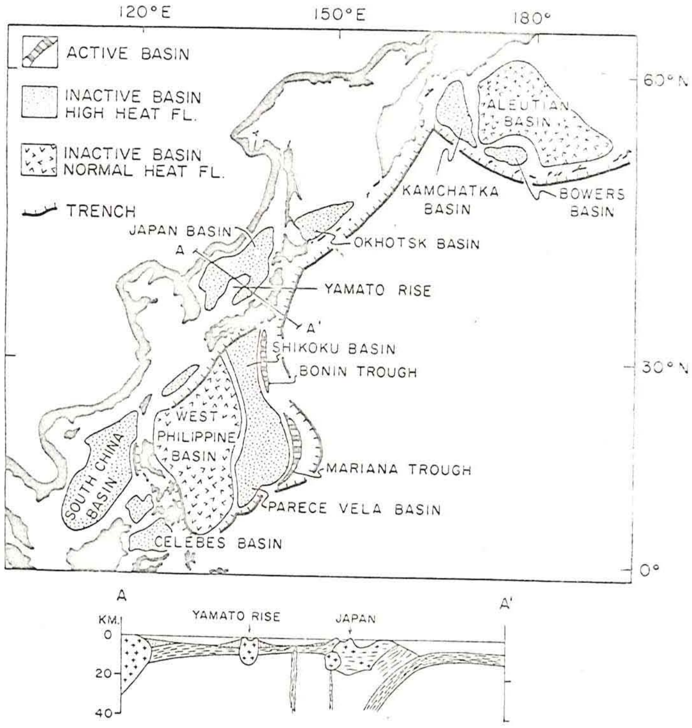
The Japan Basin is an example of a western Pacific marginal basin that is bounded by an island arc. Such basins were produced by an extensional process that involves formation of new, hot sea floor below basins that are opening as newly created arc systems migrate away from the continental borderland or older arcs. Rapid deposition of sediment on the hot basin floors allows development of steep geothermal gradients in these sedimentary prisms. In these sedimentary basins, the relationship between temperature and strata age is such that the kerogen-hydrocarbon transformation occurs in young, shallow strata. The sealing effect of turbidite deposits and the presence of numerous gravity faults ensures entrapment conditions. Hydrocarbon potential of these basins can be evaluated by considering the age of basin opening, sedimentation rates adjusted for compaction, and heat-flow data.

INTRODUCTION

Geologic and geophysical investigations of island arcs and the marginal basins that separate them from continental borderlands suggest that these marginal basins were formed by an extensional mechanism that produces new, hot, basaltic sea floor upon which the basinal sedimentary prism is deposited. Heat-flow values measured within these basins are commonly higher than normal oceanic values and indicate that steep geothermal gradients exist within the sedimentary section.

Field studies of producing oil and gas basins (Phillippi, 1965) and laboratory research on the geochemistry and kinetics of the kerogen-hydrocarbon transformation (Welte, 1972) indicate that the rate of oil and gas generation, together with accumulation and degradation, is functionally dependent on relationships between the age of the hydrocarbon-bearing strata and the temperature regime through time to which these strata have been exposed. The conclusion has been drawn that knowledge of the present, as well as past, geothermal gradients within a basin is important to the evaluation of the hydrocarbon potential of that basin. Klemme (1972a, 1972b) discussed the influence of geothermal gradients on both the size and depth distribution of oil fields of various ages and tectonic settings.

In this paper, using the Japan Basin as an example, major conclusions are integrated from the geochemical and field studies in order to outline an approach to the evaluation of hydrocarbon potential in marginal basins. The approach uses data on heat flow, thermal conductivity, and basin geometry to provide a picture of the thermal structure within the sedimentary fill of the basin. The relationship of temperature versus strata age that governs hydrocarbon generation is considered within the framework of the thermal structure to determine if the sediment has been subjected to the "correct" temperature regime for the "proper" period of time in order for significant oil and gas generation to have occurred.



(NOT TO MAP SCALE)

Figure 1. Marginal basins of northwest Pacific and cross section through Japan Basin (after Karig, 1971, 1974).

DISCUSSION

In a series of papers, Karig (1971, 1974) developed the hypothesis that the marginal basins of the western Pacific (Fig. 1) were formed essentially by extension. The kinematics postulated are simply that the island arc migrates relatively away from the mainland toward the oceanic plate after the breaking up of the continental margin. New sea floor is created between the migrating arc and the mainland. This new basin floor becomes the site of sediment accumulation. According to Karig's scheme,

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pulses of extension may produce complex marginal basins characterized by remnant arcs, such as the Yamato Rise in the Japan Basin (Fig. 1).

Heat-flow measurements within these marginal basins (Fig. 2) indicate that, given representative thermal conductivity values within their respective sedimentary covers, the basaltic basements of the marginal basins are considerably hotter than the upper surface of the plate of oceanic basalt seaward of the trench. Whatever the heat-producing and heat-transporting mechanism is beneath these marginal seas, it is sufficient for the purposes of this paper to demonstrate that steep geothermal gradients exist and most likely existed in the past in the sediment that is accumulating on the new sea floor.

On the basis of study of approximately 45,000 km of seismic reflection and bathymetric records, the heat-flow data of Yasui and others (1968), and Karig's model, Hilde and Wageman (1973) postulated that the Japan Basin first opened during a Cretaceous extensional pulse along a northeast-trending axis between the Yamato Rise and the Chinese borderland. A second extensional pulse began about 22 m.y. B.P. and further opened the Japan Sea along another northeast-trending axis between the Japanese islands and the Yamato Rise. Sediment thicknesses of as much as 2.2 and 2.6 km were found by Hilde and Wageman (1973) along the eastern and western margins of the basin, respectively. Figure 2 shows a generalized interpretation of the structure of the Japan Basin along a line from central Honshu to the Chinese borderland. The basin is characterized by high heat-flow values of from 2.0 to 2.5 μcal/cm^2/sec over areas corresponding to the extensional axes and by lower values of 1.5 to 2.0 μcal/cm^2/sec over the Yamato Rise. Other pertinent characteristics include high sedimentation rates due to intense volcanic activity, relatively high biological productivity of the surface waters in the Sea of Japan, the proximity of large land masses drained by major rivers, and the occurrence of turbidity currents. Sedimentation rates as great as 180 m/m.y. were noted at DSDP site 301 on the northwest flank of the Yamato Rise (Ingle and others, 1973) where Miocene diatomite deposits are overlain by Pliocene-Pleistocene distal turbidite deposits.

The temperature structure within the sedimentary prism in the Japan Basin can be approximated (after making suitable assumptions) by a heat-flow modeling program (D. Langenkamp and J. Combs, in prep.). A finite difference approximation was made to the heat-conduction equations, and the resulting set of simultaneous equations was solved by the method of successive overrelaxation (Young, 1954). The temperature distribution in the subsurface was calculated from the input of an arbitrary two-dimensional thermal conductivity structure and specified boundary conditions. The boundary conditions can consist of heat-flow values, heat-source distributions, and (or) fixed temperatures.

For the case study of the Japan Basin from the Yamato Rise to the Chinese borderland, Hilde and Wagemen's (1973) isopach data on the geometry of the sedimentary prism were used to fix the thermal conductivity structure. The values along the heat-flow profile, used as heat-sink inputs at the sediment-water interface, were taken from Yasui and others (1968). Temperatures of 4°C at the sediment-water interface and of 800°C for the intrusive body (Fig. 3) were assumed. All other temperature nodes were unspecified. The raw data from the computer program were temperatures printed out on a grid representing nodes 500 m apart vertically and 10 km apart horizontally. Figure 3 presents the hand-contoured output of the computer program—the subsurface isothermal distribution and heat-flow (Q) profile over the northwestern part of the Japan abyssal plain. Geothermal gradients were calculated; their steepness is considered critical to the depth at which formation of hydrocarbons takes place.

Phillippi (1965) studied the relationship between geothermal gradients and the depths at which oil generation occurred in the Los Angeles and Ventura basins. He concluded that the hydrocarbon content of a basin, given suitable source beds and trapping situations, was largely dependent on the length of time the sedimentary deposits had been exposed to temperatures higher than those needed to initiate the kerogen-hydrocarbon transformation. Since Phillippi's (1965) study, the geochemistry of the kerogen-hydrocarbon transformation has been examined in considerable detail. Tissot and others (1974) summarized the chemical changes involved. These changes include the decrease of the carbon-atom number of the *n*-alkanes, the ring number of the cycloalkanes, and the carbon-atom number of the aromatics. The chemical pathway followed during the transformation of the original organic material (biopolymers) through kerogen to oil and gas (geomonomers) takes place in several diagenetic realms and involves a complex series of reactions as shown in Table 1.

Figure 4 is a plot of various data on the relationship of temperature versus strata age that prevails during the kerogen-hydrocarbon transformation in oil- and gas-producing basins. In this paper, the kerogen-hydrocarbon transformation is discussed in a general sense, although it is realized that different kerogen types (woody and [or] coaly versus sapropelic) will yield oil over different time periods and temperature ranges. Connan

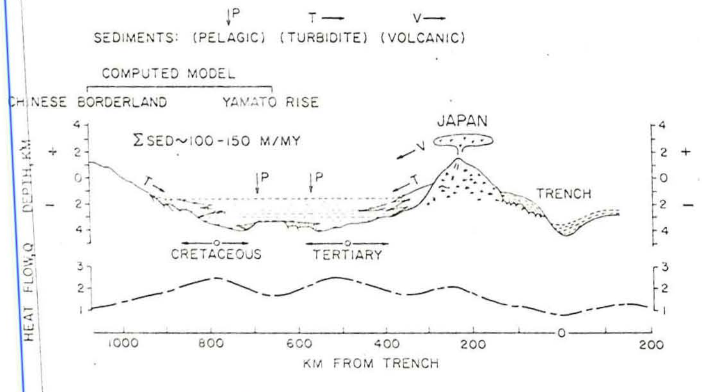

Figure 2. Generalized cross section from Chinese borderland through Japan Trench showing pertinent geologic, sedimentologic, and geophysical features (based on data from Hilde and Wageman, 1973; Yasui and others, 1968; Kitamura and Onuki, 1973; Ingle and others, 1973).

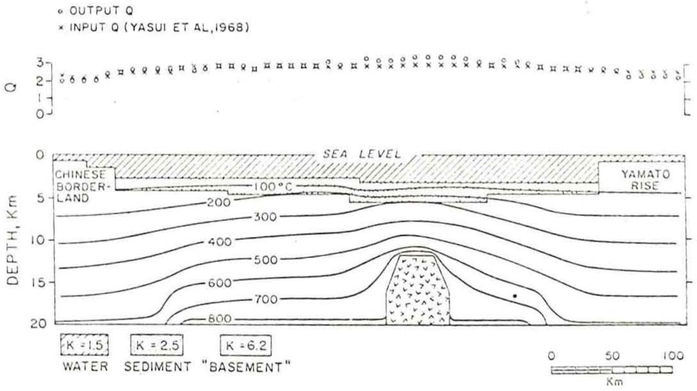

Figure 3. Computer-modeled, hand-contoured plot of subsurface isothermal distribution beneath Japan abyssal plain.

TABLE

Surface degradation

25°C, 1 m

50°C, 1,000 m

175°C, 6,000 m

Note: After I. R.

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TABLE 1. MATURATION OF HYDROCARBONS AS A FUNCTION OF TEMPERATURE AND DEPTH OF BURIAL

Surface degradation	Biopolymers:	carbohydrates proteins lipids lignin
25°C, 1 m	Biomonomers:	sugars amino acids fatty acids phenols
	Geopolymers:	kerogen and humic material
50°C, 1,000 m	Diagenesis:	reduction decarboxylation deamination cyclization demethylation thermal alteration cracking
175°C, 6,000 m	Geomonomers:	low-molecular-weight hydrocarbons other organic compounds

Note: After I. R. Kaplan, unpub. data.

(1974), using data similar to those plotted in Figure 4 plus his experimental data, applied kinetic laws for first-order reactions to the kerogen-hydrocarbon transformation to arrive at the equation

$$\log t\ (10^6\ \mathrm{yr}) = 3.014/T\ (°\mathrm{K}) - 6.498.$$

Analysis of the field data shown in Figure 4 indicates the complex relationship of temperature versus strata age. Perhaps in nature, the kerogen-hydrocarbon transformation is not taking place isothermally as is the assumption in analysis of first-order reactions.

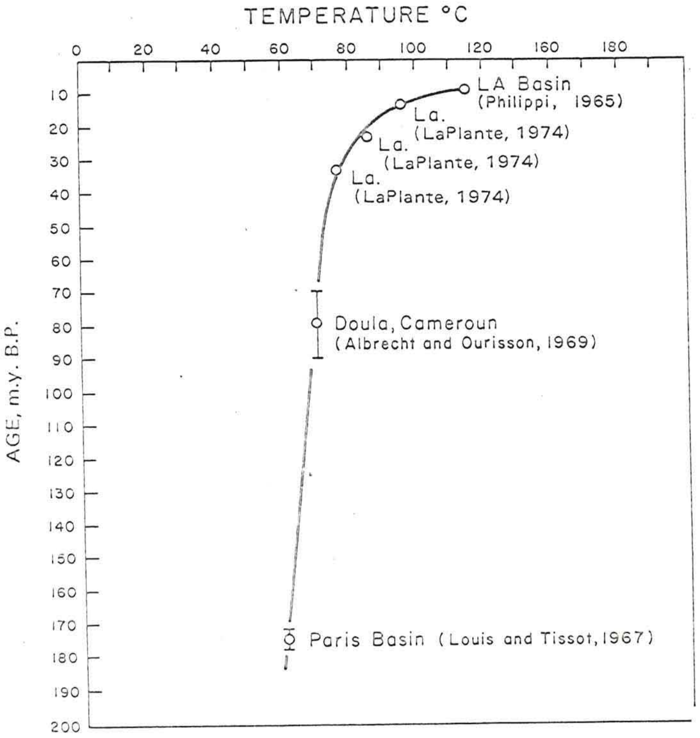

Figure 4. Plot of temperature at which initiation of hydrocarbon generation has been observed versus age of containing strata in various oil- and gas-producing basins.

Application of these studies to the geology and geophysics of marginal basins and the geochemistry of the kerogen-hydrocarbon transformation can be discussed with Figure 5 as a reference. The columns on the right in Figure 5 represent the stratigraphic sections that would result from sediment accumulating at rates of 150 and 100 m/m.y. with regular compaction of clay-rich sediment. As shown in the columns, the postcompaction boundaries of each million years' accumulation of sediment can be determined by using the method of compaction evaluation of Perrier and Quiblier (1974), thereby establishing absolute time scales within the strata.

Values used in the computer model in Figure 3 are from curve A, which represents the geothermal gradient generated by assuming a heat flow Q of 2.5 μcal/cm^2/sec and constant thermal conductivity K of 2.5 mcal/cm•sec•°C throughout the section. Actually, because of compaction and consequent increase in bulk density, the value of K generally increases with depth. Curve B was plotted by using various values for K: 2.4 for the 0- to 500-m interval, 3.0 for the 500- to 1,000-m interval, and 3.4 for depths greater than 1,000 m. These K values were given by Marshall and Erickson (1974) for sediment cored at DSDP sites 241 to 249. The effect on the shape of the geothermal gradient of upward-percolating water that is expelled from the compacting sediment (Panda, 1973) is not considered in our analysis. According to von Herzen 1973), the effect in rapidly accumulating sections would be quite small.

Curves C and C′ are the data on age of strata versus temperature from Figure 4 replotted using the time scales in the columns on the right in Figure 5. Curve C is plotted against the 150 m/m.y. section. Curve C′ is plotted against the 100 m/m.y. section. The geothermal gradient is assumed to be established in a steady-state condition as the sediment accumulates and compacts (Panda, 1973). Hydrocarbon generation from the contained kerogen would commence in strata as young as 10 to 11 m.y. old in the section deposited at 150 m/m.y. (as shown by the intersections of curves A and B with curve C) and in strata 13.5 to 14.5 m.y. old in the section deposited at 100 m/m.y. (as shown by the intersections of curves A and B with curve C′).

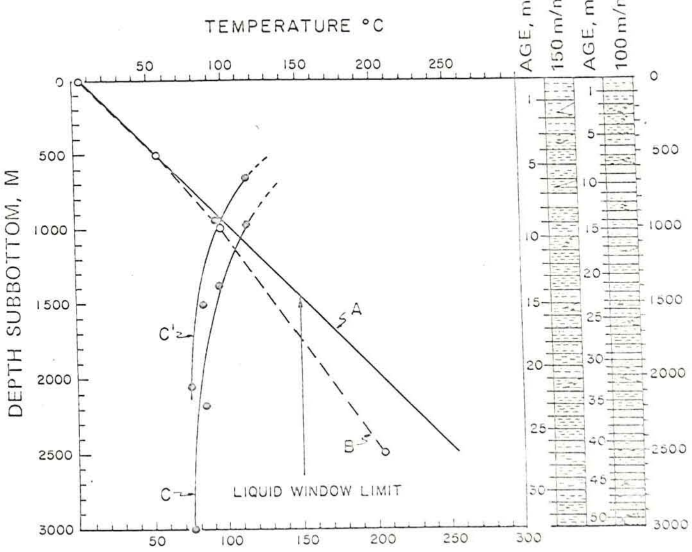

Figure 5. Geothermal gradients (curves A and B): age and thickness of sedimentary fill; and time, depth, and temperature conditions (curves C and C′) of initiation of hydrocarbon generation in a marginal basin. Circles are data points (see text for sources of data).

If Pusey's (1973) end-limit temperature of 150°C is accepted for the purpose of illustration, maturation of these hydrocarbons would continue until temperatures reached the upper temperature limit of the "liquid window" at 150°C. At this temperature and above, the destruction of liquid hydrocarbons dominates, and thermal gas is the end product of the kerogen-hydrocarbon transformation (Tissot and others, 1974). Thus, strata older than 14.5 m.y. (intersection of 150°C line with curve A) or 17.5 m.y. (intersection of 150°C line with curve B) in the section deposited at 150 m/m.y. would contain thermal gas. At a sedimentation rate of 100 m/m.y., thermal gas would be present in strata older than 22.5 m.y. (curve A) or 27 m.y. (curve B). These ages are well within the age range of strata in the Japan Basin. That such a marginal basin contains suitable stratigraphic traps is indicated by the fact that flows of ethane gas hampered drilling (Ingle and others, 1973) at DSDP site 299 between Japan and the Yamato Rise and at DSDP site 301 between the Yamato Rise and the Chinese borderland. Both gas occurrences at subbottom depths of less than 500 m were at the boundary between diatomite deposits of late Miocene age and overlying turbidite deposits of Pliocene-Pleistocene age. The impermeable turbidite section evidently had prevented the upward migration of gas.

CONCLUSIONS

The oil and gas potential of a marginal basin bounded by an island arc (for example, the Japan Basin) depends on the age of the extensional pulses that created it and the rate and duration of the extension. The basin geometry is determined by the age of opening and rate of extension, whereas the geometry of the sedimentary prism is determined by the sedimentation rate adjusted for compaction. The extensional pulse history also plays a role in the distribution and abundance of horst-and-graben or gravity-fault structures that can provide hydrocarbon-migration traps. As is the case in the Tertiary basins of Sumatra (Wennekers, 1958) and in the Tertiary and Mesozoic strata of Iraq (Dunnington, 1958), pelagic sediment within the sedimentary prism can serve as source beds. Similarly, river-borne sediment drained from large adjacent land masses can contain abundant source material as does the modern sediment of the Yellow Sea (Wageman and others, 1970). Permeability seals are provided by intercalated turbidite deposits. The texture, thickness, and frequency of occurrence of turbidite deposits in the section are a function of the geology, rate of erosion, and areal extent of the bounding land masses. Volcanic activity can contribute abundant montmorillonite, which enhances the kerogen-hydrocarbon transformation because of its catalytic effect (Andreev and others, 1968; Johns and Shimoyama, 1972). The insulating effect of the rapidly accumulating sedimentary prism on the new, hot basin floor results in the development of steep geothermal gradients, hence thin "liquid windows," and probably in very shallow production of hydrocarbons.

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ACKNOWLEDGMENTS

Reviewed by Leigh C. Price, Paul Morgan, and Dewey A. Baker. Schlanger supported by the University of California Intramural Research Fund; Combs supported by a research grant to the University of Texas at Dallas from Gulf Mineral Research Company.

We thank Lewis H. Cohen and Tien-Chang Lee for helpful discussions.

Contribution number 283, Institute for Geosciences, University of Texas at Dallas, P.O. Box 688, Richardson, Texas 75080.

MANUSCRIPT RECEIVED APRIL 10, 1975

MANUSCRIPT ACCEPTED MAY 6, 1975

ABSTRACT

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INTRODUCTION

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