

## Hydrocarbons

The purpose of this lecture is to show how an understanding of the way in which sedimentary basins form is important to the oil industry. Within any basin, exploration teams consider several important components of a successful petroleum system to decide whether they will find oil: **source, reservoir, top-seal, trap, migration pathways and timing.**

### Source

Coal, oil and gas form out of decayed organic matter that has been thermally altered. All living matter is composed of carbohydrates, proteins, lipids and lignin. Lipids are the building blocks of animal fats, vegetable oils and waxes, and they are present in seeds, spores, leaf coating and bark. Lignin is present in the walls of plant cells. On death, carbohydrates and proteins decay very rapidly. If there is plenty of oxygen available for rotting, the lipids and lignin also decay. However, if conditions at the sediment surface are *anoxic* then lipids and lignin may be buried and incorporated into the sediment. Only about 0.4% of the global net carbon production ends up within sediment in this way but this is enough to source the world's hydrocarbon provinces.

When lipids are heated they produce oil and when lignin is heated it produces gas. Volumetrically, the most important source of lipids is marine plankton, which live in surface waters, die and rain down constantly to the seabed. The best environment for formation of a world class source rock is therefore a stratified ocean basin, with an oxygen- and nutrient-rich upper water layer where the plankton bloom happily, and an anoxic lower layer where the dead plankton are preserved. Organic-rich source rocks produced in this way are known as *black shales*. Dead plant matter that accumulates in swamps and mires produces peat and coal. In summary, most oil comes from dead marine plankton in black shales and most gas comes from dead plant material in coal.

### Reservoir and top-seal

Reservoir rocks must be porous and permeable. Sandstones whose grains are relatively poorly cemented form good reservoir rocks. Some types of limestone contain cracks and holes, usually formed by post-depositional processes. The top-seal acts to seal the oil in the trap; clearly, good sealing rocks are non-porous and impermeable. A useful top-seal must directly overlie the reservoir rock. Good seals are often ductile, so that they tend not to deform by fracturing, and regionally extensive, to prevent leakage round the edges of the trap.

### Oil generation

Oil generation occurs when the source rock *matures*, i.e. when it is heated to the correct temperature. Lipid-rich organic material breaks down to form oil at temperatures between

$\sim 80$  and  $150^\circ\text{C}$ . If the resultant oil is heated further to between  $\sim 150$  and  $180^\circ\text{C}$ , it cracks to produce gas. Lignin-rich organic material forms insignificant oil; it breaks down to form gas at temperatures between  $\sim 150$  and  $220^\circ\text{C}$ .

Temperature generally increases with depth in the Earth. Temperature  $T$  within a sediment pile contained within a sedimentary basin can be determined using

$$F(t) = k(z) \frac{dT}{dz} \quad (1)$$

where  $F$  is the heatflux through the basin and  $k$  is the thermal conductivity of the sedimentary rocks. This calculation is complicated in detail because heatflux varies through time and thermal conductivity varies with depth. Conductivity varies slightly with rock type, but the main control is porosity since the thermal conductivity of water is significantly less than that of solid rock grains. In general, conductivity increases with depth as the sediment compacts. Changing heatflux through time can best be estimated through an understanding of the mechanics of sedimentary basin formation. In extensional basins, heatflux peaks during the rifting phase when the plate is at its thinnest. Foreland basins are related to tectonic shortening, so the plate remains thick and the heatflux remains low as the basin develops.

Source rock maturation can be assessed using a *stratigraphic growth* (or *cumulative stratigraphy*) plot, which is a plot of sediment thickness through time. The plot has two components. The path of each rock layer is tracked as it is buried below the surface, preferably taking full account of compaction. Then, the temperature within the basin is contoured, using equation 1 and accounting for variation in thermal conductivity with depth and heatflux with time. As a rough guide, oil generation happens at a depth of around 2 to 3 km in 'well-behaved' basins.

## Traps

A trap is any configuration of reservoir and top-seal that will pond oil as it rises buoyantly from a mature source rock. They can be classified into *structural traps* and *stratigraphic traps*. Structural traps involve faulting and/or folding. It is important to realise that the source rock can stratigraphically overlie the reservoir and top-seal rock layers, so long as the effect of the faulting/folding is to deform it to beneath the trap. Stratigraphic traps involve reservoir rock that is limited in spatial extent because of its environment of deposition.

## Migration

Migration consists of two components. First, the hydrocarbons must escape the source rock, which is usually a relatively non-porous, impermeable rock-type. Formation of hydrocarbons from organic matter involves a volume increase. The resulting over-pressure probably allows the hydrocarbons to generate small fractures and escape the source rock. Once out of the source rock, the hydrocarbons must be able to rise under their own

buoyancy to the trap. They may migrate through porous, permeable reservoir-type rock-types. Fault zones are very important; they can act either as fluid conduits or fluid seals depending upon the detailed nature of the fault rock and damage zone, which depend in turn on the rock-types cut by the fault.

### Timing

The timing of maturation of the source rock with respect to formation of the trap is absolutely critical. Timing of source maturation can be estimated from a cumulative stratigraphy plot. Timing of trap formation requires knowledge of the geological history of the area, derived from a variety of sources such as maps, cross-sections, seismic profiling and subsidence analysis. It is important to decide how many phases of tectonic deformation and trap formation have taken place. If more than one phase has occurred, early traps are likely to have been breached and oil and gas are most likely to remain trapped in the most traps formed by the most recent phase of deformation.

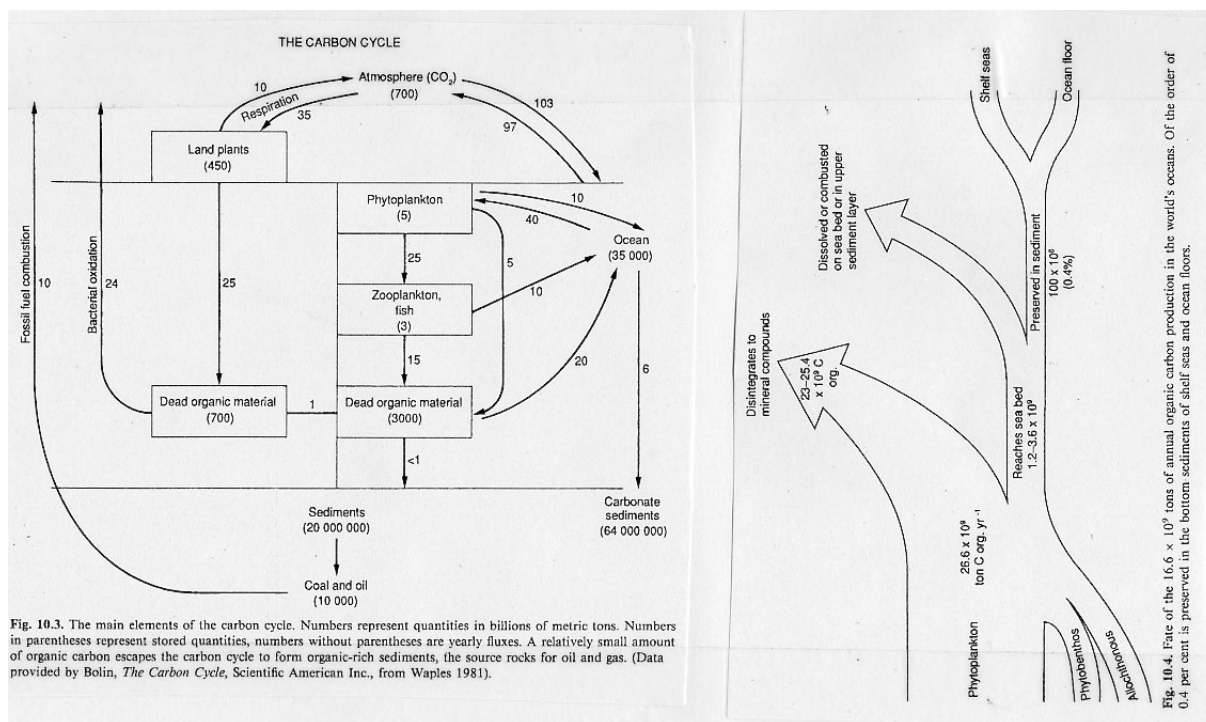


Fig. 10.3. The main elements of the carbon cycle. Numbers represent quantities in billions of metric tons. Numbers in parentheses represent stored quantities, numbers without parentheses are yearly fluxes. A relatively small amount of organic carbon escapes the carbon cycle to form organic-rich sediments, the source rocks for oil and gas. (Data provided by Bolin, *The Carbon Cycle*, Scientific American Inc., from Waples 1981).

Fig. 10.4. Fate of the  $16.6 \times 10^9$  tons of annual organic carbon production in the world's oceans. Of the order of 0.4 per cent is preserved in the bottom sediments of shelf seas and ocean floors.

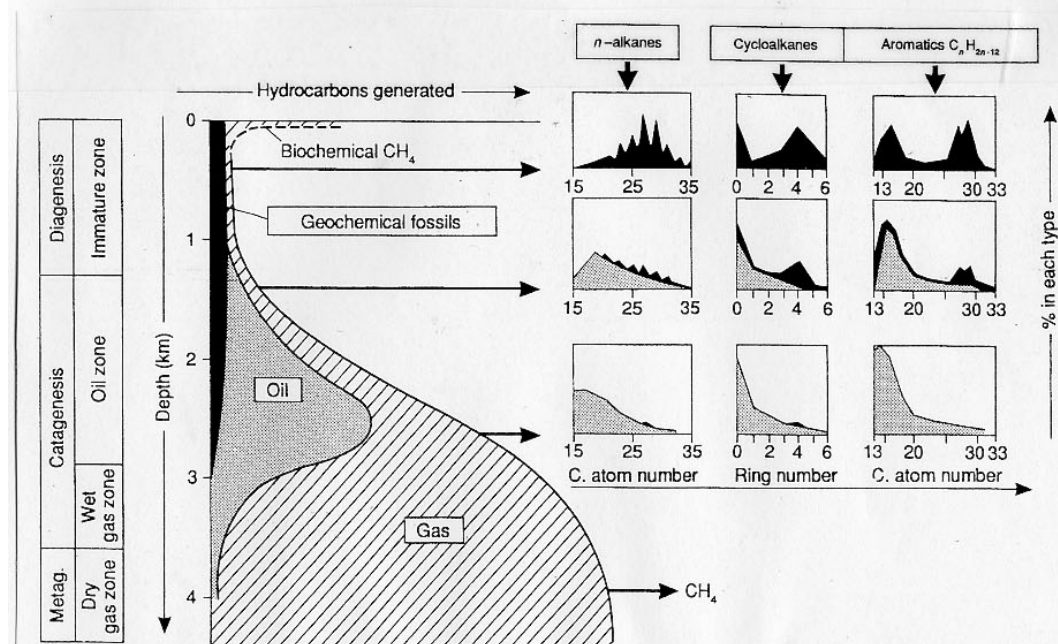
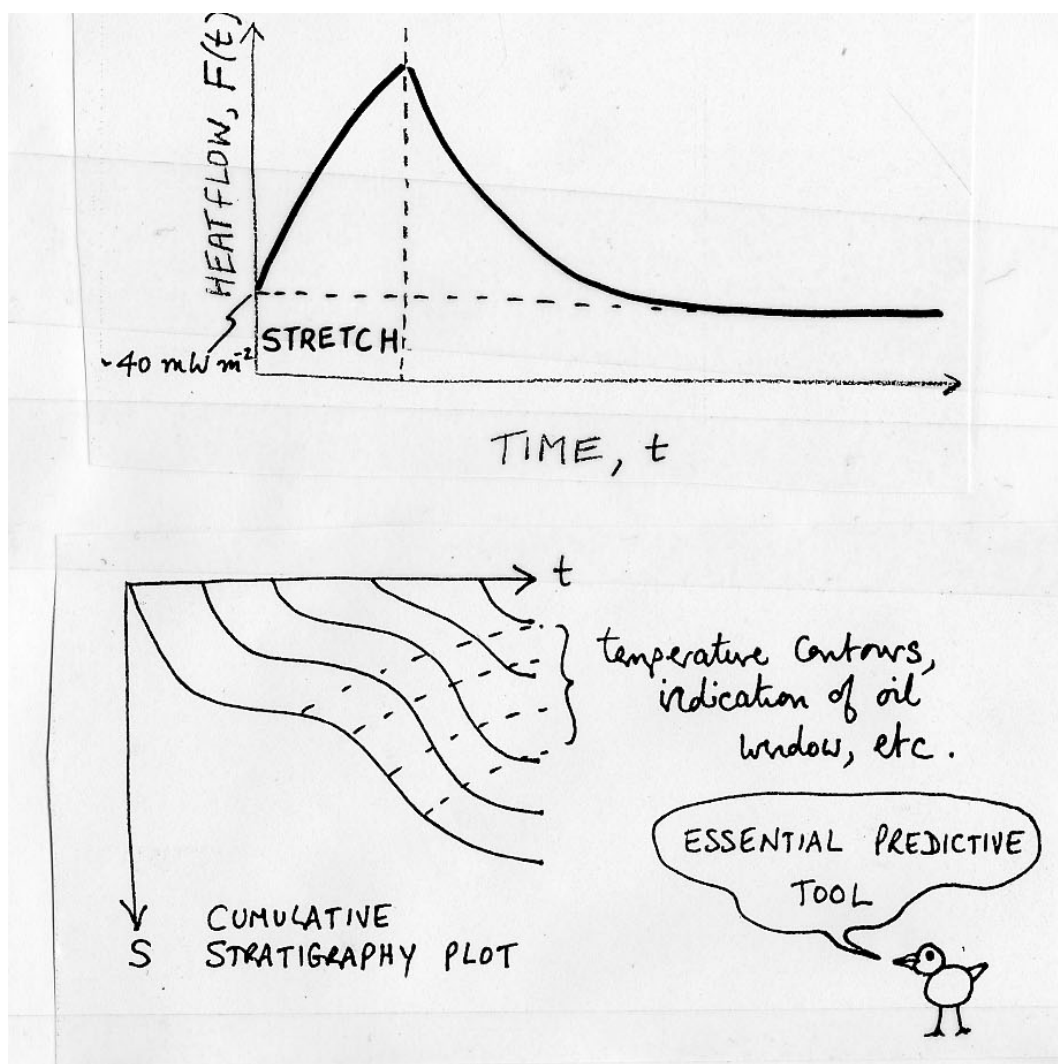
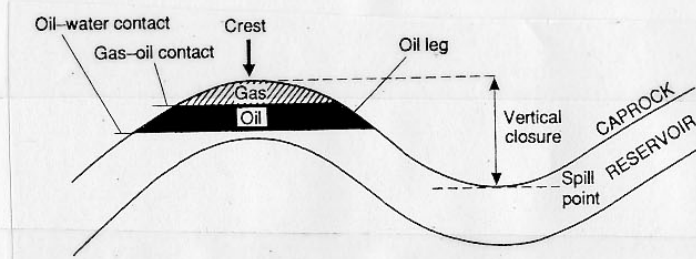
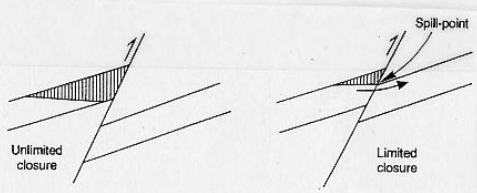


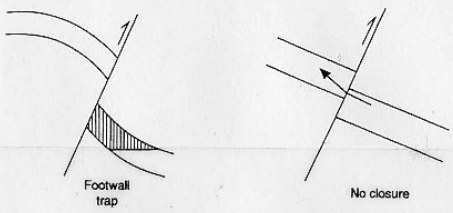
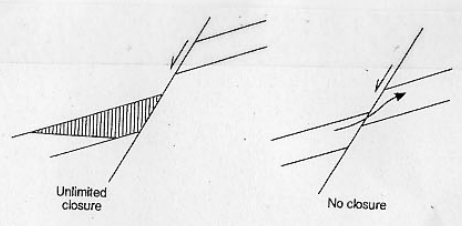
Fig. 10.25. General scheme of hydrocarbon formation as a function of burial of the source rock, according to Tissot and Welte (1978). As formation temperature rises on progressive burial, an immature stage is succeeded by stages of oil generation, oil cracking (wet gas stage) and finally dry gas generation. Typical distributions of  $n$ -alkanes, cycloalkanes and aromatics at three points in this general evolution are shown.



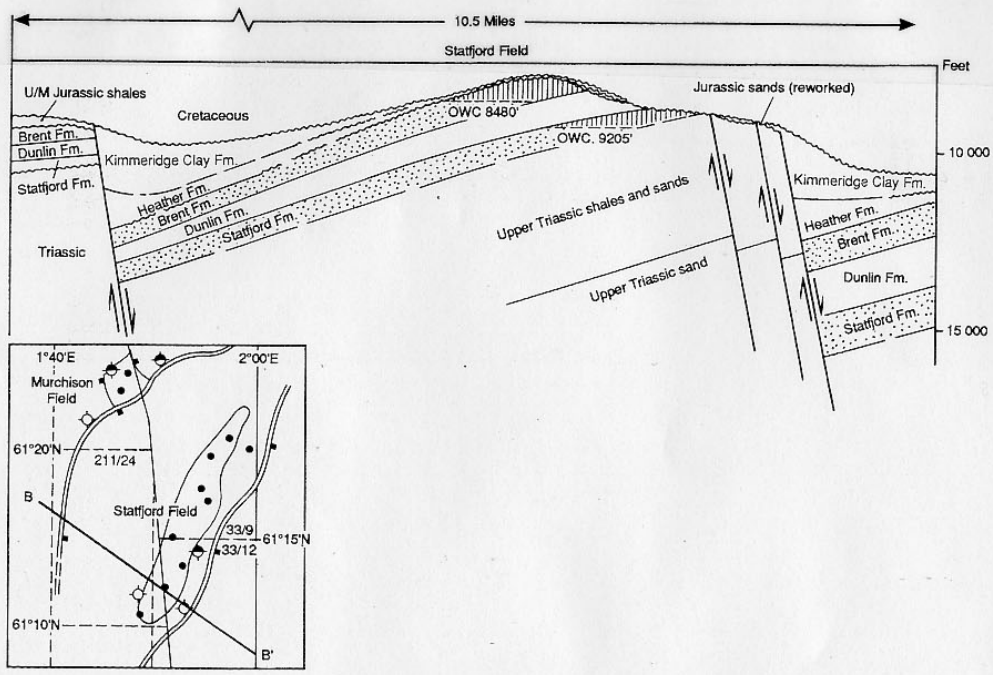
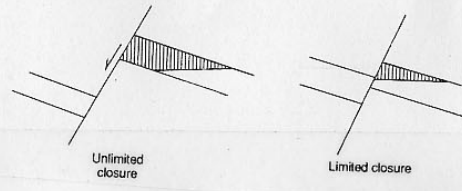
**Fig. 10.48.** Terms commonly used in the description of traps. A gas cap overlies an oil leg, and the trap in this case is not filled down to its structural spill point.



**Fig. 10.56.** Traps formed by extensional faults (after Bailey Stoneley 1981). Seal depends on the lithologies juxtaposed against the reservoir across the fault plane. Ideally, fault throw should exceed reservoir thickness.



**Fig. 10.52.** Traps formed by high-angle reverse (contractional) faults. Juxtaposition of permeable bed limits closure. For maximum closure, fault throw needs to be large in relation to reservoir thickness. All of the illustrated trap types also require closure in the third dimension, that is, into the plane of the paper. (After Bailey and Stoneley 1981).



**Fig. 10.53.** Schematic structural cross-section across the Statford field, North Sea (after Kirk 1980). Statford is a large westward-tilted fault block that has been strongly eroded at its crest. The trap at Brent Formation level is formed by seal at the erosional unconformity, but the deeper Stafford Formation reservoir depends on fault closure.

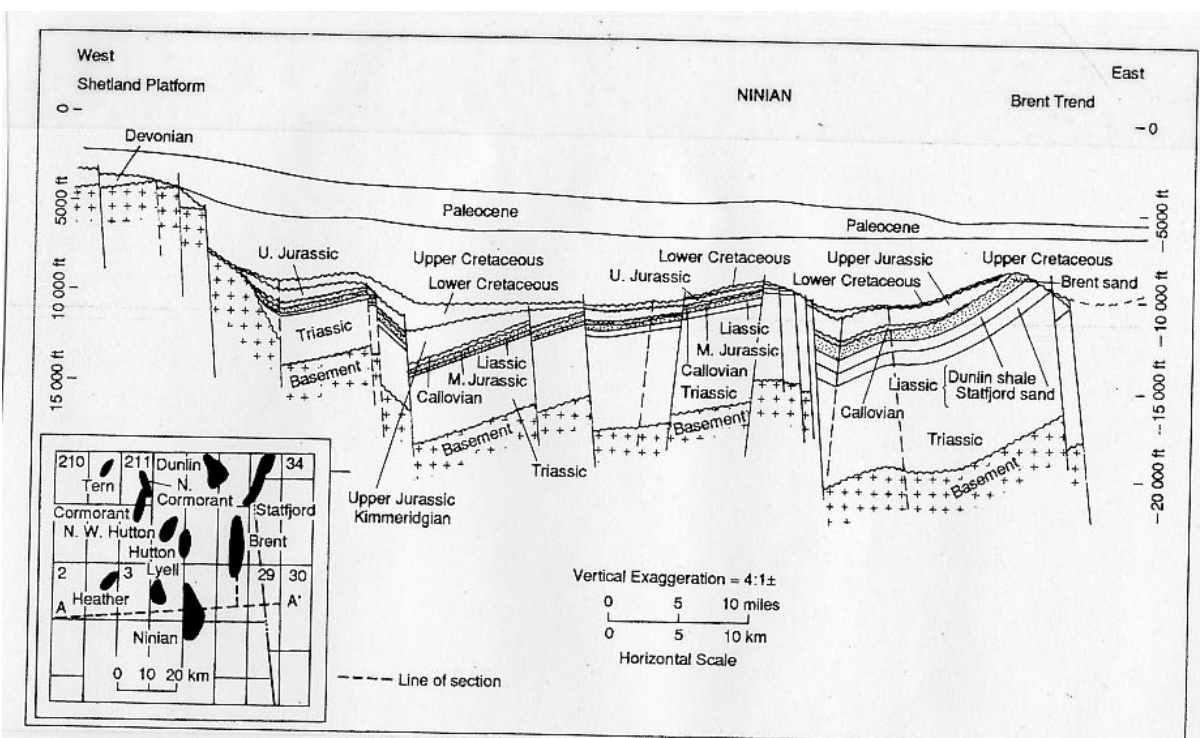


Fig. 10.54. Structural cross-section across the eroded, tilted fault blocks of the Ninian area, East Shetland Basin, North Sea (after Albright, Turner and Williamson 1980). This is a common and successful trap type in the North Sea.

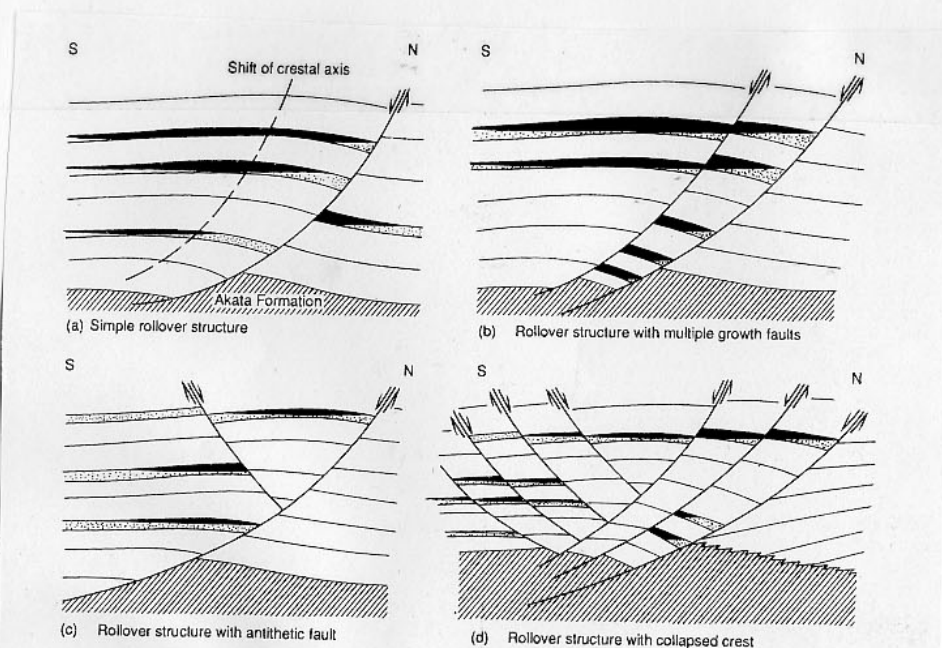


Fig. 10.59. Varieties of rollover structure forming petroleum traps in the Niger delta area (after Weber *et al.* 1980). Note: Only a few reservoir sands are shown in the schematic sections and the sand thickness has been enlarged.