POROSITY DEVELOPMENT AND PRESERVATION IN DEEP SANDSTONES, WESTERN AND SOUTHERN NEW ZEALAND

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Abstract

Reservoir quality in western and southern New Zealand basins is controlled by both depositional facies and diagenesis. Highest initial porosities and permeabilities in the Taranaki Basin were in fluvial and littoral sandstones. The ability of such facies to direct fluid flow ensured that they commonly underwent widespread cementation by silica, carbonate and authigenic clay, particularly with later dissolution of carbonates.

Recent studies have suggested that oil may not be released from terrestrial source rocks in New Zealand basins until depths of perhaps 5.5-6 kms, and that several kilometres of vertical migration, and an unknown amount of lateral migration, have been required for oil to reach the commercial fields at shallower depths. Knowledge of porosity development down to the depths of oil generation is therefore essential to an understanding of migration pathways and the controls on hydrocarbon accumulation.

It is widely accepted that organic solvents such as carboxylic acids and phenols which may form during thermal alteration of kerogen prior to liquid hydrocarbon generation are important to the dissolution of carbonates in sandstones. Further, the presence of these up to the time of hydrocarbon expulsion may inhibit recementation. High resolution nuclear magnetic resonance (NMR) spectroscopy indicates that in New Zealand basins the evolution of carboxylic acids and phenols may continue almost until the expulsion of liquid hydrocarbons. This is quite different from the situation observed in overseas basins, and suggests that porosity may be preserved, or even enhanced, to greater than usual depths.

Introduction

Recent studies have suggested that oil may not be released from terrestrial source rocks in New Zealand basins until the rocks reach depths of perhaps 5.5 to 6 kilometres. This means that the oil must have migrated a few kilometres upwards before reaching commercial fields. Knowledge of porosity development is essential to understanding the migration pathways.

Porosity Development and Preservation

Relict primary porosity is present in most Pakawau and Kapuni Group sandstones, but is usually modified by diagenesis. The most important contribution to secondary porosity has been dissolution of carbonates, mostly calcite. Unevenly distributed pores are commonly connected by large tubular pore throats. The common occurrence of several generations of authigenic minerals indicates a complex history of pore-fluid movement through the sandstones. We have tried to develop a mathematical model for the generation of acidic substances from terrestrial source rocks. We hope that our model will provide some insights into the prerequisites for oil migration.

Both carbon dioxide and organic acids may form secondary porosity in sandstones. Figure 1 shows how carbon dioxide can be generated from kerogen, either directly from carboxylic acid functional groups on the kerogen macromolecule or indirectly through fragmentation into water-soluble organic acids such as acetic acid or propionic acid. Highest concentrations of these organic acids are reached at temperatures of 80° to 120° C (Surdam *et al.*, 1989). Decarboxylation occurs at higher temperatures, producing hydrocarbon gases and carbon dioxide.

We chose nuclear magnetic resonance (NMR) spectroscopy as the method for chemical analysis. NMR spectroscopy involves placing a sample in the very strong magnetic field of a superconducting solenoid, then

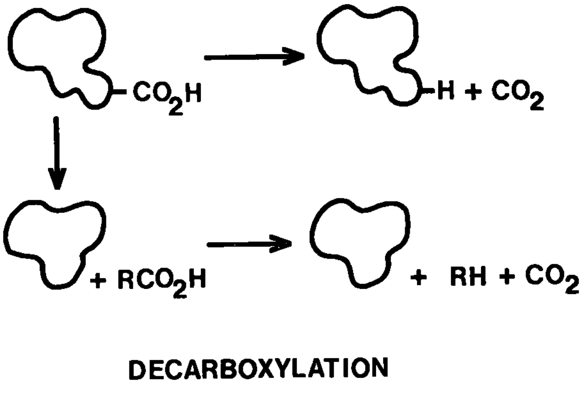

Figure 1

irradiating it with pulses of radiofrequency energy. The nuclei resonate at frequencies that depend on the chemical environment (Figure 2). Signal areas provide an estimate of the relative contents of each type of functional group. The dominant signals in Figure 2 are assigned to aromatic and saturated hydrocarbon structural units. We are interested in a weaker signal assigned to carboxylic acid functional groups.

Figure 3 shows the results of NMR analysis of a number of samples of kerogen hand-picked from drill cuttings from the Maui-4 and Tara-1 oil exploration wells. Published results from an NMR study of peat indicate a mean value of 2.6% of carbon contained in carboxylic acid groups. Our results indicate similar levels in kerogen subjected to temperatures up to about 60° C, but then the level drops rapidly and is already very low by the time the temperature reaches 80° C.

We tried to allow for the effects of variable periods of thermal alteration by using a chemical kinetic approach that is now quite frequently used in basin modelling. Figure 4 shows equations originally used by Tissot *et al.* (1987). The Arrhenius equation expresses a relationship between the reaction rate (k) and the temperature (T) in terms of a frequency factor (A) and an activation energy (E). The subscript (i) indicates that we must divide the precursor into a number of contributions, each with a slightly different chemical environment and therefore a slightly different activation energy. A single activation energy is usually used to describe the chemical reactions of pure substances, and some early studies of kerogen were based on a single value. More recent publications have shown that we need to consider a statistical distribution of activation energies. We have assumed a Gaussian distribution. Trial values of the reaction rate are inserted in the differential equation for a first-order reaction as shown below, and a computer program generates a numerical solution.

We need to know the thermal history of the kerogen. We used a simple model, plotting depth of burial against time as in Figure 5 and assumed a constant geothermal gradient over the entire period of maturation. In other words, we assumed that as the kerogen was buried the temperature rose by about 30° C for every additional kilometre of depth.

The results of computer simulations are shown in Figure 3. Our first attempts at simulations were based on parameters published by Burnham and Sweeney (1989). We then refined the fit by lowering the activation energy from 48 to 44 kilocalories per mole, but we retained Burnham and Sweeney's standard deviation of 3 kilocalories per mole. We believe our results are more reliable than those of Burnham and Sweeney, since those authors studied decarboxylation indirectly through measurements of reflectance combined with an empirical correlation between reflectance and the oxygen content of coal. The carboxylic acid content was then estimated from the total oxygen content. In contrast, we measured the carboxylic acid content directly. We increased our estimate of the initial precursor content slightly to improve the fit. The scatter of our experimental results is however too large for us to justify further refinement of the chemical kinetic parameters.

Now that we have obtained estimates of these parameters we can speculate on what might have happened over the past 80 million years. The curves in Figure 6 were simulated for

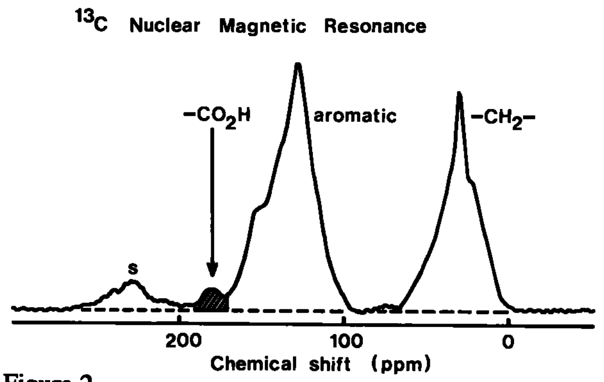

Figure 2

Arrhenius equation

$$k_i = A\exp(-E_i/RT)$$

A = frequency factor

E = activation energy

$$dP_i/dt = -k_iP_i$$

Figure 4

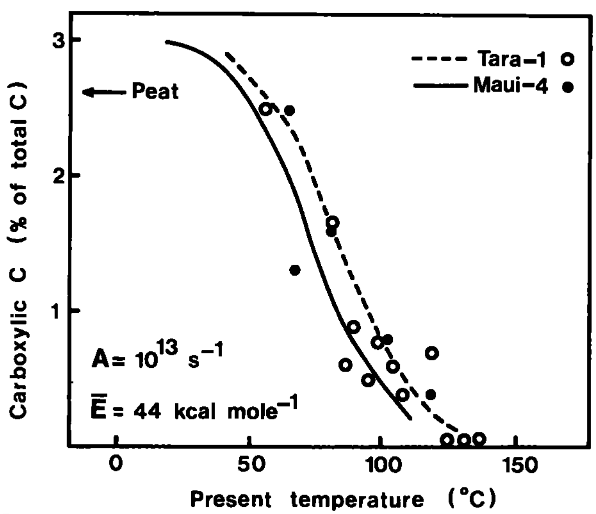

Figure 3

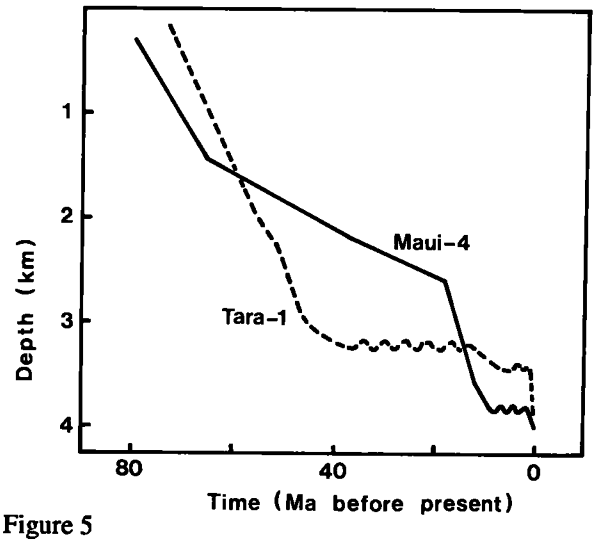

Figure 5

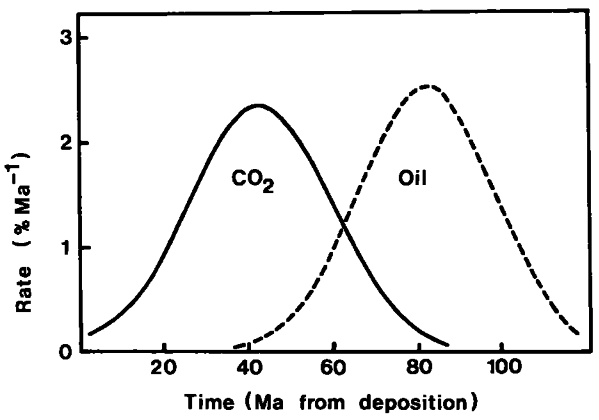

Figure 6

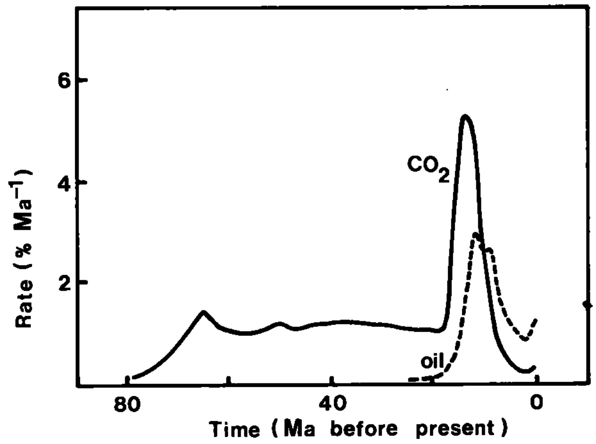

Figure 7

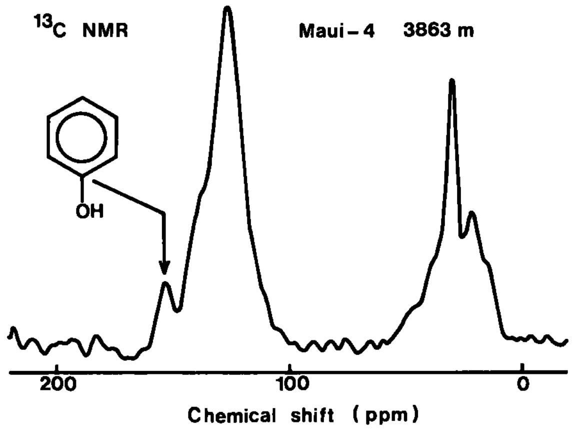

Figure 8

a hypothetical example of kerogen buried at a steady rate of 50 metres per million years through a constant geothermal gradient of 30° C per kilometre. The vertical axis shows the reaction rate in terms of the percentage of precursor consumed over each interval of one million years. The curve for carbon dioxide was simulated from the best-fit parameters already described. The curve for oil was simulated for parameters suggested by Burnham and Sweeney (1989) as appropriate for kerogen of terrestrial origin. There is some overlap between the two curves, but the two maxima are separated by a gap of 39 million years. This leaves plenty of time for recementation to occur before generation of oil reaches its peak. One feature I wish to emphasise about this model is that the consumption of the carbon dioxide precursor never rises above 2.5% per million years.

In contrast, computer simulations for the Maui-4 oil exploration well (Figure 7) show highly irregular curves in response to the uneven rates of burial. These curves were calculated for kerogen now buried at a depth of 3919 metres. They indicate a burst of activity during the mid-Miocene during which the precursor of carbon dioxide was consumed at a rate of more than 5% per million years. We have tried to estimate the consequences of this burst of activity. Numerous coal seams between depths of 2030 and 3840 metres raise the average carbon content of the sediments to 7.4% by weight. Curves like this one were generated for several of the seams, and the reaction rate was integrated over an 8-million-year period. We assumed a porosity of 20% and calculated that the acidic material released into the pore water averaged 0.5 mole per litre of water in the sandstones of the Pakawau and Kapuni Groups. This acidic material would include both carbon dioxide and water-soluble organic acids.

The release of acidic material was followed by generation of oil, without the long delay simulated for the hypothetical model. It is therefore reasonable to suppose that this oil could migrate through the pathways created by the acidic material. Oil was found at a depth of 2030 metres, flowing at 575 barrels per day. Our simulations indicate that only 0.1% of the oil precursors would have been consumed at this depth, so the oil must have migrated from greater depths. Figure 7 showed just less than one third of the oil precursors consumed at a depth of 3919 metres. Oil may have migrated from similar sediments buried at greater depths some distance away from the Maui-4 site.

Our simulations indicated only negligible amounts of carbon dioxide released from kerogen buried below 4 km. We sought other sources of acidic material that might become important at greater depths. Figure 8 shows an NMR spectrum of kerogen sampled at a depth of 3863 metres down the Maui-4 well. One of the signals can be assigned to phenolic material, that is, aromatic structures with hydroxyl groups. These hydroxyl groups are acidic. We do not know how much water-soluble phenolic material can be released into the pore water, but it is interesting to find such acidic material still present in terrestrial source rocks even at a depth of nearly 4 kilometres. These phenolic structures are believed to be derived from plant material, for example, lignins from wood and perhaps tannins from leaves and bark.

In conclusion, we have found evidence to suggest that the evolution of carboxylic acids, carbon dioxide and phenols may continue almost until the expulsion of liquid hydrocarbons. The prerequisites for this situation seem to be a high content of terrestrial material in the source rock and an uneven rate of burial. We hope that the chemical kinetic model might help us evaluate and compare the potential for migration of hydrocarbons through sandstone in different basins.

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