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Hydrocarbon Potential of Deep Water

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Hydrocarbon potential of deep water

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[Plate 1]

In recognizing that we are at a very early stage of exploring the geology and hydrocarbon potential of the Earth's deeper water areas, an attempt is made to generalize the geological conditions that exist on the continental slopes, the rises and the remainder of the oceanic provinces.

An attempt is also made to relate the postulated geology of these provinces to the conditions of structure and stratigraphy required to yield commercially extractable hydrocarbons in what must be a high cost operation.

It is fully appreciated that there is much that we do not know about the geology of the more deeply submerged regions and that no accurate costs can be attributed to methods of hydrocarbon extraction that have not yet been devised; nevertheless it is felt that the current stage of knowledge and feeling for the order of magnitude of costs is adequate to provide some indication of hydrocarbon potential. This potential is not considered adequate to give any optimism for the deeper waters providing substantial additions to the reserves of exploitable hydrocarbons.

1. Introduction

As a normal product of the diagenesis of organic material trapped in sediments, and subjected over the long periods of geological time to the temperatures and pressures of deep burial, hydrocarbons are everywhere a common constituent of the fluids of the upper part of the Earth's crust. The concentration of hydrocarbons into accumulations sufficiently large to be commercially extractable calls for the coincidental combination of various geological factors throughout long periods of geological time; hence large accumulations are rare and impossible to predict in any one unexplored basin. We are only just beginning the search for hydrocarbons in deeper water and therefore do not know the geological conditions obtaining in many of the deeper water areas. Any attempt to quantify the hydrocarbon potential of such an imperfectly known domain can only be an informed guess. To assess the recoverable hydrocarbons also requires consideration of the time and cost of extraction and again we lack enough experience of deep-water production systems to make anything other than 'broad-brush' guesses of their cost; this factor again militates against precision in any estimates of recoverable hydrocarbons.

It is impossible to cover the detailed geology of the large areas of deep water of the whole world; this paper can therefore only describe the generalities of the main types of deeper-water provinces and consider the premises and problems bearing on the likelihood of the existence of commercial hydrocarbons and guess as to their quantities.

From what is known it is considered that appreciable quantities of oil and gas will be found beneath the deeper waters and that extraction of these hydrocarbons will develop rapidly over the next two or three decades. It would seem, however, that the deep-water areas do not have the potential for producing as much oil and gas as the land and shallow-water areas of the world and that although the contribution from deep water will be significant it will not postpone to any great extent the relatively imminent shortages of oil to meet our current demands.

2. REQUIREMENTS FOR COMMERCIAL PRODUCTION OFFSHORE

Hydrocarbons can only be produced if the cost of their production can be commercially met either by price in the market or by their relative attraction in a planned economy. With other fossil fuels such as coal being in relative abundance, and with the availability of other forms of energy such as nuclear power, cost must in the long term and in any form of society be a critical factor in determining the use made of hydrocarbons. One of the relative advantages of oil in the last few decades has been its low cost. In the heyday of abundant cheap oil from the Middle East, small onshore oilfields in many parts of the world could not be developed commercially. Now that governments in the major producing countries have quintupled the cost of world oil by their increased tax take, relatively small oilfields onshore can be commercially developed, but even now in remote and undeveloped areas onshore fields of capacity less than about 50000 barrels per day are not worth developing unless they are associated with other fields and production facilities.

Offshore fields of very modest sizes can be commercially exploited, but the inhibiting effect of steeply rising costs due to increasing water depths and to exposure to severe weather conditions can be illustrated by quoting some figures for the North Sea. In the British sector and under U.K. tax rules an acceptable commercial rate of return can be made from a field with recoverable reserves of around 40×10^6 barrels and individual wells flowing at a peak of 1000 barrels per day under as much as 50 m of water. A field of 10–20 million barrels of oil can be commercial, utilizing a floating production system that can handle few wells and modest production, but in this case well productivities need to be in the range of 5000–10000 barrels per day. In the main oil-producing area of the North Sea, i.e. with water depths in the range of 100–200 m, to meet the same financial criteria it is necessary to have fields in the range of 200–300 million barrels of recoverable reserves and well productivities in the range of 3000–5000 barrels per day at peak and maintainable for several years. It must be remembered of course that northern North Sea conditions are unusually severe and that costs of bottom-resting platforms in offshore areas with less severe combinations of wave heights and wind strengths are considerably less.

If we attempt to project our assessment of profitabilities out into water depths significantly greater than 200 m we must do so largely on conjectured costs of engineering concepts backed by little or no experience. Such a projection would indicate that at today's prices and today's value of oil, fields with recoverable reserves of at least 0.5×10^9 barrels and productivities of 5000 barrels per well per day would be required. The incidence of such fields in the world is limited. To date the total number of fields discovered in the world with oil or a quantity of gas of the equivalent thermal value is only 332, of which some 240 are oilfields (Klemme 1976). Of this total, somewhere between 15 and 20 % have reservoirs incapable of productivities likely to be economic in the deep offshore. Half of the giant fields occur in two basins (West Siberia and the Persian Gulf) which appear to be unique in their concentration of large fields. Outside these two basins such concentrations of giant fields are unusual and such fields are sparse and widely scattered. The North Sea stands out as exceptional and has 6 % of the total number.

After considering briefly some of the geological requirements for the formation of the large and high-productivity fields necessary to make deep offshore drilling attractive, I shall consider the likelihood of finding these conditions in deep water.

Nearly all large fields have a considerable element of structure in their trapping mechanism – in which a moderate degree of deformation is required to form large simple traps. Coupled with this, adequate reservoir qualities, particularly permeability, must exist in reservoir rocks to allow not only accumulation in quantity but also to allow extraction at high rates.

A sufficient quantity of organic material must be trapped in the sediments and subjected to the temperature (variable with the heat flow of the region) and pressures resulting from burial in order to generate hydrocarbons and cause their migration into reservoirs.

The range of depth of burial for oil generation appears to be from about 1 to 3.5 km with an optimum for giant fields in the range 1.5–3 km. Gas is most abundant in the range 3.0–4.5 km. Gas exists below that to considerable depths, in fact at least to 10 km, but below 4.0 km there is normally a marked and continuous decrease in reservoir porosity and permeability.

Deformation to form traps must occur at the correct time to collect the hydrocarbons produced during the main period of migration.

All these requirements must be met for the formation of large and highly productive fields.

3. Geological régimes of deep water areas

The oceanic domain can be divided into three main categories of geological units: the mid-oceanic ridges, the abyssal plains or ocean basins, and the continental margins; the latter include microcontinents and foundered remnants or slivers of continental crust.

(*a*) *Mid-oceanic ridges*

The combined area of the oceanic ridges and their associated rises, some 118×10^6 km^2 (Menard & Smith 1966), constitutes 32.7 % of the total oceanic areas. The ridges consist of oceanic basalts with virtually no sedimentary cover; the rises on the flanks of the ridges have basalts covered by only a thin veneer of sediments varying from a few tens to a few hundreds of metres in thickness. These sediments are mostly pelagic, with no significant matrix permeabilities that could produce hydrocarbons at a significant rate.

The combination of meagre sediment thickness and adverse reservoir character enable us to dimiss totally the hydrocarbon potential of this régime.

(*b*) *Abyssal plains or ocean basins*

The ocean basins are large areas of low relief, including abyssal hills and archipelagic aprons, but typically consisting of featureless plains. The basins, which are everywhere under more than 4000 m of water, constitute 41.8 % of the total area of the oceans. In all the oceans there are scattered volcanic features, some of which rise to the surface of the waters, or nearly so.

Our scattered knowledge of these basins depends on the combination of reflection and magnetic profiles, dredged samples, and the sparse but invaluable boreholes of the Deep Sea Drilling Project. It is clear that these regions have a uniform basaltic floor and the veneer of sediments is, like that of the ridge and rise province, too thin and lacking in permeable rocks to be considered seriously as a major contributor of producible hydrocarbons. Evidence of gas and of some oil should not be allowed to generate too much enthusiasm for the prospects of producible hydrocarbons. Details of the better known occurrences are given by McIver (1974) but his concluding paragraph comments '...each is an encouraging sign that one of the essentials for petroleum occurrence (i.e. source rocks) will be found in sediments presently under deep water. If there are reservoir rocks, if there are large enough traps, and if the source sediments have undergone enough alteration, large deep-water oil fields may be counted on one day...'. His optimistic conclusion could in my opinion be more suitably expressed as outlining the improbability of significant oil in the two régimes so far discussed which constitute some 75 % of the oceans.

One environment in the deep ocean areas that has potential reservoir rocks is that associated with coral reefs. Many of the volcanic and other topographic features that rise from ocean depths to near sea level have thick coral caps and flanking aprons of coral detritus. Many of these reefs and detrital aprons have been forming at least through much of the Tertiary and appear to obtain thicknesses up to 2000 m. Some of the aprons of detritus descend at steep angles to considerable depths; doubtless some guyots have coral caps but it is very unlikely that many, if any, of these young reefal developments are in contact with enough source material to have been filled with hydrocarbons, even in the rare cases where impermeable caps have been formed, and where burial of whatever source material there is has been adequate to generate hydrocarbons. Certainly significant numbers of oilfields are unlikely in these young and largely exposed reefs; in the rare cases where traps exist, gas is more of a possibility. In the island archipelagos and shallow seas of the East Indies the main hydrocarbon content of the buried Tertiary coral reefs and coralliferous limestones appears to be gas rather than oil, as for example in the Gulf of Papua, the southern South China Sea, southern Celebes. Oil is nevertheless present in significant quantities in reefs in western New Guinea and the adjacent Arafura Sea.

(*c*) *The continental margins*

The continental margins, as defined below, include the main deep-water areas that have significant prospects of producing hydrocarbons in significant quantities. Oil and gas have already been proved in the shallower parts of this environment and similar geology can be traced on seismic profiles into the deeper water where similar prospects for hydrocarbons must also exist. The main uncertainties in assessing the oil prospects are related to those parts of the margins where the geology is not that of the continental shelf, foundered or declined under deeper water, but in large volumes of sediment deposited in deep water and having always remained under deep water and in the geological environment peculiar to those regions. Representatives of such deeper-water deposits are known from the examples which have been lifted up and are now known as exposures on land or from drilling in shallow waters.

The continental margin as considered here is from the shelf break at or around 200 m, down the slope and out to the edge of the land-derived sediments which form a prism of variable thickness and width and which are more or less synonymous with the physiographic feature commonly called the continental rise.

In a paper of this scope it is clearly not possible to give detailed descriptions of the many and varied margins but some generalities of the main types of margins will be sketched and some examples considered briefly.

Although there is much variety in detail the two main types of continental margin are distinct and have very different prospects for hydrocarbons. The passive or pull-apart types characterised by the margins of the Atlantic are also present around the Indian Ocean, the Arctic Ocean and around Antarctica. For reasons that will be discussed later the Atlantic type margins have better prospects of containing exploitable hydrocarbons than the collision margins of Pacific type, typical of most of the deep water margins of the Pacific Ocean.

4. The margins of the Atlantic Ocean

Figure 1 is a simplified map (after Roberts & Caston 1965) which shows the total extent of sediments that could be remotely likely to contain extractable hydrocarbons, i.e. up to 1 km thick. A depth of 1 km is probably too little for the generation of oil, and the biochemical gas in shallow sands at less than this depth is not likely to be an attractive commercial prospect. The probable practical limit for any significant hydrocarbons is probably nearer to a minimum isopach in the 3–4 km range. In any case the thinner, oceanward, edge of these land derived clastics is almost certainly composed of extreme distal turbidite facies with little sand and high clay content, and hence holds little prospect of reservoirs.

Within the parts of the margins considered under our definition as being prospective there are two main categories of prospects. The first is in sediments that were deposited in shallow waters but which have foundered and now occur beneath the continental slopes or rises, and perhaps even in occasional segments of deeper oceanic floors which appear to be continental in origin.

(*a*) *Shallow water sediments of Atlantic slopes*

In most of the lands bordering the Atlantic there are thick sequences of Palaeozoic sediments; most of them have undergone various periods of disastrophism causing deformation varying from gentle folding to intensive metamorphism. Nowhere in these Palaeozoic onshore sediments bordering the Atlantic are there any oil or gas fields of the size and productivity required for commercial development in the deep offshore. There are no grounds for expecting any different conditions offshore and it is therefore considered unlikely that there will be any appreciable quantity of extractable Palaeozoic oil on the Atlantic margins.

Before the main drifting apart of the Atlantic margins there were developed extensive subsidiary basins in which were deposited considerable thicknesses of terrestrial and shallow marine sediments. Seismic profiles continuing out from the shelves allow confident identification of such sedimentation in many areas. In the early stages of rifting shallow water sediments probably deposited on the young oceanic basaltic crust. Roberts & Caston (1975) give a brief and clear discussion of the evidence for this. Evaporites are widespread along the margins of both the North and South Atlantic and may well cap underlying shallow water sediments containing suitable reservoirs. Diapiric structures, principally of halites, are locally abundant. The continuation of the oil provinces of Gabon and Angola from the shelf to deep water are discussed and clearly illustrated by Beck & Lehner (1974).

Reflexion profiles across typical slopes of oceanic margins (figure 2, plate 1) show the style of tectonics that typify many of these margins, i.e. with relatively little compressional or other folding, but down-to-the-ocean faulting and common diapiric intrusions.

Although oil and gas must occur in appreciable quantities in these sediments on the slopes there are great uncertainties in any attempts to envisage how much will meet the above-mentioned criteria for commercial extraction. There is no reason to believe that the hydrocarbon prospects are any better than on the adjacent shelf areas; the reverse is probably true as structures tend to decrease in number below the shelf edges and the regional oceanwards dip and down-faulting will in a general sense reduce closure. While exploration in many of the shelf areas around the Atlantic has been inhibited or prevented for reasons of politics or policy, a considerable number of wells have been drilled in shelf areas within the past decade or so and only a few fields have been discovered that approach our economic criteria, other

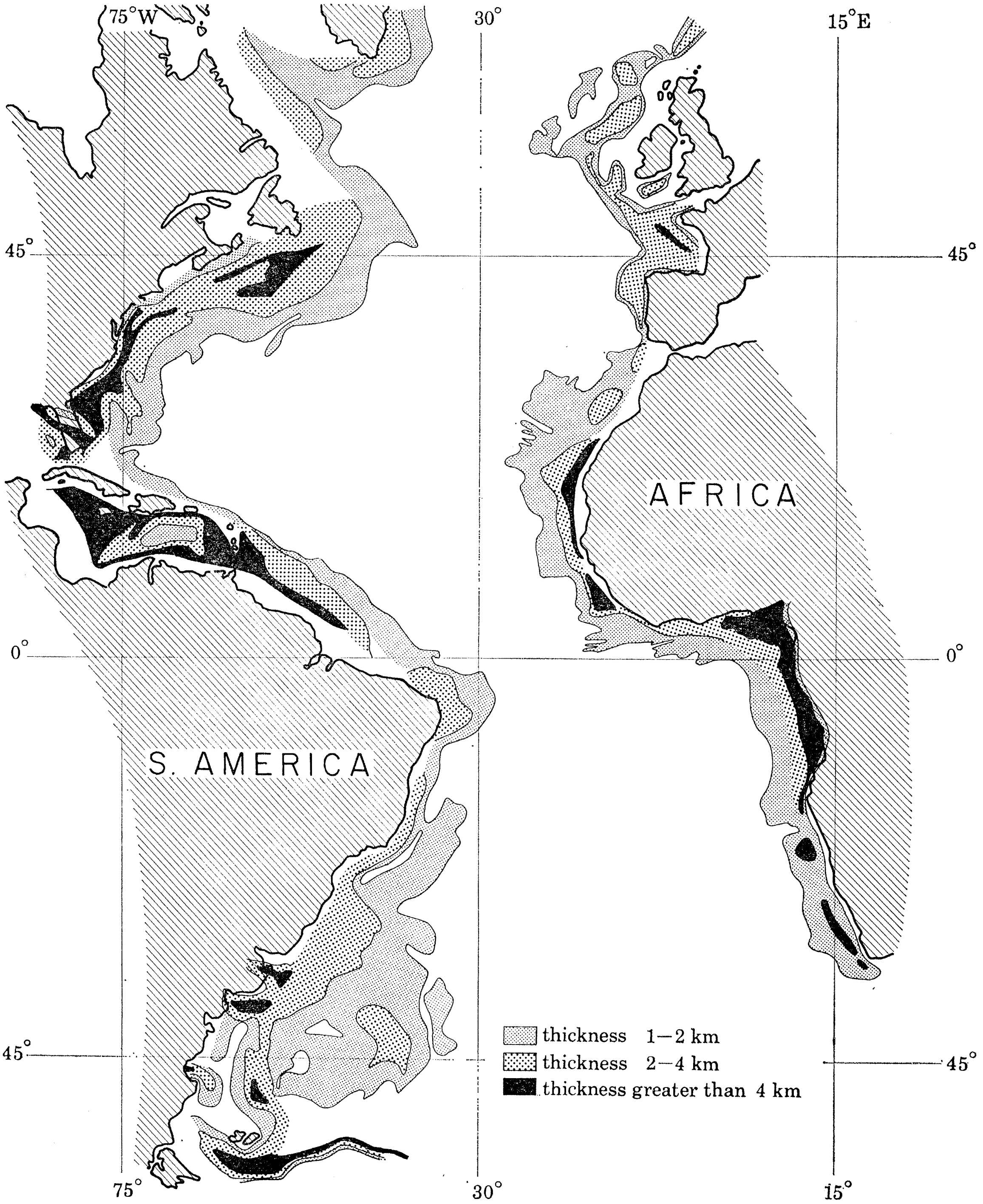

Figure 1. Atlantic sediment thicknesses.

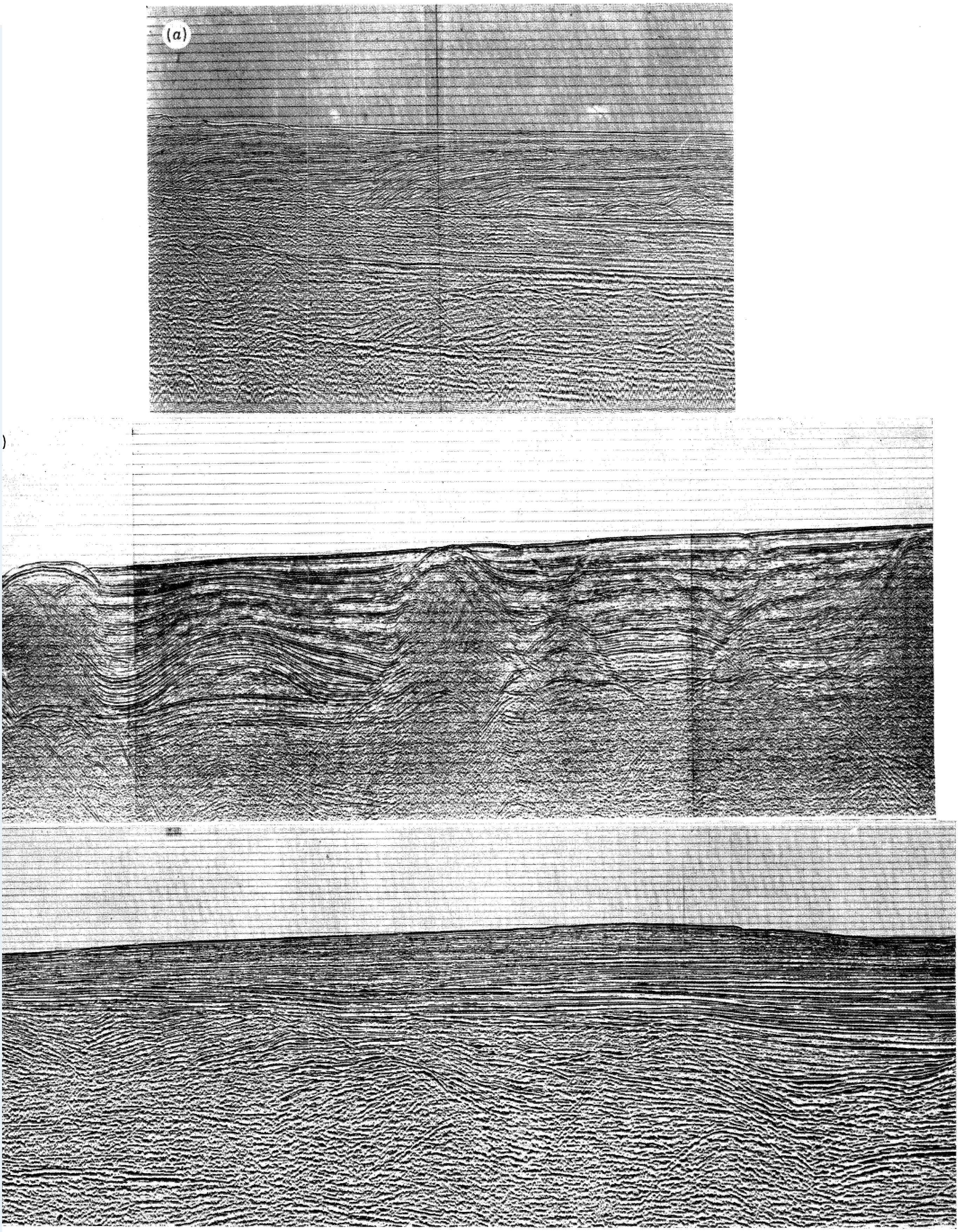

FIGURE 2. (*a*) Gravity tectonics above plane of décollement formed by messinian salt: W Mediterranean. By courtesy of the Western Geophysical Company. (*b*) Halokinesis, including classic 'turtle-back': Angola. By courtesy of J. Sefel and associates. (*c*) Pre-rift structurally deformed sediments underlying break-up unconformity: NW Australia. By courtesy of Geophysical Service Incorporated.

than those of the rather unique depositional and tectonic environment of the North Sea. Even with an increased tempo of exploration due to the increase in value of oil and the increase in availability of drilling equipment for the more exposed offshore areas it is difficult to imagine more than a further ten such oilfields and perhaps a similar number of gas fields being found in the next 10 years. As a guess one could attribute to these some $7-10 \times 10^9$ barrels of oil and $15-20 \times 10^{12}$ ft^3 of gas, these figures being of recoverable quantities.

(*b*) *Deep water sediments of Atlantic slopes*

An important domain in which hydrocarbon prospects exist in all oceanic areas but more particularly in passive, or pull-apart, types is in those sediments which have been laid down in the deeper waters and are by their nature related to the special depositional conditions below the edges of the continental shelves. The special conditions of gravity flow and turbidity current deposition are related to the gradients of the slopes and rises. Some examples of deposit of this type are known from onshore exposures where a combination of tectonic events and uplift have elevated such deposits above sea level. There are some examples of major oilfields in turbidite sands, including fields in Californian basins and some North Sea Palaeocene oilfields such as Forties. However, these fields are in fact in turbidite sands of rather special character, which have accumulated within enclosed or semi-enclosed basins close to a source of quartzose sand.

All of the available evidence suggests that the predominant sediments of the Atlantic slopes and rises deposited in deep water, which are predominantly of Cretaceous and Tertiary age, consist of hemipelagic fine-grained material with at best only thin turbidite sandstones which are probably not only thin but also poorly sorted and with very little reservoir potential. The only deep-water sediments with much promise for hydrocarbons are the relatively localized concentrations of sands that occur as fans and slumped masses associated with discharge from submarine canyons, together with the spill of deltas that have prograded to the edge of the shelf, and by combinations of longshore currents, mass sediment flow and turbidity currents have provided great thicknesses of coarser clastics. Although the conglomerates and massive sands of some of these bottom-of-the-slope deposits can and do provide excellent reservoirs, they tend to be very localized in channels and fans and pass rapidly into turbidite sands and silts of poor quality. While the presence of channels and fans can be detected on reflexion profiles, and doubtless with time and experience this ability will improve, traps will be unpredictable. Within the complex of channels and fans there are normally adequate hemipelagics to provide cap-rocks but there is little compressional folding along most Atlantic type margins, and structures tend to be gentle. As there is ubiquitous down-slope dip it only requires one thin poor sand to connect with the upper part of a sand body to provide an up-dip leak; this appears to be a problem in Palaeocene reservoirs in the North Sea. Some sand bodies must have adequate trapping by passage up-dip into impermeable facies but the risk factor will be high; this in an environment of expensive deep water exploration drilling.

There are, however, known exceptions to the lack of structures. Beck & Lehner (1974) and Lehner & De Ruiter (1976) describe and illustrate the large structures associated with the delta toe overthrusts in the deep water at the foot of the Niger Delta which must encourage the expectation that the oil-rich province of the Niger extends into deep water.

Organic material is commonly trapped in turbidites and although the facies does not always appear to be well endowed with good hydrocarbon source material the very high oil content per unit volume of sediment in the Los Angeles basin attests to the effective source and generation ability on occasions. Samples from the Deep Sea Drilling Project illustrate the apparent maturity of hydrocarbon genesis at deeper levels with hydrocarbons of increasing carbon number with depth. Although the low-temperature gradient in most young slope-and-rise deposits militate against hydrocarbon maturity at shallow depth, the thickness of several kilometres in many areas will ensure both oil and gas generation in adequate quantities.

Some of the more comprehensive papers on the mode of deposition of the sediments of the slope and rises are those by Emery (1969), Middleton & Hampton (1973), Sangree *et al.* (1976), Walker & Normark (1976) and Woodbury, Spotts & Akers (1976). These papers have comprehensive lists of references.

We can be confident that these deep-water sediments contain oil and gas accumulations, some of which will be large enough to justify the cost of deep-water exploration and production. No meaningful way is available to quantify the distribution of such fields. As a complete guess one could imagine perhaps ten oil 'giants' (recoverable reserves of 0.5×10^9 barrels or more) and a similar number of gas 'giants' (recoverable reserves of 3.5×10^{12} ft^3 or more). In such fields in the Atlantic one could therefore postulate perhaps 7.5×10^9 barrels of recoverable oil and a comparable thermal equivalent of gas. In addition, one can expect there to be in this geological environment a large number of smaller accumulations totalling perhaps two or three times the reserves in the larger fields.

5. Margins of the Indian Ocean

Prospects around the margin of the Indian Ocean are similar to those of the Atlantic with the considerable exception of the collision-type margins of the island arcs extending from Burma through the Andamans, Nicobars and the islands of Indonesia to Timor.

Along the coasts of Africa and India, particularly the former, terrestrial Triassic–Jurassic deposits such as the Karroo and later Mesozoic shelf deposits dip under thick prisms of deep water late Cretaceous and Tertiary sediments. With the exception of the oil sands of Madagascar a modest but significant amount of exploration along the east coast of Africa has been singularly unsuccessful in finding hydrocarbons in quantity or commercial significance. Although one cannot dismiss the possibility of hydrocarbons being found in the older sediments, it is difficult to attribute them with any quantifiable potential. An exception to this is on the Australian margin of the Indian Ocean, where the Permian to Jurassic clastics which have yielded some oil and a lot of gas drop along down-faulted margins into deep water. Particularly off the NW shelf of Australia large structures exist in this environment which have good potential for hydrocarbons, although with the main likelihood being of gas.

Deep water sediments, including gravity flow and turbidites of Cretaceous and Tertiary age similar to those described in the Atlantic, occur around much of the margin of the Indian Ocean and again these must locally have prospects. Considerable attention has been focused on the enormous sediment cones off the mouths of the Indus and Ganges, but on the basis of exploration to date it is suspected that these will in large part be very short of adequate reservoir sands.

It is again virtually impossible to quantify the reserve expectations of the deep-water regions of the Indian Ocean, but as a wild guess one is tempted to suggest figures similar to those postulated for the Atlantic.

For a fuller definition of the main prospective areas of the Indian Ocean reference is made to Schott, Branson & Turpie (1975).

6. Margins of the Pacific Ocean

One cannot do justice to the extensive and complex margins of much of the Pacific in this paper but a few generalities can be made. Most of the typical collision margins of the Pacific have no significant deep-water prospects in beds older than Middle Cretaceous; such older beds have generally been too tectonized and metamorphosed to be prospective. Off the narrow shelves of much of the Pacific the descent to great depths of water is rapid. Prisms of Cretaceous to Recent sediment, often of great thickness, occur along the Pacific margins, but in these sediments off the classic arcs stretching from New Guinea to Alaska there is a high proportion of volcanogenic sediments, a factor that will downgrade the already poor reservoir prospects in the deep-water sediments. In some areas, particularly off coasts with good granitic sources for arenaceous sediments, reservoirs will exist with oil accumulations comparable to those of offshore California, but they will take time to identify and even then prolific fields for economic production will be hard to find.

Quantification of the hydrocarbon potential of the deep-water margins of the Pacific is, if that is possible, even more uncertain than for the Atlantic and Indian Oceans. It is, however, unlikely that reserves will exceed those predicted for either of these oceans.

Although there are parts of the Arctic Ocean margins that have some prospects similar to those of the other oceans, the problems of ice in deep-water drilling production make such prospects of no interest for the forseeable future.

7. Hydrates

Although there are very large total volumes of hydrates dispersed through the top layers of sediments of the deep oceans it is at present inconceivable that these could gainfully be liberated and collected on any meaningful scale and they will not be further considered.

8. Conclusions

From this very cursory consideration of prospects for deep water producible hydrocarbons it can be said that the large areas of the deep ocean basins have little prospect of containing large hydrocarbon reserves. The continental margins down to the rise clearly do have prospects of producing both gas and oil but the incidence of fields of sufficient size and productivity to warrant production will be limited. Finding such accumulations will not be easy and the cost of exploration alone will be considerable.

Over the next decade or two it is difficult to visualize the finding of more than 20 or 30×10^9 barrels of recoverable oil and within that time span not a great deal of this discovered oil is likely to be on production. Gas in comparable quantities will probably also be found but the increased problems of getting it ashore means that little, if any, will be produced in water depths greater than 500 m before the end of the century.

Although it is the province of the engineering contributions to this symposium to predict the availability of systems for really deep-water production it is considered by many workers that we shall be restricted within the next couple of decades to production from the upper portions of the slopes – perhaps down to 2000 m. The prospects of oil or gas production from the lower parts of the slopes and from the rises would seem more likely for the next century rather than before the year 2000.

The above estimates and predictions are based on so much uncertainty and assumption that they are prone to gross error. There is room for some major surprises in both the amount of hydrocarbon discovered and the ability to extract it at economic rates. It is not long ago that we were saying that 100 m of water was the likely limit of economic production. When significant finds are made in deep water, and they undoubtedly will be, there will be an enormous acceleration in engineering development to produce it. There is certainly enough prospect of deep-water hydrocarbons to encourage exploration for them in the face of the impending shortage from other areas, but this search will be neither cheap nor easy, and with the cost of single exploration wells running at £5–10 M each the pursuit of more subtle exploration plays will require considerable financial encouragement and attractive terms.

I wish to express my indebtedness to Dr V. Caston of British Petroleum for his guidance and assistance in preparing this paper.

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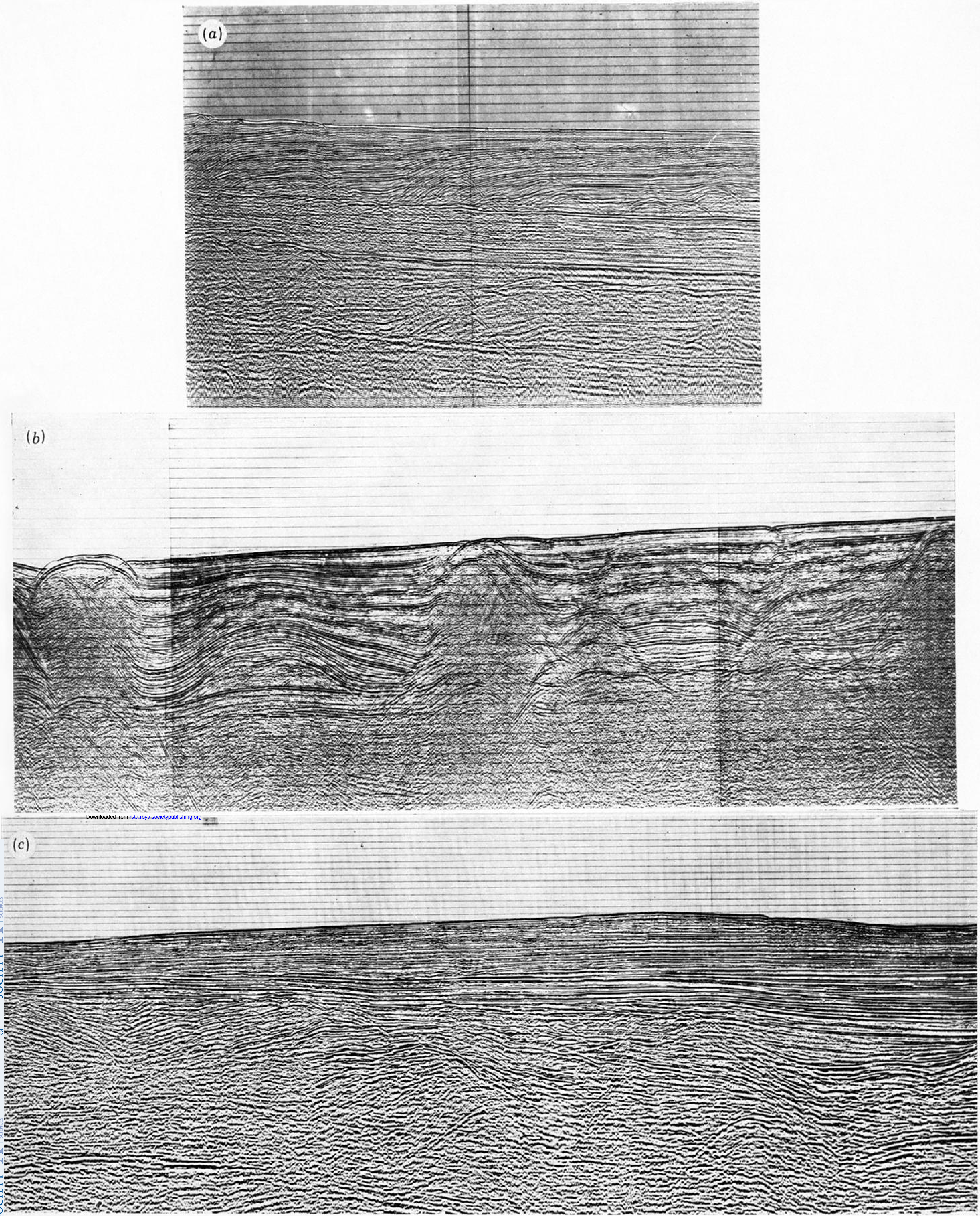

FIGURE 2. (*a*) Gravity tectonics above plane of décollement formed by messinian salt: W Mediterranean. By courtesy of the Western Geophysical Company. (*b*) Halokinesis, including classic 'turtle-back': Angola. By courtesy of J. Sefel and associates. (*c*) Pre-rift structurally deformed sediments underlying break-up unconformity: NW Australia. By courtesy of Geophysical Service Incorporated.