DEVELOPMENTS IN PETROLEUM GEOLOGY—1

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PREFACE

The past twenty-five years have seen a great expansion in knowledge relating to petroleum geology. This is not a case of developing new basic concepts, but rather a matter of having obtained new and better supporting data, and the acquisition of information on significant details by the use of new techniques and instruments.

Those active in particular branches of petroleum geology will have kept pace with developments relating to such branches, but it would require a most voracious reader or well-financed conference attender to cover fully the many aspects of this subject. Indeed, it might be wondered whether such a person, if he or she exists, could be doing much beyond acting as a sponge for information. The contents of the *American Association of Petroleum Geologists Bulletin* were equivalent to about 1·2 million words in the 1952 volume and 1·9 million words in 1976, having gone through a peak of some 2·2 million words in 1974. This is by no means the only journal containing papers concerned with points of interest in petroleum geology.

The basic aim of this volume is to put in the picture those who are not already experts in a particular branch of petroleum geology so that they may become aware of what has been going on elsewhere during recent years and to enable them, where applicable, to make use of such knowledge in their own work. Various considerations have precluded the writing of exhaustive texts, including the fact that many readers might find them overwhelming; yet it is believed that there has been judicious selection of detail, and that the bibliographies will allow the ready acquisition of additional information where required.

Team-work is an essential feature in the effective search for and development of oil and gas fields, for the application of petroleum geology does not end with the drilling of a discovery well. Hence, an understanding of the techniques and the kinds of information employed by other members of the team can be beneficial. It is also important to recognise the limitations of techniques and the uncertainties which can be inherent in the interpretation of observations. Sometimes over-enthusiasm may lead to the inappropriate application of some techniques or ideas, and to a failure to recognise the possibility of alternative explanations of the observations. Cautionary notes are to be found in various places in this volume.

The fascinating subject of plate tectonics, the modern and decidedly more all-embracing version of continental drift, bids fair to co-ordinate much in geology that tended formerly to be treated separately. The patterns of occurrence of mineral deposits have begun to receive consideration against the background of plate tectonics. Major tilts, fractures and displacements affecting lithospheric plates may lead to the advance or retreat of seas as sedimentary basins evolve, and there are effects which determine the nature, extent, mode of emplacement and thickness of sedimentary sequences. Temperature levels play a major role in the development and evolution of oil and natural gas, and variations in temperature history from place to place are dependent on factors involved in plate tectonics.

Detailed knowledge on the components in crude oil and in solvent extracts from sediments has grown apace, while ideas are developing on the structure of the intractable solid organic matter and on the origin of the asphaltic materials in sediments. Although details concerning the formation of petroleum have become much clearer, important aspects of the mechanism of oil and gas migration remain to be elucidated. Water and its movement and associations in sediments are of importance in various connections: migration, mineralogical changes and mineral redistribution which affect porosity and permeability, and even general geological structure; while what may be considered to be less than normal water displacement leads to over-pressured clays, with bulk densities lower than are usual for their depths of burial.

Wells provide the only direct data on some matters such as lithology, fluid content of the rocks, etc., and in certain cases sound deductions concerning the origins and alterations of the rocks may be made with considerable assurance from observations made in wells or on cores, cuttings and fluids obtained from wells. In view of the high cost of wells, as drilling depths have increased and oil exploration has moved offshore, there has been a strengthening of the incentive to make deductions about the fluid content or the nature of the rocks in advance of drilling. Seismic surveys have long been used to try to ascertain rock boundary shapes and arrangements suitable for trapping hydrocarbons. Improvements in the acquisition and treatment of seismic data have aided in the better definition of possible trapping situations. At the same time features have been recognised on seismic records which could be indicative of the presence of free gas in the rocks. In addition, the prospect of satisfactorily deducing something about the lithology from seismic observations has emerged. Certain characteristics of the processed seismic data are involved, as well as the shapes which they indicate. In the latter respect it is clear that reflection seismic surveys can provide information at laterally far closer spacing than is ever practicable by drilling deep wells.

The contributors to this volume worked with an awareness of the general aims and a knowledge of the proposed titles of other chapters; they did not have access to the manuscripts of the other chapters. Their efforts, including the speed with which they dealt with minor queries arising from the original texts, are gratefully acknowledged.

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CONTENTS

Chapter 1

SOME FUNDAMENTAL ASPECTS OF PLATE TECTONICS BEARING ON HYDROCARBON LOCATION

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SUMMARY

The interpretive framework of plate tectonics is carefully reassessed and considerably extended with particular regard to the problems of hydrocarbon exploration. It is found that the seismic low-velocity zone lies wholly within the plates, which are thus very much thicker and stiffer than previously recognised. The consequences impinge upon surface and near-surface phenomena to a quite remarkable degree, offering (inter alia) *major and unifying advances in the interpretation of basins, whether in orogenic settings, at ocean margins, or within continents. Specifically, the persistent and episodic differential epeirogenic movement of block-and-basin crustal mosaics is shown to be characteristic of basin complexes formed by limited plate separation at a much earlier time (even as long ago as Late Precambrian). Island inliers (micro-continents) detached at that time provide buried structural highs important for hydrocarbon accumulation. Extremely precise (~5 km) reconstructions are achievable.*

Plate stiffness makes epeirogenic processes at plate edges felt at great distances from them, often causing flexural failure, intra-plate rifting, intra-plate volcanism and further epeirogeny. Thick plates enhance thermal epeirogenic effects, enable shelf emplacement of ophiolite slices to occur during early separation, explain certain features of the subduction process, and shed light on the incidence and petrogenetic mechanisms of intra-plate volcanism. Correct treatment of plate thermal epeirogeny shows the previous wholly-vertical contraction/expansion requirement to be erroneous.

The plate tectonics of the Phanerozoic of north-western Europe and the post-Palaeozoic of the Middle East are among the examples discussed.

With this greatly increased relevance and precision, plate tectonic analysis is clearly capable of playing a valuable and detailed part in hydrocarbon exploration, contributing directly both to the precise delineation of basement structural outlines and to the interpretation of subsequent structural, sedimentary and thermal evolution.

INTRODUCTION

The location of hydrocarbon accumulations requires the detailed application of a highly developed technical and interpretive expertise. At present, however, the role of plate tectonics in this process is rarely more than to provide a fascinating backdrop whose detail is nowhere precise enough for direct use. Margins appear blurred, the plate motion significance of particular events obscure or ambiguous and, even when the causative motion is clear, the geological consequences sometimes vary sharply and apparently unpredictably from place to place. Are these merely the teething problems of a new scientific field or are they truly random features bringing fundamental limitations upon its economic usefulness? In particular, can plate tectonics be made sufficiently precise and comprehensive to contribute usefully to the detailed interpretation (and prediction?) of the structural, sedimentary and thermal development of sedimentary basins?

The high costs of exploration make these questions extremely important. This chapter shows that certain widely accepted features of plate tectonics are capable of radical reappraisal, and the effect of this will be shown not only to widen greatly the probable applicability and scope of interpretations based on plate tectonics, but also to offer a possible way of making them more precise and economically useful. To do so requires an excursion into deep geophysical matters far beyond the shallow effects we seek to interpret.

Plate tectonics as a field of study rests on the firm establishment of two essential discoveries. One is that the Earth's lithosphere† is formed of a rather small number of major plates which, to a remarkable degree, behave as mechanical entities and are outlined by belts where they interact.[1,2] The

† The term is used here in its usual plate tectonic sense to include both the crust and a substantial thickness of mantle material to a depth beyond which flow-creep becomes the dominant feature of any response to stresses imposed at rates typical of plate motion.

other is that this interaction consists of large-scale separative motion involving lithosphere creation, and commensurate approximative‡ motion made possible by lithosphere consumption or plate-edge deformation.[3,4]

A thorough understanding of the basic processes involved in large-scale lithosphere genesis and consumption is a central aspect of plate tectonics study, as the way to enable an interpreter to relate the general to detailed matters of exploration concern.

The grand scale of plate genesis provides widespread clues about the basic mechanisms of oceanic plate evolution. In particular, the coherence of the data leaves no doubt that the (3 km +) subsidence of ocean floors with increasing age is due to progressive heat loss from and density increase *within the plate itself*, thus stressing the direct role of plate tectonics in long-term epeirogenic movement and suggesting that sub-plate processes (e.g. convection) may have, for practical purposes, no direct surface manifestation apart from the plate motions themselves. Evidence of the processes involved in subduction, on the other hand, although supporting the general picture of calc–alkaline volcanism induced by shearing-produced heat at Benioff planes, seems in detail to be much less coherent than ocean floor data, and this may partly be due to the fact that here we have the interaction of two plates, each of which has a distinctive prior history and resulting constitution.

The highly ordered features of large parts of the ocean floor seem a far cry from the complex plate fragmentation and reorganisation which must have characterised plate interaction elsewhere (e.g. the Alpide belt, the east Asian margin, or western Europe), if the resulting mosaics of basins and highs are to prove tractable in plate tectonics terms. However, it seems wholly premature to invoke some entirely different plate interaction process for these until all the possibilities for complex interplay of 'normal' kinds of plate genesis and consumption have been fully explored. In regions such as these it is important to remember that interactions between major plates probably proceed at typical plate relative speeds (5 cm/y is 250 km in 5 my), so that what now appears to have been a continuum of interaction may turn out to have been a series of rapid discrete phases blurred by overlapping after-effects. As discussed later, there seems to be evidence for this in the Caledonian–Appalachian orogenic belt. The notion that plate motions do

‡ As the kinematical opposite of *separative* this term is preferable to the frequently used *convergent*, which is ambiguous; having also a static geometrical meaning, to which use in plate tectonics it should desirably be restricted. Otherwise, consider the possible confusion when discussing the convergence (motion) of convergent (geometrical) margins.

not start or stop abruptly was born of unrestrained convection hypotheses but is probably incorrect, especially in situations where motions may be guided or limited by plate obstructions.

For the basin analyst a crucial question concerns the duration and nature of the after-effects of plate interaction, particularly separation. Indeed, its initial main concern with the nature of interaction at plate boundaries made some geologists feel that plate tectonics could have little bearing on geological events at places that were far from a plate boundary at the time. Recent developments make it clear, however, that the after-effects of lithosphere genesis are active for much longer and are far more widespread than seemed likely a few years ago. Because these after-effects are mainly thermal, epeirogenic and sedimentary in character, and provide important control on the location of faults, they bear on many aspects of hydrocarbon occurrence.

We discuss first a wide variety of evidence bearing upon the thickness and constitutional variation of plates, showing how it is upon these that much of the residual (and sometimes highly correlated) activity at the surface depends. This provides a basis for the treatment of basins (*chasmic* basins) of true plate separation origin and yields strong arguments that such basins are also a widespread feature of the continents. Attention will be drawn both to the influences of various tectonic environments upon the potentially lengthy evolutionary course of chasmic basins, and to the peripheral and other effects associated with the separative mode of origin. Finally, we will consider what happens when plates thus constituted are involved in approximative motions, both subduction and collision. There are numerous factual examples to guide us in the construction of this interpretive framework.

PLATE THICKNESS AND ITS IMPLICATIONS

Plate thickness is a matter of direct significance for the evolution of basins of plate separative origin because, as we shall see, the amount and especially the duration of the ensuing subsidence are greater when the plate thus generated is very thick. A related effect is that the heat introduced into a thick plate, when magma intrudes it from its base, is greater and produces larger and more extensive epeirogenic movements at the surface. Thickness also affects a plate's flexural stiffness, and hence the lateral distance to which plate epeirogenic behaviour can be influenced by density anomalies which develop within it.

Before the days of plate tectonics, adherents of continental drift thought that perhaps only the continental crust was involved in the motion, but the currently most widely held view, that plate thickness under oceans is 50–100 km, is based on a remarkable coincidence of information from four different kinds of study. It is now likely, however, that this coincidence has another explanation and that plate thicknesses are very much greater even than this. The reasons are outlined in the following sections.

Existing Ideas on Plate Thickness

When the seismic shear wave low velocity (LV) zone, which has a well defined top at an average depth of about 70 km beneath ocean basins, came to be interpreted as a zone of partial melting,[5] it was quickly adopted as marking the base of tectonic plates. Petrogenetic studies,[6-8] suggesting that magmas like the bulk of those found on oceanic islands underwent primary segregation from mantle material at depths of 60–80 km, apparently supported this view. Another indication came from theoretical studies of plate genesis by the continuous lateral accretion of hot material at the axes of mid-ocean ridges. These suggested that the heat embodied in the accreted plate material is gradually dissipated upwards through the ocean floor, resulting in a gradual density increase and subsidence which is evident as the sloping flanks of ocean ridges. Analyses of age, heat flow and subsidence data from the ocean floor have consistently shown that the main feature is the progressive cooling of a slab of material 50–100 km thick.[9-14] Finally, there was the discovery that seismic wave travel times in the neighbourhood of Benioff zones outline a tongue of relatively cool descending lithosphere, which is also of about this thickness initially.[15-17]

Can all these apparent indications of plate thickness really be mistaken?

The Thick-Plate Model

Notice first that there could be a substantial difference between lithosphere thickness and plate thickness, for the former relates to material in a particular physical state whereas the latter is concerned with the entire thickness of co-moving material; the two would be similar only if the underside of the lithosphere were vigorously swept by differently moving material. It is not clear whether this is anywhere the case.

Evidence that at least the continental parts of plates may be very thick is of long standing. In 1961 Bernal[18] pointed to the fact that some Benioff zones extend to nearly 700 km depth as an indication that the LV zone might merely constitute 'the paste in a sandwich', the whole of which could undergo rifting. Since 1960, evidence has been accumulating that the geophysical properties beneath continents and oceans differ to a depth of at least 400 km,[19-25] and there is evidence from volcanism that they are geochemically distinct to as much as 400 km depth also;[26] all of which implies that, beneath continents at least, the material to this depth retains more or less permanently its relation to the continent above. Notice particularly that this depth comfortably encompasses the entire sub-continental LV zone, where present. Recently, Morgan[27] was prepared to envisage an oceanic plate thickness of 150 km, thus including a substantial thickness of what he considered to be asthenospheric material.

The main question concerns the physical significance of the LV zone. In fact, a fluid content of only 0·1 % to 1 % could be enough to produce the observed seismic velocity and attenuation properties, if the fluid were present in the likely form of very thin intergranular films[28,29] instead of the globules previously envisaged by Birch.[30] Thus, it could be scarcely more than the presence of free volatiles,[31] and not a substantial melt, that is being observed. This type of interpretation is strongly favoured by other considerations. The LV zone is not equally present everywhere, but is well marked only where the heat flow being transmitted upwards through the relevant depth range probably exceeds a value in the region of 30 mW/m^2 (0·7 HFU); this includes the oceans and active orogenic belts but excludes many shield areas (where total heat flow, including the crustal contribution, is sometimes no more than this). Recent work in the Pacific[32,33] shows that, as cooling proceeds, the LV zone deepens to about 55 km during the first 30 my and then more slowly to 85 km at 100 my. Furthermore, the seismic velocities in the 'lid' above the LV zone have been shown[30] to imply a temperature gradient which attains near-solidus temperatures at the LV zone.

A point which has been overlooked hitherto is that any build-up of interstitial fluid would produce a marked lowering of the thermal conductivity, especially if any of the volatile content were present as a gas phase, which Eggler[34] has shown is likely in the case of CO_2. As the LV layer is 100–250 km thick it is therefore probable that the thermal resistance of the layer largely controls the heat flow through it. In that case the influence of its fluid content upon its thermal resistance will have a strongly stabilising effect on the heat flow; any cooling within the layer would (since the temperature of its top is, by definition, close to the solidus) reduce the fluid content in the layer, and the resulting decrease in overall thermal resistance would tend to prevent the heat flow from dropping. Ocean floor heat flow and subsidence studies have suggested that the heat flow out of the top of the oceanic LV zone is indeed remarkably constant, but this was regarded by McKenzie[13] as strong evidence for heat transport by convective flow to near the top of the LV zone. It appears, however, that an LV zone entirely integral with the plate would have the same property.

It also follows from this argument that within the LV zone the geotherm will tend to follow a line giving constant fluid content (or to be more exact, constant thermal conductivity), which would explain why, in any one place, the seismic shear velocity, V_s, rises only slowly throughout the thickness of the LV layer. As the plate ages, cooling will eventually lower the level of fluid content in the layer and raise V_s as is seen beneath parts of continents. The base of the LV layer is probably determined by the rise in (solid) thermal conductivity at depth, which will flatten the temperature gradient. The layer will finally disappear when the slope of the geotherm is too low to produce interstitial fluid at any depth. A possible sequence of geotherms is sketched in Fig. 1.

The proposed plate model which emerges has a thickness which extends at least to the *base* of the LV zone (where present) at a depth which ranges to more than 300 km. The LV zone is due to interstitial free volatiles and incipient melting, giving a fluid content probably ranging up to rather more than 1 % and stabilising the transmitted heat flow as outlined above. If sedimentary rocks are any guide, such a low fluid content would have a negligible effect upon the structural integrity of the material. Its temperature, on the other hand, almost certainly implies susceptibility to creep. Nevertheless, the conclusion we shall reach in succeeding sections is that not only does this material not, in fact, undergo general displacement with respect to the material above, but it contributes substantially to the overall plate stiffness, enabling plates to transmit flexural stresses for long times (several tens of my) over large distances (upwards of 1000 km).

These conclusions make very little difference to the interpretation of the subsidence pattern and sedimentary evolution of plate areas generated within the past 80 my, because this is the interval during which the cooling of plate material above the LV layer is the dominant factor. They are likewise consistent with the seismically observed cool tongue effect at Benioff zones, for the deeper material in the plate will have cooled too little to be seismically distinguishable. They are immensely significant, however, for older basins of plate separative origin because it means that these will continue to subside and to constitute receptacles for sediments throughout the greatly increased time scale required for the slow cooling of the LV layer and any even deeper material in the plate. Recent ocean floor data confirm the first part of this slow process, in the form of markedly slower subsidence (0·5 km total) between 80 my and 140 my.[14,32,35] Our result is relevant