THERMAL BASIN MODELING INCLUDING COMPACTION AND FLUID FLOW

C. D. McElwee

Kansas Geological Survey
The University of Kansas
Lawrence, Kansas 66046

and

G. C. Bohling

Department of Geology and Geophysics
University of Wisconsin
Madison, Wisconsin 53706

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C. D. MCELWEE (Kansas Geological Survey, Lawrence, KS 66046)
G. C. BOHLING (Dept. of Geology and Geophysics, University of Wisconsin, Madison, WI 53706)

One of the current tools available to analyze sedimentary basins for potential hydrocarbon generation is thermal modeling, which allows calculation of the time-temperature index (TTI). The TTI is a measure of the maturity of the source beds and can indicate whether they have generated hydrocarbons. Thermal models that are in common usage are fairly simple and may only allow the solution of the heat-flow equation with varying geothermal gradient and varying thermal conductivity for the sediments.

This paper will present a fairly general set of equations coupling fluid flow, compaction, and heat flow. The solution algorithm presented will allow the physical parameters such as fluid density, porosity, compressibility, permeability, viscosity, thermal conductivity, and specific-heat capacity to vary with temperature and pressure. The equations are highly nonlinear, so an iterative numerical scheme is necessary for their solution.

In particular, we will examine the effect of the pore fluid and compaction on the thermal predictions of TTI. Results for two models will be presented: a gulf-coast model and a model of the Salina basin in Kansas. Both models indicate that a simple Lopatin model may incorrectly estimate TTI in comparison to our more complex model in certain situations.

NOTATION

V_D – Darcy velocity

σ_T – Total stress

α – Compressibility of rock matrix

β – Compressibility of water

n – Porosity

p – Fluid pressure

k – Permeability

μ – Water viscosity

ρ_w – Density of water

ρ_r – Density of rock matrix

g – Acceleration of gravity

$\hat{z}$ – Unit vector in z direction

$\frac{dl}{dt}$ – Sedimentation rate

V_s – Grain velocity

T – Temperature

K_r – Thermal Conductivity of rock matrix

K_w – Thermal Conductivity of water

c_{pr} – Specific heat capacity of rock matrix

c_{pw} – Specific heat capacity of water

WATER FLOW EQUATION

$$\vec{\nabla} \cdot \vec{V}_D = \alpha \frac{d\sigma_T}{dt} - (\alpha + n\beta) \frac{dp}{dt}$$

$$\vec{V}_D = -\frac{k}{\mu} \left[\vec{\nabla} p + \rho_w g \hat{z} \right]$$

$$\frac{d\sigma_T}{dt} = g \left[n \rho_w + (1 - n) \rho_r \right] \frac{dl}{dt}$$

GRAIN VELOCITY OR COMPACTION EQUATION

$$\vec{\nabla} \cdot \vec{V}_s = -\alpha \left[\frac{d\sigma_T}{dt} - \frac{dp}{dt} \right]$$

V_s

HEAT FLOW EQUATION

$$\vec{\nabla} \cdot \left[K_{wr} \vec{\nabla} T \right] - \rho_w \, c_{pw} \vec{\nabla} \cdot \left[\vec{V}_w T \right] = c_{pwr} \, \rho_{wr} \frac{\partial T}{\partial t}$$

$$\rho_{wr} = n \rho_w + (1 - n) \rho_r$$

$$K_{wr} = K_r \left(\frac{K_w}{K_r} \right)^n$$

$$c_{pwr} = (1 - n) \, c_{pr} + n \, c_{pw}$$

$$\vec{V}_w = V_D / n$$

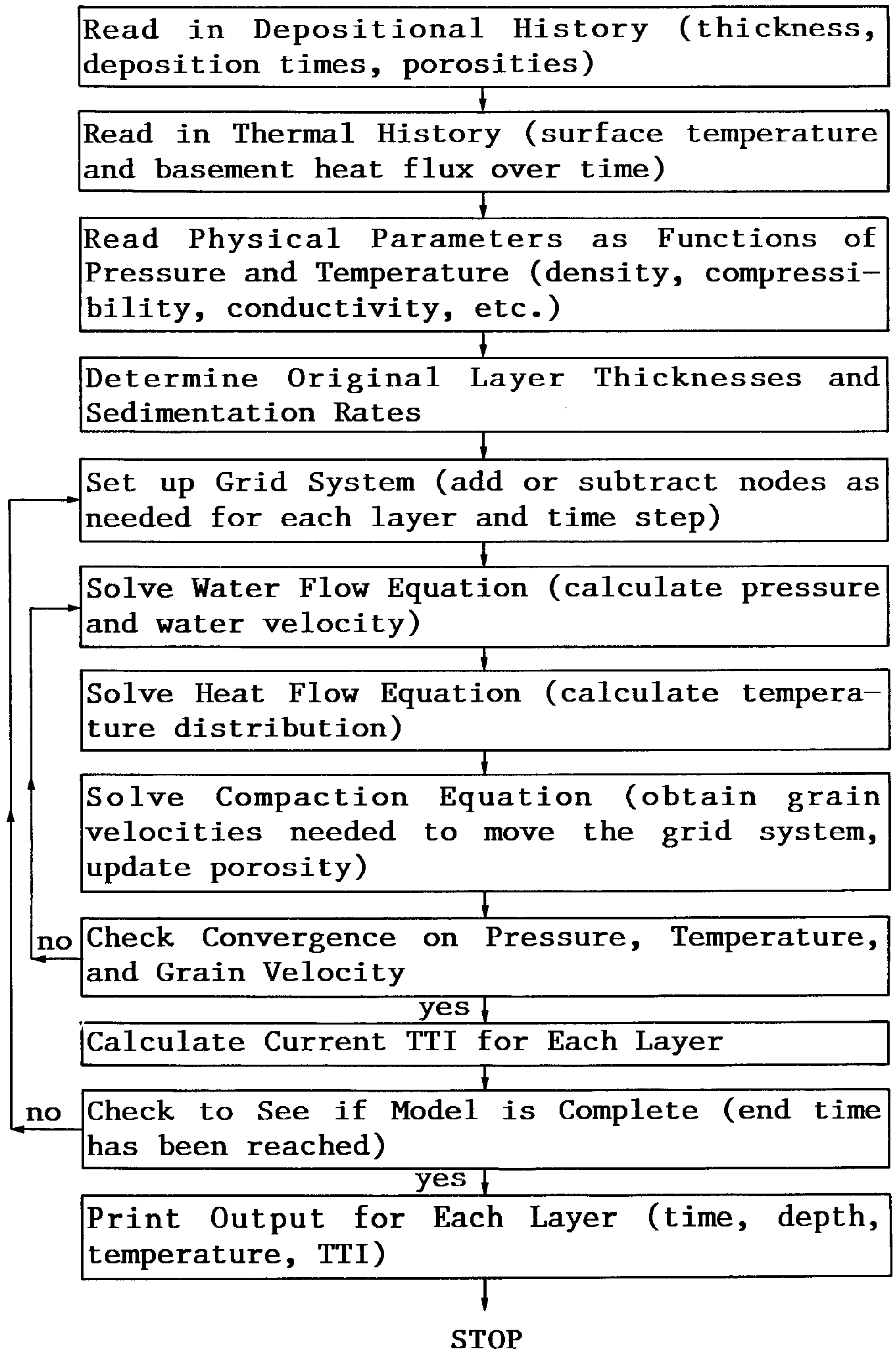
$$TTI = \int_{t_o}^{t} r_B 2^{\left(T(t) - T_B\right)/10^oC} dt$$

LOPATIN'S TIME TEMPERATURE INDEX (TTI)

TTI is a measure of the thermal maturity of an oil source rock. It depends on the time the source rock spent at a given temperature. This assumes the maturity reaction rate doubles every 10^oC. T_B is a base temperature and r_B is the reaction rate at that temperature. Lopatin chose $T_B = 105^oC$ and $r_B = 1$. t_o is the deposition time of the source rock and t is the time at which the thermal maturity is being calculated.

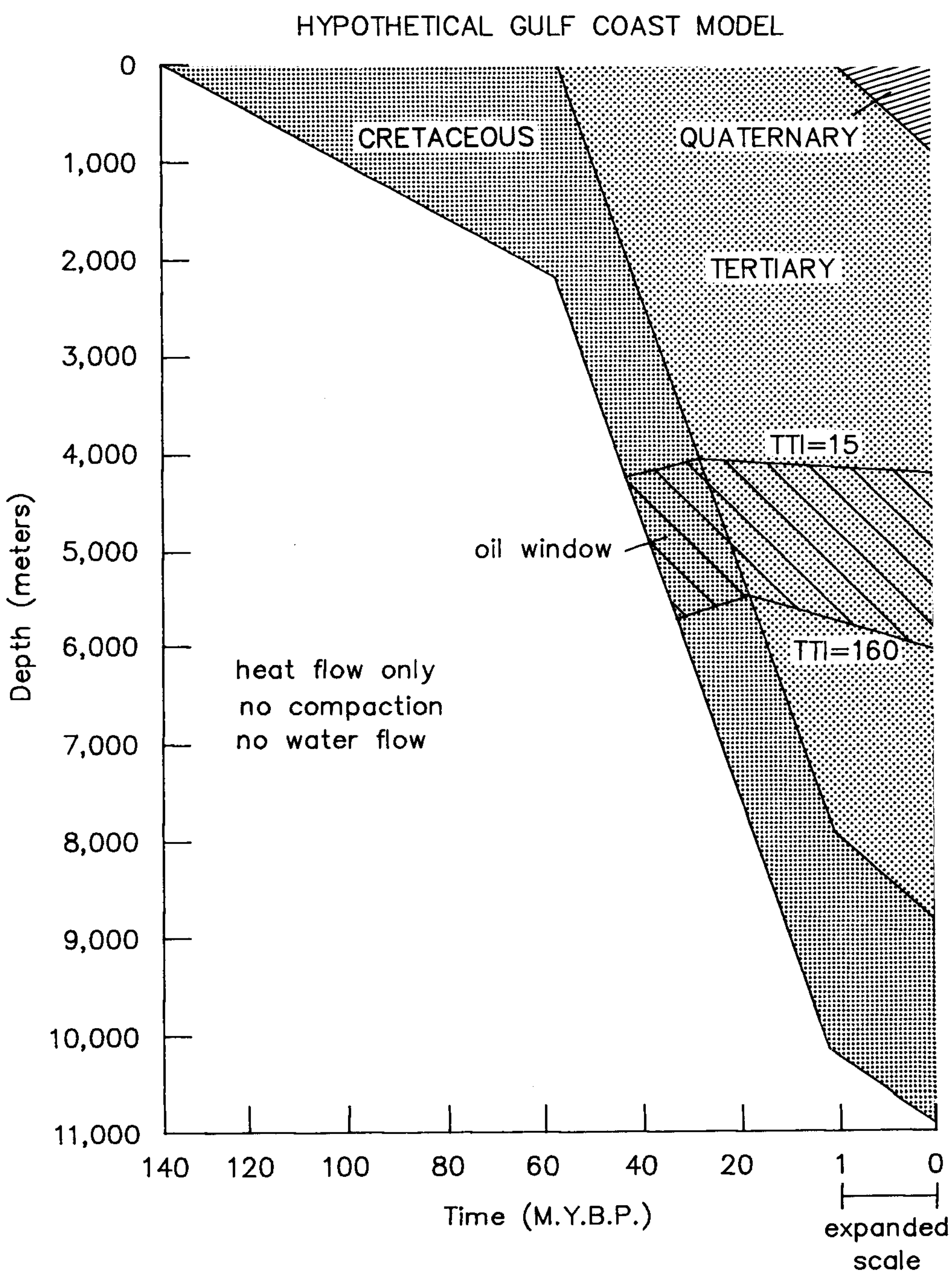
Waples suggests that oil is generated in an "oil window" between TTI = 15 and TTI = 160.

COMPUTER PROGRAM FLOW CHART



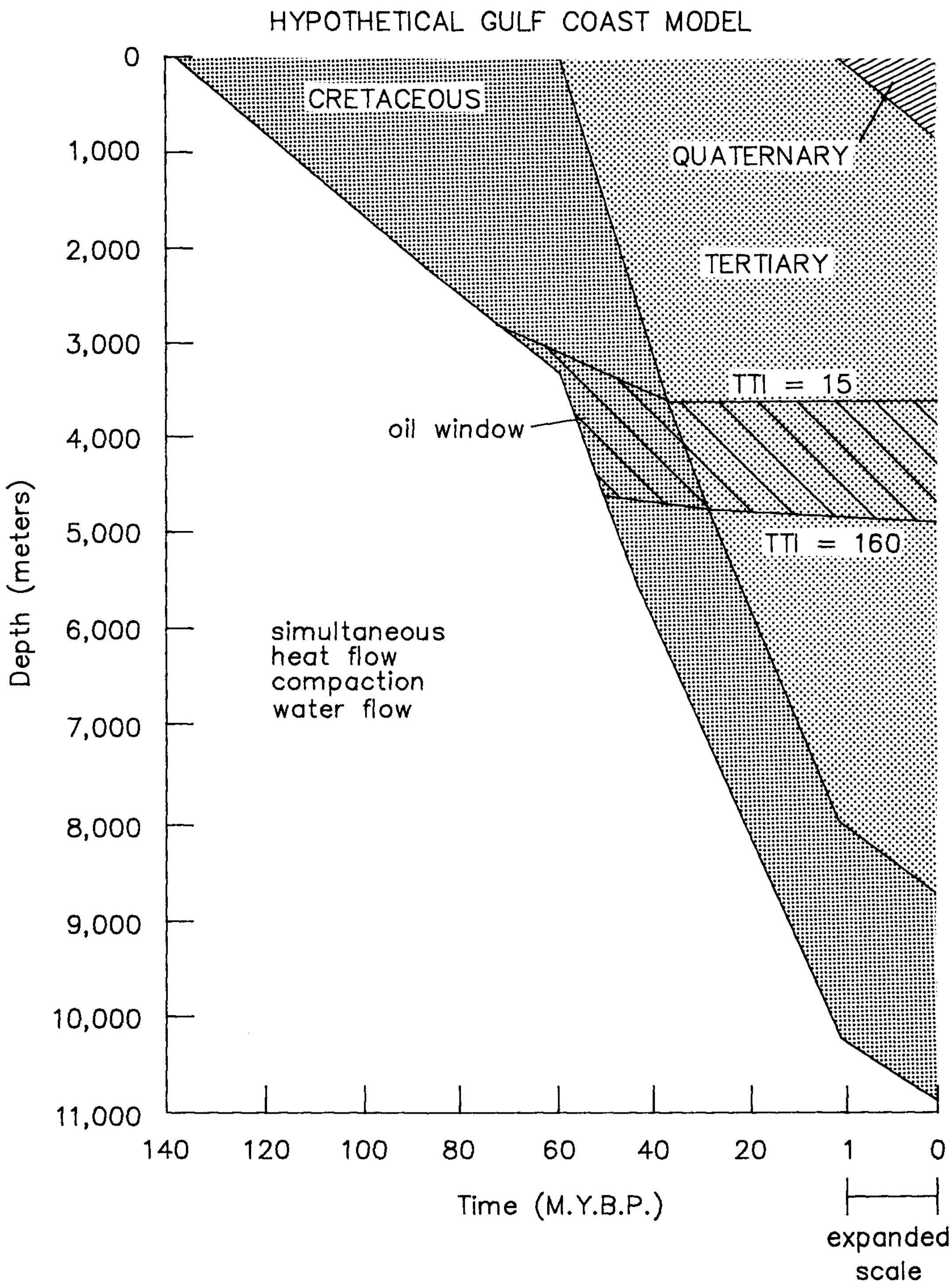
GULF COAST MODEL

The Lopatin model, with no compaction or fluid flow, predicts that the Cretaceous enters the oil window at 43 M.Y.B.P. at a depth of 4250 M. This model predicts that the Cretaceous left the oil window at 19 M.Y.B.P. at a depth of 5450 M. The maximum depth of the oil window is about 6000 M. at the present time in the Tertiary sediments.


HYPOTHETICAL GULF COAST MODEL
CRETACEOUS
QUATERNARY
TERTIARY
TTI=15
TTI=160
oil window
heat flow only
no compaction
no water flow
Depth (meters)
0
1,000
2,000
3,000
4,000
5,000
6,000
7,000
8,000
9,000
10,000
11,000
140
120
100
80
60
40
20
1
0
Time (M.Y.B.P.)
expanded scale

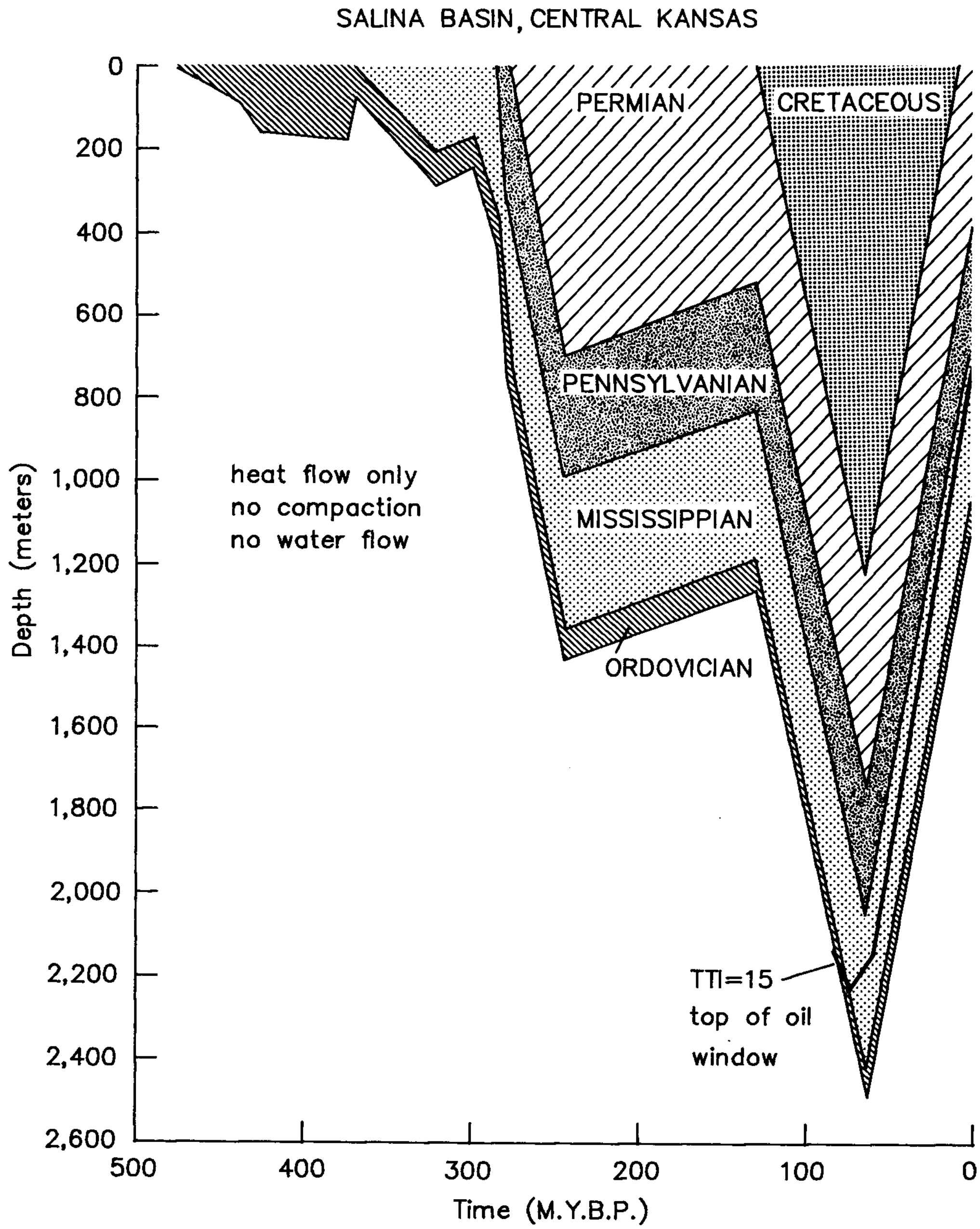
GULF COAST MODEL

The more general model, which allows compaction and fluid flow, predicts that the Cretaceous enters the oil window at 71 M.Y.B.P. at a depth of 2850 M. These results also predict that the Cretaceous left the oil window at 28 M.Y.B.P. at a depth of 4700 M. At the present time, the oil window is at about 4850 M. in the Tertiary sediments.


HYPOTHETICAL GULF COAST MODEL
CRETACEOUS
QUATERNARY
TERTIARY
TTI = 15
oil window
TTI = 160
simultaneous
heat flow
compaction
water flow
Depth (meters)
0
1,000
2,000
3,000
4,000
5,000
6,000
7,000
8,000
9,000
10,000
11,000
140
120
100
80
60
40
20
1
0
Time (M.Y.B.P.)
expanded
scale

SALINA BASIN MODEL

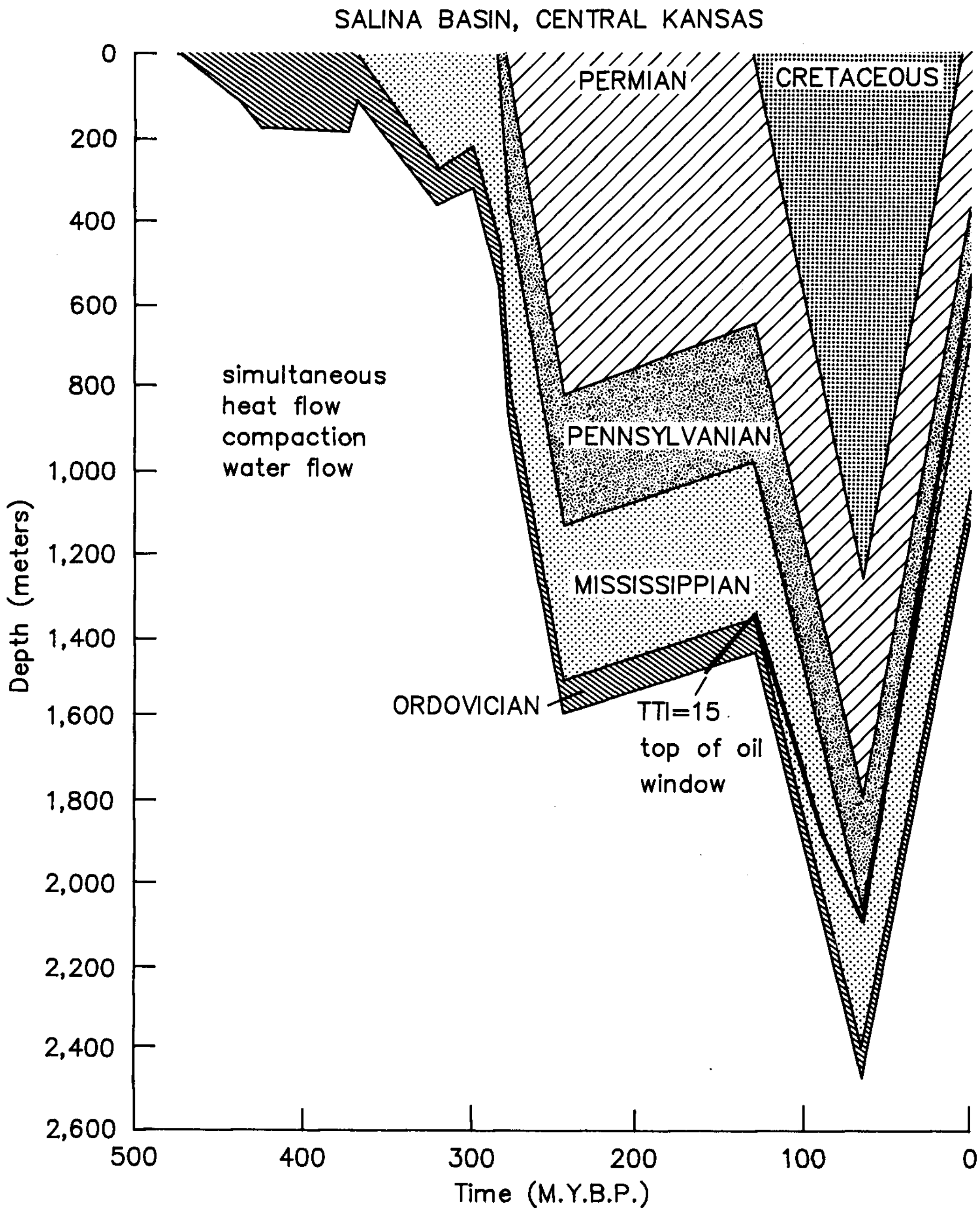
The Lopatin model, with no compaction or fluid flow, predicts the onset of oil generation at 82 M.Y.B.P. at a depth of 2160 M. Only Ordovician and Mississippian sediments are predicted to have entered the oil window. The model predicts this is a very immature basin. No sediments have reached the bottom of the oil window at TTI = 160.



SALINA BASIN, CENTRAL KANSAS
PERMIAN
CRETACEOUS
PENNSYLVANIAN
MISSISSIPPIAN
ORDOVICIAN
heat flow only
no compaction
no water flow
TTI=15
top of oil
window
Depth (meters)
0
200
400
600
800
1,000
1,200
1,400
1,600
1,800
2,000
2,200
2,400
2,600
500
400
300
200
100
0
Time (M.Y.B.P.)

SALINA BASIN MODEL

The more general model, which allows compaction and water flow, predicts the onset of oil generation at 157 M.Y.B.P. at a depth of 1480 M. In addition to the Ordovician and Mississippian sediments, this model predicts that about half of the Pennsylvanian sediments are in the oil window today. This model predicts the basin is somewhat more mature.


SALINA BASIN, CENTRAL KANSAS
PERMIAN
CRETACEOUS
PENNSYLVANIAN
MISSISSIPPIAN
ORDOVICIAN
TTI=15
top of oil
window
simultaneous
heat flow
compaction
water flow
Depth (meters)
0
200
400
600
800
1,000
1,200
1,400
1,600
1,800
2,000
2,200
2,400
2,600
500
400
300
200
100
0
Time (M.Y.B.P.)

CONCLUSIONS

The two basin models considered here indicate that a simple Lopatin type model, without fluid flow and compaction, may underestimate TTI in comparison to a more general model in certain situations. The reason for this seems to be related to two factors. First, if compaction is not adequately described, the thermal conductivity of the sediments will not be correct since the pore space contains water which has a relatively low thermal conductivity. Second, for thick highly compressible sediments, the depth of burial through geologic time will not be correct for the simple model. The simple model uses present day thicknesses and will thus underestimate the depth of burial. The net effect for the two basin models presented here is that the predicted maturity is too low for the simple Lopatin model.

Accurate prediction of the thermal maturity for petroleum source beds is important for a number of reasons. If one can accurately predict maturity, it is possible to predict which source beds have generated hydrocarbons and which ones are still immature. The time of generation relative to the presence of traps is critical. If traps are not present at the time of generation, no oil will be retained in the area. Accurate temperature modeling should allow one to estimate the maximum depth for productive drilling, below which oil would not occur. Therefore, it seems that a general model allowing water flow and compaction with more accurate prediction of TTI is desirable.

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