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Thermal Mechanisms of Basin Formation [and Discussion]

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Thermal mechanisms of basin formation

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Thermal subsidence of the sea floor explains the observed bathymetry of ocean ridges. A similarity solution for a one-dimensional cooling model successfully predicts bathymetry, heat flow and geoid anomalies under a wide range of conditions. This similarity solution can be modified to predict the thermal subsidence of sedimentary basins. For older sedimentary basins it is necessary to consider an input of heat to the base of the lithosphere that places a limit on subsidence. The similarity solution for thermal subsidence is in quite good agreement with the observed subsidence history of a variety of sedimentary basins. Some basins subside freely and in others the flexural rigidity of the elastic lithosphere inhibits subsidence.

An empirical model is proposed for the conversion of kerogen to oil and the subsequent conversion of oil to gas. This model is then used in conjunction with the thermal evolution predicted by the similarity solution in order to determine the oil window and relative volume of oil as a function of the age of the basin.

Introduction

Sedimentary basins can be formed in a variety of ways. The subsidence history of many sedimentary basins appears to be consistent with a thermal time constant (Sleep 1971; Sleep & Snell 1976). As the lithosphere cools and thickens, the lithospheric rocks become more dense owing to thermal contraction. Isostatic subsidence follows and a sedimentary basin is formed. The time constant for thermal subsidence is of the order of 50 Ma. For smaller basins the flexural rigidity of the elastic lithosphere restricts the subsidence.

If the lithosphere initially has zero thickness, a similarity solution for the thermal structure of the lithosphere and sedimentary basin as well as the subsidence of the basin can be obtained (Turcotte & Ahern 1977). The primary advantage of a similarity solution is that an analytic solution is obtained. This similarity solution has been used to predict the thermal subsidence of the Los Angeles Basin (Turcotte & McAdoo 1979) and the Baltimore Canyon Trough (Angevine & Turcotte 1981) and is in quite good agreement with observations.

Lithospheric thinning must precede thermal subsidence. One mechanism for lithospheric thinning is the diapiric replacement of cold lithospheric rock by hot mantle rock. A variation on this hypothesis is the convective heating of the lithosphere due to the upward migration of magma (Lachenbruch 1978). An alternative hypothesis is lithospheric delamination (Bird 1979). In this hypothesis the lower part of the dense lithosphere breaks away and founders into the asthenosphere. The cold rocks of the delaminated lithosphere are replaced by hot asthenospheric rocks.

Lithospheric thinning would be expected to lead to crustal uplift through isostasy. Continental domes such as the Ethiopian Swell and the East African Swell on the East African Rift system, the Tibesti uplift, and the uplift associated with the Rhine Graben are attributed to this mechanism.

In many cases lithospheric thinning is associated with continental rifting. The horizontal strain associated with rifting can lead to crustal thinning (Bott 1976; McKenzie 1978; Jarvis & McKenzie 1980). Crustal thinning results in isostatic subsidence and the formation of a sedi-

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mentary basin. Subsequently, thermal subsidence can occur. Partial rifting can lead to a sedimentary basin within a continent such as the North Sea Basin. If rifting leads to the formation of an ocean basin, sedimentary basins can form on the passive continental margins. There are a number of examples along the margins of the Atlantic Ocean (Keen 1979).

In some cratonic basins there is no evidence for tectonic thinning or thermal uplift before the initiation of subsidence, even though the subsidence exhibits a thermal time constant. An example is the Michigan Basin. The subsidence of this basin requires an increase in density of the rocks within the elastic lithosphere. One hypothesis that explains this increase in density is that a phase change is occurring in the deep crustal rocks; an example of such a phase change is the transformation of basalt to eclogite (Joyner 1967; Haxby *et al.* 1976).

One purpose for studying the subsidence and thermal structure of sedimentary basins is to determine the location of oil in a sedimentary basin. If the thermal history is known, the conversion of kerogen to oil and the subsequent conversion of oil to gas can be studied. We first consider this problem and then introduce several similarity solutions.

Petroleum generation

In the upper few metres of subsiding sedimentary basins, organic molecules such as lignin, carbohydrates and proteins are broken down as a result of microbial action. The remaining portion of organic sediment undergoes a chemical condensation that produces molecules of high molecular mass. With increasing depth these macromolecules become even more insoluble; the end result is the petroleum precursor kerogen. As temperature increases progressively with depth the molecular structure of kerogen is altered, giving off medium and high mass hydrocarbons or oil in the process (Tissot & Welte 1978).

Tissot & Espitalie (1975) proposed a quantitative model for the rate of thermal alteration of kerogen to petroleum (petroleum includes both oil and gas):

$$\frac{\mathrm{d}n_{\mathrm{k}i}}{\mathrm{d}t} = -n_{\mathrm{k}i} A_i \exp\left(-\frac{E_i}{RT}\right) \quad i = 1, 2, \ldots, 6, \tag{1}$$

where $n_{\mathrm{k}i}$ is the mass fraction of the ith kerogen, E_i is its activation energy and A_i is a pre-exponential factor, R is the universal gas constant and T is thermodynamic temperature. The mass fraction of petroleum created at a particular horizon is

$$n_{\mathrm{p}} = n_{\mathrm{p}0} + \sum_{i=1}^{6} (n_{\mathrm{k}i0} - n_{\mathrm{k}i}) \tag{2}$$

where $n_{\mathrm{p}0}$ represents the fraction of petroleum due to microbial action (such as the synthesis of lipids) and $n_{\mathrm{k}i0}$ is the mass fraction of the ith kerogen that was present initially. Values of $n_{\mathrm{k}i0}$, A_i and E_i are given in table 1 for the six type I kerogens of Tissot & Espitalie 1975); they also give $n_{\mathrm{p}0} = 0.05$. This model has been used with good results to estimate the thermal maturity of the Los Angeles Basin (Turcotte & McAdoo 1978) and the Baltimore Canyon Trough (Angevine & Turcotte 1981).

If the altered kerogens and their liquid petroleum by-products are buried to even greater temperatures, carbon–carbon bonds will crack to produce gas. Oil is destroyed during the cracking process. We have constructed a simple model based on a rate equation of the form (1) to account for the generation of oil and its subsequent destruction. Figure 1 illustrates the conversion

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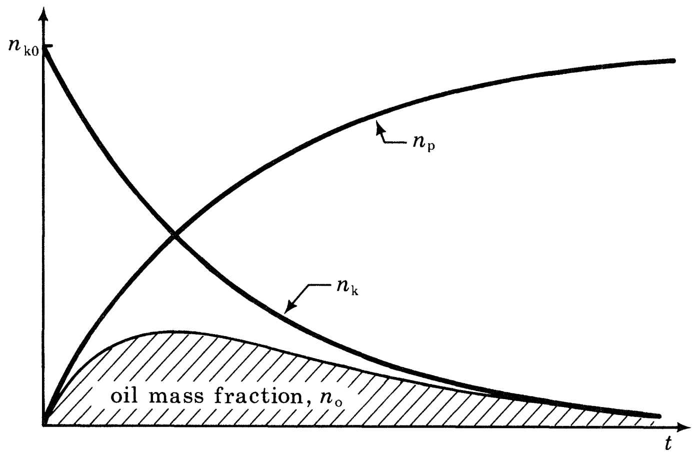

FIGURE 1. Mass fractions of kerogen, petroleum and gas as a function of time.

TABLE 1. PROPERTIES OF TYPE I KEROGEN

(From Tissot & Espitalié (1975).)

i	E / kJ mol^{-1}	A_i / Ma^{-1}	n_{ki0}
1	42	4.75×10^{4}	0.024
2	125	3.04×10^{16}	0.064
3	209	2.28×10^{25}	0.136
4	251	3.98×10^{30}	0.152
5	293	4.47×10^{31}	0.347
6	335	1.10×10^{34}	0.172

of kerogen to oil and gas at a single sedimentary horizon. We assume that the mass fraction of kerogen decreases at the rate

$$\frac{dn_k}{dt} = -n_k A \exp\left(-\frac{E}{RT}\right), \tag{3}$$

while the petroleum mass fraction increases at the rate

$$\frac{dn_p}{dt} = -\frac{dn_k}{dt}, \tag{4}$$

where n_k and n_p are related by

$$n_k + n_p = n_{k0}. \tag{5}$$

We further assume that the mass fraction of oil n_o present at any time is given by

$$n_o = n_k n_p / n_{k0}. \tag{6}$$

This is an empirical relation that is consistent with the thermally activated conversion of kerogen to oil and the subsequent cracking of oil to produce gas. Substituting (5) into (6) yields

$$n_o = n_k(n_{k0} - n_k)/_{k0}. \tag{7}$$

The rate of petroleum formation may be obtained by differentiating (7) with respect to time and substituting for dn_k/dt from (3)

$$\frac{dn_o}{dt} = \left(2\frac{n_k}{n_{k0}} - 1\right) n_k A \exp\left(-\frac{E}{RT}\right). \tag{8}$$

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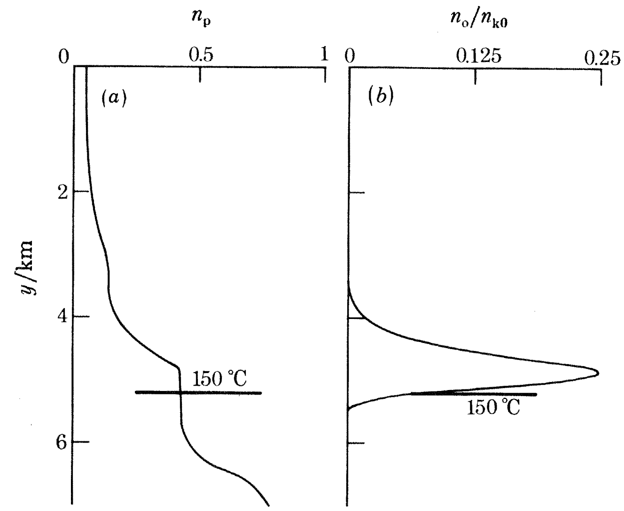

FIGURE 2. (a) Mass fraction of petroleum as a function of depth after 50 Ma with $T_0 = 20$ °C and a constant thermal gradient $\mathrm{d}T/\mathrm{d}y = 25$ K km^{-1} from (1) and (2) and values given in table 1. (b) Corresponding mass fraction of oil from (8) with $A = 1.3 \times 10^7$ Ma^{-1} and $E = 230$ kJ mol^{-1}.

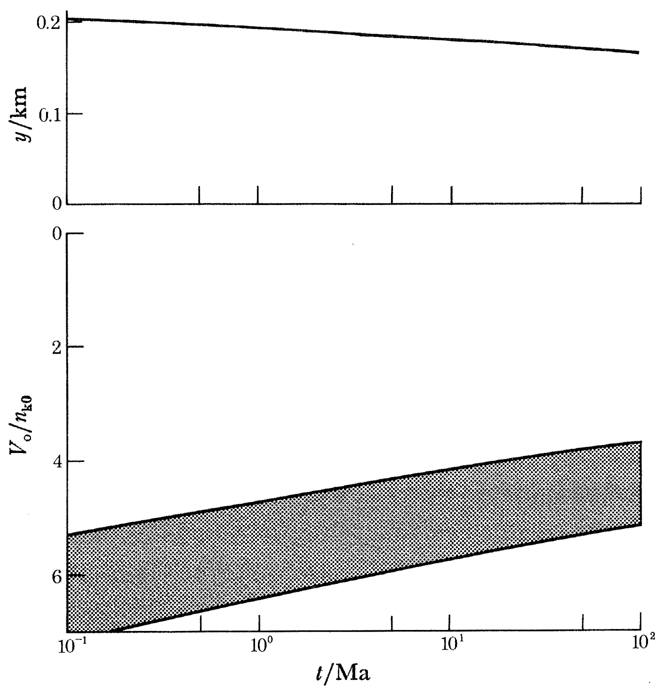

FIGURE 3. The oil window and volume of oil as a function of age in a sedimentary basin with $T_0 = 20$ °C and a constant thermal gradient $\mathrm{d}T/\mathrm{d}y = 25$ K km^{-1}.

If the constants A and E of the rate equation are known, then (7) may be evaluated over the depth of the sedimentary basin to determine the position of the oil window.

To calibrate our petroleum model with that of Tissot & Espitalie we consider a 10 km thick sequence of sediment that has been exposed to a constant thermal gradient of 25 K km^{-1} and a surface temperature of 20 °C for 50 Ma. Figure 2*a* shows the mass fraction of kerogen converted

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to petroleum as a function of depth from (1) and (2). The 150 °C isotherm is thought to be the oil limit, that is the temperature above which oil cannot survive for long periods. For this thermal history the zone of maximum petroleum production lies between 3.8 and 5.2 km in depth. In comparison, figure 2*b* shows the oil window predicted by our model. Here we take the rate constants to be $A = 1.3 \times 10^{27}\ \mathrm{Ma^{-1}}$ and $E = 230\ \mathrm{kJ\ mol^{-1}}$; these values will be used in all subsequent calculations. The bulk of production occurs between the depths of 4.0 and 5.2 km. It is possible to calculate the area under this curve and to determine the volume of oil in the sediment. The volume obtained is only important in a relative sense because the volume of organic material in the sediment is generally not known. Also, we do not consider the upward or lateral migration of oil. A significant fraction of the oil produced may be lost to the surface.

The position of the oil window and the volume of oil in the producing zone depends upon the thermal history of the sediments. Before proceeding to more complicated thermal histories it is worthwhile to understand how our oil model behaves in a simple situation. Once again we consider a 10 km thickness of sediment. The thermal gradient is held at $25\ \mathrm{K\ km^{-1}}$ while the surface temperature is fixed at 20 °C. Figure 3 shows the oil volume and location of the oil window as a function of time. The oil window is defined by the condition $n_o/n_{k0} > 0.01$ and the volume of oil V_o is given by

$$V_o = \int_0^\infty (n_o/n_{k0})\, \mathrm{d}y. \tag{9}$$

Time is plotted on a logarithmic scale between 0.1 and 100 Ma.

Depth to the oil window (the stippled region) decreases rapidly in the first 10 Ma, and more gradually afterwards. As shown in the upper part of figure 3, the petroleum volume also increases at first rapidly and then more slowly. Below the 150 °C isotherm, at depths greater than 5.2 km, petroleum is rapidly created and then destroyed. Above this limit more time is needed to create petroleum but its subsequent destruction occurs much more slowly.

Since it is unlikely that 6 km of sediments will be deposited in 100 000 years the production of petroleum in young sedimentary basins is likely to be dominated by the time-dependent history of sedimentation and the thermal history of the basin. In the next section we shall develop a similarity solution for this problem.

Similarity solution

A similarity solution for the subsidence of sedimentary basins can be obtained if several assumptions and approximations are made. These include the following.

(i) It is assumed that initially at $t = 0$ the temperature of the basement rock is a constant T_m and that a constant melt fraction χ_m is present. This is equivalent to assuming that a uniform asthenosphere reaches the surface.

(ii) It is assumed that sediments fill the basin caused by subsidence. At $t = 0$ basement rock fills the region $y > 0$. The position of basement as a function of time is $y_b(t)$. Sediments of density ρ_s fill the region $0 < y < y_b$. The model is illustrated in figure 4. In order to simplify the analysis we further assume that the physical properties of the sediments and basement rock are constant, and we neglect compaction. These assumptions are not necessary in order to obtain a similarity solution.

As the lithosphere cools and thickens, the original surface subsides owing to isostatic subsidence.

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The surface is covered by a thickening layer of sediments. The temperature within the sediments satisfies the equation (Carslaw & Jaeger 1959, p. 148)

$$\frac{\partial T_s}{\partial t}+v\frac{\partial T_s}{\partial y}=\kappa\frac{\partial^2 T_s}{\partial y^2}, \tag{10}$$

where v is the subsidence velocity and κ is the thermal diffusivity. The temperature within the basement satisfies the equation

$$\frac{\partial T_b}{\partial t}+v\frac{\partial T_b}{\partial y}=\kappa\frac{\partial^2 T_b}{\partial y^2}. \tag{11}$$

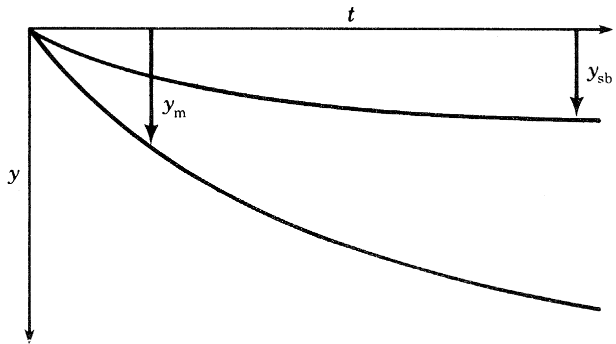

FIGURE 4. Illustration of the similarity model for thermal subsidence.

The boundary condition on the temperature at the surface is $T = T_0$. The temperature and heat flow must be continuous at the sediment–basement interface. Thus we have

$$T_s = T_b \quad \text{and} \quad \frac{\partial T_s}{\partial y}=\frac{\partial T_b}{\partial y} \quad \text{at} \quad y = y_{sb}. \tag{12}$$

The base of the lithosphere is a solidication front migrating through the asthenosphere (Oldenburg 1975). The heat flux at the lithosphere–asthenosphere boundary must match the heat produced by the solidification. Thus we have

$$T_b = T_m,\ \chi_m \rho_m L\frac{\mathrm{d}y_m}{\mathrm{d}t}=k\frac{\partial T_b}{\partial y} \quad \text{at} \quad y = y_m, \tag{13}$$

where χ_m is the melt fraction present in the asthenosphere.

The governing equations are reduced to total differential equations by introducing the similarity variable

$$\eta = y/(\kappa t)^{\frac{1}{2}}. \tag{14}$$

Substitution of (14) into (10) and (11) gives

$$(\lambda_s-\tfrac{1}{2}\eta)\frac{\mathrm{d}T_s}{\mathrm{d}\eta}=\frac{\mathrm{d}^2T_s}{\mathrm{d}\eta^2} \tag{15}$$

and

$$(\lambda_s-\tfrac{1}{2}\eta)\frac{\mathrm{d}T_b}{\mathrm{d}\eta}=\frac{d^2T_b}{\mathrm{d}\eta^2}. \tag{16}$$

In order to obtain a similarity solution we further require that

$$y_{sb} = 2\lambda_s(\kappa t)^{\frac{1}{2}}, \tag{17}$$

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where λ_s is a constant that must be determined. The velocity of subsidence is

$$v = \mathrm{d}y_{sb}/\mathrm{d}t = \lambda_s(\kappa/t)^{\frac{1}{2}}. \tag{18}$$

We further require that

$$y_m = 2\lambda_m(\kappa t)^{\frac{1}{2}}, \tag{19}$$

where λ_m is a constant that must be determined.

The solution of (15) that satisfies the boundary condition $T_s = T_0$ at $\eta = 0$ is

$$T_s - T_0 = C\{\mathrm{erf}\,\lambda_s - \mathrm{erf}\,(\lambda_s - \tfrac{1}{2}\eta)\}. \tag{20}$$

The solution of (16) that satisfies the boundary condition $T_b = T_m$ at $\eta = 2\lambda_m(y = y_m)$ is

$$T_m - T_b = B\{1 - \mathrm{erf}\,(\tfrac{1}{2}\eta - \lambda_s)/\mathrm{erf}\,(\lambda_m - \lambda_s)\}. \tag{21}$$

In order to satisfy the matching condition on temperature at $\eta = 2\lambda_s(y = y_s)$, we require

$$T_0 + C\,\mathrm{erf}\,\lambda_s = T_m - B. \tag{22}$$

In order to satisfy the matching condition on the heat flux at $\eta = 2\lambda_s$ $(y = y_s)$ we require

$$C = B/\mathrm{erf}\,(\lambda_m - \lambda_s). \tag{23}$$

Substitution of (22) and (23) into (20) and (21) gives

$$\frac{T_s - T_0}{T_m - T_0} = \frac{\mathrm{erf}\,\lambda_s - \mathrm{erf}\,(\lambda_s - \frac{1}{2}\eta)}{\mathrm{erf}\,(\lambda_m - \lambda_s) + \mathrm{erf}\,\lambda_s} \tag{24}$$

and

$$\frac{T_m - T_b}{T_m - T_0} = \frac{\mathrm{erf}\,(\lambda_s - \lambda_s) - \mathrm{erf}\,(\frac{1}{2}\eta - \lambda_s)}{\mathrm{erf}\,(\lambda_m - \lambda_s) + \mathrm{erf}\,\lambda_s}. \tag{25}$$

We next satisfy the condition on the heat flux at $\eta = 2\lambda_m(y = y_m)$ given in (13) and from (14), (19) and (25) we obtain

$$\frac{\chi_m \pi^{\frac{1}{2}}}{c_p(T_m - T_0)} = \frac{\mathrm{e}^{-(\lambda_m - \lambda_s)^2}}{\lambda_m[\mathrm{erf}\,(\lambda_m - \lambda_s) + \mathrm{erf}\,\lambda_s]}. \tag{26}$$

In order to complete the formulation of the problem we must consider the isostatic subsidence of the sedimentary basin. Assuming that $\rho = \rho_m$ at $t = 0$, the condition of isostasy requires that

$$\int_0^\infty (\rho - \rho_m)\,\mathrm{d}y = 0. \tag{27}$$

For our problem this can be written

$$\int_0^{y_b} (\rho_m - \rho_s)\,\mathrm{d}y = \int_{y_b}^{y_m} (\rho_b - \rho_m)\,\mathrm{d}y. \tag{28}$$

The densities of the sediments, basement rocks and mantle are given by

$$\rho_s = \rho_{s0}[1 - \alpha(T_s - T_0)], \tag{29}$$

$$\rho_b = \rho_{m0}[1 + \alpha(T_m - T_b)] \tag{30}$$

and

$$\rho_m = \rho_{m0}(1 - \chi_m) + \rho_1 \chi_m, \tag{31}$$

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where ρ_{s0} is the surface density of the sediments, ρ_{m0} is the density of basement rocks at $T = T_m$, and ρ_l is the density of the magma fraction in the asthenosphere. Substitution of (29) to (31) into (28) gives

$$(\rho_{m0}-\rho_{s0})\,y_b+\alpha\rho_{s0}\int_0^{y_{sb}}(T_s-T_0)\,dy = (\rho_m-\rho_l)\,\chi_m y_m+\alpha\rho_{m0}\int_{y_b}^{y_m}(T_m-T_b)\,dy; \tag{32}$$

substitution of (24) and (25) yields

$$(\rho_{m0}-\rho_{s0})\,\lambda_s-(\rho_m-\rho_l)\,\chi_m\lambda_m = \frac{\alpha(T_m-T_0)}{\pi^{\frac{1}{2}}}\,\frac{\{\rho_{m0}(1-e^{-(\lambda_m-\lambda_s)^2})-\rho_{s0}(1-e^{-\lambda_s^2})\}}{\{\operatorname{erf}(\lambda_m-\lambda_s)+\operatorname{erf}\lambda_s\}}. \tag{33}$$

Values of λ_s and λ_m are obtained by solving the coupled transcendental equations (26) and (33).

If the solidification of the asthenosphere is neglected, it is appropriate to assume that $\lambda_m \to \infty$. This approximation is usually made when considering the thermal structure of the lithosphere. In addition, if the depth of the sedimentary basin is small compared with the thickness of the thermal lithosphere, it is appropriate to assume that $\lambda_s \ll 1$. In these two limits the above results simplify considerably. The depth of the sedimentary basin is

$$y_{sb} = \frac{2\rho_{m0}\alpha(T_m-T_0)}{(\rho_{m0}-\rho_{s0})}\left(\frac{\kappa t}{\pi}\right)^{\frac{1}{2}}. \tag{34}$$

Neglecting compaction, the depth of a sedimentary layer deposited at time t_s after the initiation of subsidence can be obtained as a function of time. At time t_s the depth of basement is obtained from (34) by setting $t = t_s$. The sediment deposited at time t_s will always be this distance above basement. However, the depth of the basement at time t is given directly by (34). Thus the depth to the sediment deposited at time t_s at a later time t, denoted by y_s, is given by the difference between the depth to basement at t and t_s,

$$y_s = \frac{2\rho_{m0}\alpha(T_m-T_0)}{(\rho_{m0}-\rho_{s0})}\left(\frac{\kappa}{\pi}\right)^{\frac{1}{2}}(t^{\frac{1}{2}}-t_s^{\frac{1}{2}}). \tag{35}$$

Turcotte & McAdoo (1979) have shown that this subsidence relation is in good agreement with the subsidence record in the southwestern block of the Los Angeles Basin.

As long as the thickness of sediments is small, the presence of the sediments has a small influence on the temperature distribution in the lithosphere. Also, the temperature distribution in the sediments can be taken to be linear. Thus the temperature distribution in the sediments is

$$T_s = T_0+\frac{(T_m-T_0)}{(\pi\kappa t)^{\frac{1}{2}}}\,y. \tag{36}$$

The temperature of a sedimentary layer deposited at time t_s at a subsequent time t is obtained by substituting (34) in (35) with the result

$$T_s = T_0+\frac{2}{\pi}\,\frac{\rho_{m0}\alpha(T_m-T_0)^2}{(\rho_{m0}-\rho_{s0})}\left\{1-\left(\frac{t_s}{t}\right)^{\frac{1}{2}}\right\}. \tag{37}$$

This result along with (8), can be used to determine the location of petroleum in a sedimentary basin for which the similarity solution is valid.

We consider the development of oil in a sedimentary basin for which the similarity solution is valid. Taking $T_0 = 20\,°C$, $T_m = 1200\,°C$, $\alpha = 3\times10^{-5}\,K^{-1}$, $\rho_{m0} = 3300\,kg\,m^{-3}$, $\rho_s = 2500\,kg\,m^{-3}$, $A = 1.3\times10^{27}\,Ma^{-1}$, and $E = 230\,kJ\,mol^{-1}$, the oil window and the volume of oil as a function of age are given in figure 5. The volume of oil increases with age and the oil window deepens. It

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should be emphasized that kerogens must be present for the production of oil and that oil will often migrate upwards in the section.

The results obtained above predict that the depths of sedimentary basins increase with the square root of time. For many sedimentary basins this is a good approximation for about the first 80 Ma of their evolution. The depth of older sedimentary basins appears to remain approximately constant. This deviation from the cooling model given above is probably due to the input of heat to the base of the thermal lithosphere. Possible causes of this heating are mantle convection beneath the rigid lithosphere or frictional heating. An empirical equation that predicts the flattening of the subsidence curve with time has been proposed by Turcotte (1980) and has the form

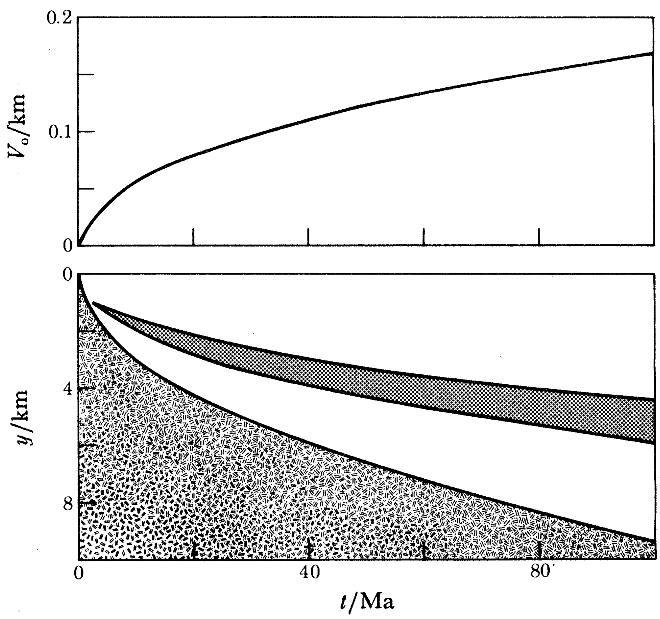

FIGURE 5. The oil window and the volume of oil as a function of age in a sedimentary basin for which the similarity solution (37) is valid.

$$y_{sb} = y_{sb0}(1 - e^{-(t/\tau)^2})^{\frac{1}{4}}, \tag{38}$$

where y_{sb0} is the depth of the sedimentary basin at large times and τ is a characteristic subsidence time. For small times $t \ll \tau$ this reduces to (34) if

$$\tau = \frac{\pi}{\kappa}\left\{\frac{y_{sb0}(\rho_{m0} - \rho_{s0})}{2\rho_{m0}\alpha(T_m - T_0)}\right\}^2. \tag{39}$$

The depth to sediments deposited at time t_0 is given by

$$y_s = y_{sb0}\{(1 - e^{-(t/\tau)^2})^{\frac{1}{4}} - (1 - e^{-(t_s/\tau)^2})^{\frac{1}{4}}\}. \tag{40}$$

Turcotte (1980) has shown that this semi-empirical relation predicts with reasonable success the subsidence record of the Michigan, Appalachian, Atlantic Coast and Gulf Coast sedimentary basins.

The near-surface thermal gradient β in the basin can be modelled in a similar way by assuming that

$$\beta = \beta_0(1 - e^{-(t/\tau)^2})^{-\frac{1}{4}} \tag{41}$$

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where β_0 is the thermal gradient at large times. The temperature distribution in the sediments is

$$T_s = T_0 + \beta_0 y (1 - e^{-(t/\tau)^2})^{-\frac{1}{4}}. \tag{42}$$

The temperature of a sedimentary layer deposited at t_s at a subsequent time t is obtained by substituting (39) into (41) with the result

$$T_s = T_0 + \beta_0 y_{sb0} \left\{ 1 - \frac{(1 - e^{-(t_s/\tau)^2})^{\frac{1}{4}}}{(1 - e^{-(t/\tau)^2})^{\frac{1}{4}}} \right\}. \tag{43}$$

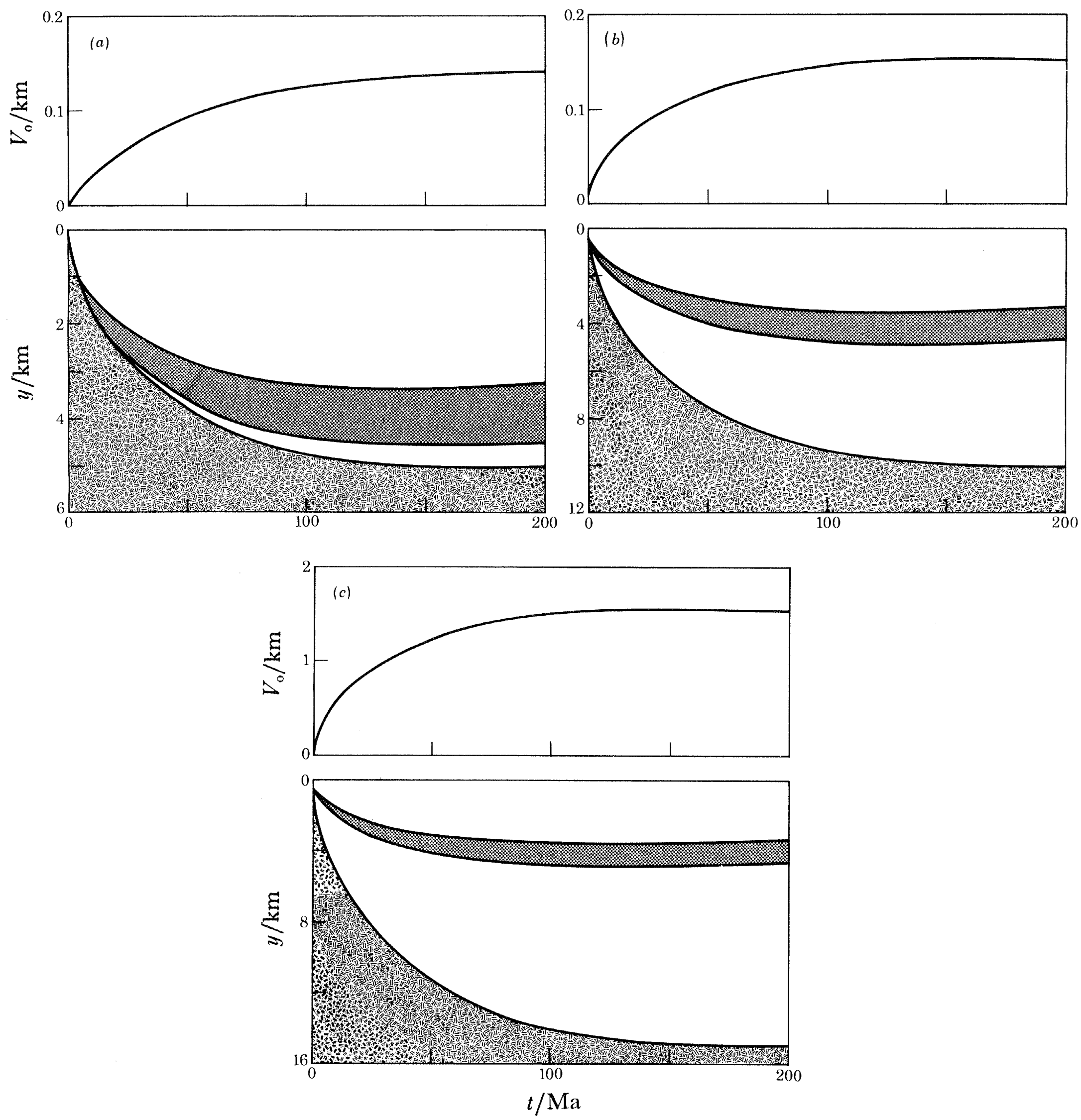

FIGURE 6. The oil window and the volume of oil as a function of age in a sedimentary basin for which the empirical thermal subsidence model (42) is applicable. (*a*) $y_{sb0} = 5$ km, (*b*) $y_{sb0} = 10$ km, (*c*) $y_{sb0} = 15$ km.

This result can be used along with (8) to determine the location of petroleum in a sedimentary basin for which the empirical thermal subsidence model is applicable.

The oil window and volume of oil are given as a function of age in figure 6 for $\beta_0 = 25\ \mathrm{K\,km^{-1}}$, $\tau = 80$ Ma, $A = 1.3 \times 10^{27}\ \mathrm{Ma^{-1}}$, $E = 230\ \mathrm{kJ\,mol^{-1}}$ and $y_{sb0} = 5$, 10 and 15 km. For the deep basins half the oil is produced in about the first 20 Ma whereas in the shallow basin (5 km) half

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of the oil is produced after about 30 Ma. The total amount of oil produced in each of the basins is about the same and the depth to the oil window as a function of age is about the same.

Conclusions

The direct applicability of the similarity solution for thermal subsidence requires a number of assumptions. However, experience with similarity solutions in other applications indicates that the results are relatively insensitive to some of the requirements. For example, the condition of constant temperature at $t = 0$ may be a rather poor approximation and the similarity solutions will still be a good approximation at large times.

For many sedimentary basins a significant fraction of basin subsidence may not be of thermal origin. For example, oceanic crust is normally formed at a depth of about 2.5 km. If this crust is formed near a continental margin with high sedimentation rates, 5 km or more of sediments may be deposited in a very short period. As the oceanic lithosphere subsequently cools, the similarity solution would be expected to be a satisfactory approximation for later sedimentation. If sedimentation does not keep pace with subsidence, deep water can develop and the sedimentary record is irregular. Also, changes in sea level can have a significant effect on the rate at which sediments accumulate.

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Discussion

G. Karner. In the oceans, the mass that is loading the oceanic plate appears to be more easily recognized, for example seamounts and their respective moat infill material. However, within the continents, it is not obvious what constitutes the load acting on the continental plate. In relation to the Appalachian Basin, is it possible that the load giving rise to the foreland basin is within either the basin or crust?

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D. L. Turcotte. As Beaumont argued earlier, the best method of detecting loads is to use the gravity observations. Over the Appalachians there is a gravity low and high, the low corresponding to the flexure and the high occurring towards the east. But the load involved is small and can only account for perhaps 30 % of the observed subsidence that produced the basin. In the Michigan Basin there is also a gravity high along what is believed to have been a Keweenawan Rift, flanked by lows on either side. But here also neither the high nor the flanking lows are large enough to account for the subsidence. In both these areas there must be some process other than loading involved, such as metamorphic reactions in the crust.

G. Dungworth. Dewey and Watts and the authors have all used Lopatin's expression to relate the thermal history of a source bed to its maturation. This relation requires the reaction rate to double for every 10 K increase in temperature. In some of the figures in this paper this relation leads to a rather restricted depth range in which oil generation can occur. The authors also mentioned that they used Tissot's expression, with a pre-exponential factor and an activation energy. Of Tissot's three kerogen types only type 2 is relevant, and those reactions, which have activation energies of 42 or 125 kJ/mol^{-1}, will occur at low temperatures. Only the oil generation, which has activation energies of 210 and 250 kJ/mol^{-1} in Tissot's model, is of importance here. The authors used 230 $kJ\ mol^{-1}$, the average of these. Tissot also argued that the pre-exponential factor is linearly related to the activation energy, an argument for which there is no theoretical justification. Presumably this is why the authors used a pre-exponential factor of 1.3×10^{27}. Because both the activation energy and the pre-exponential factors are large the oil generation occurs in the authors' model over a rather limited depth range. Have they examined the width of the oil generation window when they make different assumptions?

D. L. Turcotte. What we attempted to do was to match the observed maturation by using the simplest model.

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