Pelagic Sediments: on Land and under the Sea

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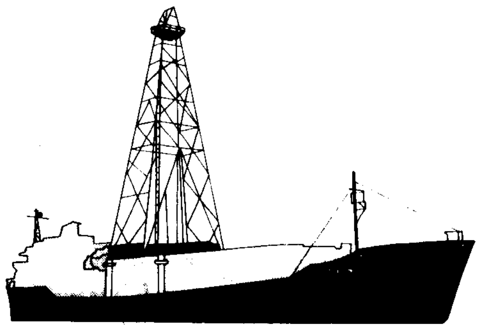

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Pelagic Sediments: on Land and under the Sea

An introduction

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A little over 100 years ago, on 21 December 1872, H.M.S. *Challenger* sailed from Portsmouth Harbour. By the time she returned to England, on 24 May 1876, she had founded the science of oceanography and ushered in a new era of geology. It is to C. Wyville Thomson and John Murray of the *Challenger's* scientific staff that we owe the pioneer studies of Recent oceanic deposits that decades of further work have merely embellished. A preliminary report on the nature of Recent pelagic sediments was published by Thomson in 1874(a); an account by Murray followed in 1876. These papers documented the pteropod, *Globigerina*, diatom and radiolarian oozes and the abyssal red clays. Both of these papers also refer to the first discovery of marine ferromanganese deposits, one catch of which was described by Thomson (1874a, p. 45), in flowing Victorian prose, as 'nearly a bushel of nodules, from the size of a walnut to an orange'.

Some 15 years prior to the departure of the *Challenger*, H.M.S. *Cyclops* had been despatched by the British Admiralty to ascertain the depth and nature of the sea bottom where it was proposed to lay the Atlantic telegraph cable. A sample of the mud obtained was sent to Thomas Henry Huxley for examination. In an appendix to the captain's report, published in 1858, Huxley described from the sediment some tiny concentrically layered calcareous objects that he termed 'coccoliths' (Huxley, 1868).

In 1861 Henry Clifton Sorby published a paper in which he mentioned the occurrence of bodies in the English Chalk that were 'identical with the objects described as Coccoliths by Professor Huxley' (Sorby, 1861, p. 193). The stage was thus set for a comparison between Recent *Globigerina*-bearing ooze and Cretaceous Chalk. Such graphic expressions as 'we are still living in the Cretaceous epoch' began to ornament the literature, although this particular remark incurred the wrath of Sir Charles Lyell and Sir Roderick Murchison (Thomson, 1874b, p. 470). In his classic paper of 1879 Sorby wrote (p. 78) that Chalk was 'very far from being identical with the *Globigerina*-ooze of our modern deep oceans' but was analogous to 'deep ocean mud comparatively free from volcanic and other mechanical mineral impurities . . . '. Although we would not now agree with the imputation of great depth inherent in Sorby's comparison of an ocean mud with the Chalk, his comment underlines recognition of the pelagic nature of this shelf-sea sediment. And by 1891 Cayeux had stressed that the presence of sponges and bivalves in this Cretaceous deposit and the local abundance of rounded quartz grains suggested more near-shore shallow-water environments.

Interpretation of Alpine rocks was, however, to prove more problematic.

Suess, writing in *Entstehung der Alpen* (1875), clearly felt that Alpine Mesozoic rocks were pelagic. However, he wrote before the *Challenger's* results were widely known and his conclusions may have been largely instinctive. He assumed (Suess, 1875, p. 98) that in the northern part of the Eastern Alps the Rhaetian rocks were the least pelagic and that overlying deposits had been laid down in progressively deeper water. This is perfectly in accord with modern interpretation (e.g. Garrison & Fischer, 1969). Suess also suggested (1875, pp. 98–99) that uninterrupted marine sedimentation across the Jurassic-Cretaceous boundary in the Alps signified pelagic conditions; and he contrasted this with the fresh-water Wealden environments that characterized north Germany and England at the same time. He furthermore attributed the formation of the great limestone deposits of the Alps ('die . . . Bildung der grossen Kalkablagerungen der Alpen') to a pelagic setting; although it is unclear to which formations he was referring. If he had waited a year or two he could have made more sophisticated interpretations on the basis of comparative sedimentology by utilizing the *Challenger's* results.

In 1877 Fuchs published a brilliant study on the origin of Aptychus Limestones. Aware of the differential solubility of calcite and aragonite, and inspired by the findings of the *Challenger* on carbonate dissolution in deep seas, Fuchs rejected the idea of post-mortal separation of aptychi from buoyant air-filled ammonite shells, and concluded that the preferential preservation of calcitic operculae resulted from selective dissolution of the aragonitic phragmocones.

In the following year Gümbel (1878) compared ferromanganese nodules from red pelagic limestones of the Lower Jurassic, Eastern Alps to those forming on the ocean floors. Fuchs, following up ideas expressed in his earlier (1877) paper produced, in 1883, a comprehensive treatise that posed the question: 'Welche Ablagerungen haben wir als Tiefseebildungen zu betrachten?'. In this account Fuchs over-reached somewhat in his enthusiasm to attribute a deep-sea setting to all rocks containing pelagic organisms. Nevertheless he was correct in interpreting the red ammonite limestones of the Alpine chain as pelagic deposits and, returning to the problem of the Aptychus Limestones (Fuchs, 1883, pp. 510–512), had no alternative but to suggest their formation in great depths since the *Challenger* had found that delicate aragonitic pteropods could survive down to 4000 m.

Neumayr published his *Erdgeschichte* in 1887 in which he reiterated some of the interpretations of his colleague Fuchs on Alpine Mesozoic rocks. Realizing that the red ammonite limestones of the Trias (Hallstatt facies) and Jurassic owed their pigment to iron-rich argillaceous matter, Neumayr (1887, pp. 364, 366) suggested that they had formed in depths between the present accumulation level of *Globigerina* ooze and red deep-sea clay. Neumayr also considered that the ferromanganese nodules in these ammonite limestones signified great depths. He was thus at pains to stress the similarity of Alpine rocks to Recent oceanic deposits, and (Neumayr, 1887, p. 364) wrote the following: 'Murray, der die Challenger-Expedition mitgemacht und die bei dieser Gelegenheit gesammelten Meeresgrundproben untersucht hat, fand eine Probe jener alpinen Vorkommnisse den Tiefseevorkomnissen unter allen ihm bekannten Gesteinen am nächsten stehend.' Murray's seal of approval was thus stamped on the deep-water interpretation of Alpine pelagic rocks. This, however, was not to last.

Recognition of deep-sea deposits on land was not limited to the Alpine-Mediterranean area. Some Recent *Globigerina* and pteropod limestones from the Solomon Islands described in 1885 by Guppy (in a paper communicated by John Murray), radiolarian cherts from the Ordovician of southern Scotland described by Hinde (1890), certain Tertiary chalks and marls from Barbados (Harrison & Jukes-Browne, 1890), were also interpreted as oceanic sediments. Nicholson, Regius Professor of Natural History at the University of Aberdeen, summarizing these occurrences, wrote the following in his address on recent progress in palaeontology for the year 1890: 'An interesting point in connection with the Radiolarian hornstones of the Mesozoic period, and the chalk-like Radiolarian marls of Barbados and of various parts of Southern Europe and Northern Africa, is that these deposits seem to be clearly ancient representatives of the modern "Radiolarian ooze" of the deep sea. If this point be admitted . . . then we have in these old accumulations indubitable "deep sea deposits;" and it cannot be asserted that no deposits similar to the deep-sea oozes of the present day are to be recognised among the stratified rocks which compose the greater part of the earth's crust. This admission will necessarily have an important bearing upon the modern theory that the present continental areas have been in the main regions of elevation, and the existing oceans in the main areas of depression, since the beginning of the Cambrian period, if not from still earlier times.' (Nicholson, 1890, p. 56.) This last sentence of Nicholson's embodies a controversy; clearly the occurrence of true oceanic deposits on land was incompatible with the permanency of continents and ocean basins. And this particular dogma was to pervade late nineteenth and twentieth century geological thought. This conceptual strait-jacket seems finally to have led John Murray to reject the oceanic nature of pelagic rocks on land. Murray's weighty words in the *Challenger* report on deep-sea deposits, co-authored with the Belgian Renard, read as follows: 'With some doubtful exceptions, it has been impossible to recognise in the rocks of the continents formations identical with these pelagic deposits.' (Murray & Renard, 1891, p. 189.) The 'doubtful exceptions' included the Scottish Ordovician cherts and the Oceanic Deposits of Barbados* alluded to above.

Murray's influence was considerable. No less an authority than Johannes Walther (1897) expressed the view that pelagic sediments were not necessarily deep and oceanic; he even ascribed to a near-shore environment some of the deposits claimed as deep-sea sediments by Fuchs (1883). The inspiration for Walther's interpretations are betrayed by the following sentence: 'Der beste Kenner recenter Tiefsee-Ablagerungen, Dr. JOHN MURRAY, liess sich von vielen Geologen solche Gesteine zusenden, die man für Tiefsee-Ablagerungen hielt, und konnte feststellen, dass unter diesen Proben mit Ausnahme des Kalkes von Malta kein Sediment sei, das mit recenten Tiefsee-Ablagerungen übereinstimmt.' (Walther, 1897, p. 237.)

Murray's views found many adherents amongst the Anglo-American geological fraternity. Nevertheless certain European workers persisted in the belief that oceanic deposits could be found in ancient mountain chains. Most important among these was Steinmann who in 1905 (p. 50) wrote the following: 'Im Gegensatz zu Murray . . .

* There seems little doubt, in fact, that these rocks *are* truly oceanic (Lohmann, 1973) and their equivalents have been sampled by Deep Sea Drilling in the western Atlantic (Bader *et al.*, 1970).

habe ich mit Hinde . . . u.a. stets die Ansicht vertreten, dass die reinen, kalkfreien Radiolariengesteine, wie sie uns in der Form gleichartiger Massen von mehr oder minder erheblicher Mächtigkeit aus mesozoischen und paläozoischen Formationen bekannt sind, echte Tiefseeabsätze darstellen, denen die gleiche geologische Bedeutung zuzuerkennen ist wie dem Radiolarienschlamm der heutigen Tiefsee.' He then goes on to state (p. 57): 'Die ophiolithischen Massengesteine sind in ihrem Auftreten an die Tiefseezone gebunden . . . ' and later adds (p. 59): 'Wir können uns wohl vorstellen, dass unter den grossen Meerestiefen sich magmatische Massen von extremer Basizität ansammeln und dass bei der Auffaltung der abyssischen Regionen diese Massen mit aufsteigen und zur Injektion gelangen . . . '. Already implicit in this paper is the concept of ophiolites as ocean crust and radiolarites as ancient analogues of deep-sea siliceous oozes; with the advantage of hindsight it makes sobering reading. Yet clearly Steinmann was decades before his time; outside continental Europe his paper was largely ignored. Arnold Heim's (1924) classic publication on Alpine sedimentary facies suffered the same fate, as he himself sadly observed in a later work (Heim, 1958). A subsequent paper of Steinmann (1925), including some pioneering petrographic studies, also made little impression in extra-Alpine circles. Molengraaf's work (1909, 1915, 1922) on Mesozoic deep-sea deposits and ferromanganese nodules from Borneo, Timor and Rotti went generally unheeded; certainly the tectonic implications were never followed through. These early European workers waited in limbo until the more permissive framework of the new global tectonics earned them their respectability.

Perhaps at least some of the controversy was semantic in nature. A clear distinction between the words 'pelagic'=pertaining to the open sea, with no depth connotation, and 'oceanic' with implications of great depth and specific type of basement might have clarified the issue. In the Alpine-Mediterranean system the situation is complicated by the fact that Mesozoic pelagic sediments are floored by both continental and oceanic crust (Bernoulli & Jenkyns, 1974). And the Jurassic radiolarites, much discussed by Steinmann, occur in both continental-margin and true oceanic settings. Clearly the situation was ripe for confusion.

On 28 July 1968, the newly built drilling vessel *Glomar Challenger* sailed from Orange, Texas. This date marked the start of a new era in marine geology. Early drilling results (e.g. Peterson *et al.*, 1970; Maxwell *et al.*, 1970), persuaded all but a few diehards of the reality of a spreading ocean, of drifting and colliding continents. The classical Alpine concepts were exhumed: it was no longer unthinkable that oceanic sediments should be found in mountain chains. On the contrary, the zone of collision of two continental masses was the logical place to find slivers of oceanic crust and their sedimentary cover. Deep Sea Drilling results have thus given new impetus and new understanding to studies of Alpine pelagic rocks.

A further push to the bandwagon has been given by the recent discoveries of prolific oil fields under the North Sea where the Cretaceous chalk is a main petroleum reservoir.

Although some preliminary studies of core material have been already published in the Initial Reports of the Deep Sea Drilling Project, it was felt that much detailed information and final interpretations remained in the files of individual workers. And land-locked geologists studying ancient pelagic sediments could clearly benefit from close co-operation with sea-borne specialists. Accordingly, it was proposed that the International Association of Sedimentologists hold a special symposium on pelagic sediments and that the papers be published as the first of a series of special publications. Both of these proposals were approved by the council. The symposium was held in Zürich during 25–26 September 1973, and all but a few of the oral presentations are included in this volume.

The first paper, by Berger and Winterer, is an analytical treatise on the interrelationships between plate tectonics and pelagic sedimentation. An underlying assumption is the rule of thumb discovered during the first *Challenger* expedition that carbonate dissolution closely governs the nature of deep-sea sediments. As an oceanic plate moves laterally away and vertically down from a ridge crest the sediments deposited upon it should change from calcareous to non-calcareous as the calcite compensation depth is crossed. This idealized model is, however, complicated by horizontal displacement of plates across belts of differing organic productivity. Synthesizing all these variables, Berger and Winterer have produced a survey of *Plate stratigraphy and the fluctuating carbonate line*. They demonstrate the great temporal variation in the calcite compensation depth.

Studies on dissolution facies in Recent oceanic facies have been tolerably common (e.g. Hay, 1970; Hsü & Andrews, 1970; Berger, 1972; Roth & Thierstein, 1972). However, in pelagic sediments on land, diagenesis has greatly obscured the evidence of penecontemporaneous solution of micro- and nannofossils; only the corrosion of megafossils can be readily documented. Carrying the study of Garrison & Fischer (1969) a step further, Schlager has investigated the *Preservation of cephalopod skeletons and carbonate dissolution on ancient Tethyan sea floors*. He describes the preferential solution of aragonitic phragmocones over calcitic skeletal parts, and stresses that leaching of most aragonite took place after the fossil had been embedded in bottom sediment. By studying the mode of cephalopod preservation he proposes a hierarchy of dissolution facies.

The next two papers present case histories of Palaeozoic cephalopod-bearing pelagic limestones. Tucker deals with all aspects of the *Sedimentology of Palaeozoic pelagic limestones: the Devonian Griotte (Southern France) and Cephalopodenkalk (Germany)*. These facies, partly nodular, contain a fauna of cephalopods, thin-shelled bivalves, conodonts, styliolinids and ostracods; the rocks also bear witness to early lithification and solution, and they are stratigraphically condensed. Bandel, more specifically, describes *Deep-water limestones from the Devonian-Carboniferous of the Carnic Alps, Austria*. He distinguishes two broad facies groups, one containing only rare redeposited units, the other containing abundant turbidites derived from a shallow-water carbonate platform. Widespread traces of dissolution in the pelagic facies serve as the main criterion for deciphering palaeobathymetry.

The next four articles have chalk as their theme. Schlanger and Douglas, both veterans of the *Glomar Challenger*, have studied the *Pelagic ooze-chalk-limestone transition and its implications for marine stratigraphy*. They describe the diagenesis of calcareous oozes in an oceanic environment where meteoric ground water is necessarily excluded, and show that although lithification generally increases with age and depth of burial there are many departures from this ideal state. They introduce the concept of 'diagenetic potential' (the potential of a sediment to form a chalk or limestone) to explain this, such potential being dependent on the nature and abundance of certain diagenetically soluble calcareous components in the original bottom sediment, this in turn being governed by palaeo-oceanographic conditions.

Neugebauer, concerning himself with both oceanic and shelf-sea facies, has looked at *Some aspects of cementation in chalk.* His main thesis is that chalk remains soft and uncemented because marine magnesium-rich pore fluids, which are oversaturated with respect to low-magnesian calcite, inhibit pressure solution/precipitation until considerable overloads are reached. At some critical depth solution of low-magnesian calcite at grain contacts is possible, and its reprecipitation as a higher magnesian calcite elsewhere leads to progressive depletion of magnesium in the pore fluid. With this inhibiting factor removed pressure solution and cementation can proceed at an accelerated pace. There is some agreement here with the trends observed by Schlanger and Douglas in Deep Sea Drilling cores.

Scholle presents his ideas on *Diagenesis of Upper Cretaceous chalks from England, Northern Ireland, and the North Sea.* It is well known that the chalk in Great Britain differs radically in hardness; soft chalks in southern England become harder when traced northward into Yorkshire, being replaced by the completely lithified White Limestone in Northern Ireland. The hardness of the Irish Chalk has been variously attributed to presence of aragonite in the initial sediment and to metamorphism by overlying basalts (see Black, 1953; Hancock, 1961, 1963). Drawing on petrographic and isotopic data and scanning electron microscopy, Scholle proposes an increasing gradient of hydrothermal and meteoric recrystallization from the North Sea to Northern Ireland related to rifting in the North Atlantic. Compaction and lithification of Irish chalk are attributed to expulsion of original marine pore fluids (after the hypothesis of Neugebauer) and loading by basalts.

The final paper on chalk, co-authored by Håkansson, Bromley and Perch-Nielsen, is titled, *Maastrichtian chalk of north-west Europe—a pelagic shelf sediment.* They remind us that pelagic sediments can be formed in shallow epeiric environments, a fact which may, however, be discernible from the presence of coccolith floras that are not fully oceanic. They also discuss the genesis of flint in the light of studies on cherts from Deep Sea Drilling cores.

Nodular limestones constitute our next theme. Alpine geologists have long been intrigued by the Triassic and Jurassic red nodular limestones that have facies equivalents in the Devonian and Carboniferous of central Europe (described here by Tucker and Bandel). The Tethyan Jurassic facies are known locally as *Knollenkalk* and *Ammonitico Rosso*. Up till now no modern equivalent of these facies had been found. The paper of Müller and Fabricius, *Magnesian-calcite nodules in the Ionian deep sea: an actualistic model for the formation of some nodular limestones* may, however, have solved this age-old puzzle. These authors describe nodules of centimetre scale that apparently form at or just below the sediment-water interface, their cement being derived from Mediterranean sea water. They suggest that the Tethyan nodular limestones were formed in a setting similar to the present-day Mediterranean.

Working independently, Jenkyns has also suggested a diagenetic process for nodule formation; his paper is titled: *Origin of red nodular limestones (Ammonitico Rosso, Knollenkalke) in the Mediterranean Jurassic: a diagenetic model.* He presents a series of petrographic criteria that suggest the nodules were formed by a solution-precipitation process rather than by irregular dissolution of a cemented calcareous sea bottom (a process advocated by Bandel for Palaeozoic pelagic nodular limestones). The cement for the nodules is assumed to derive from very fine-grained low-magnesian calcite and aragonite dissolved from within the sediment. An origin of the cement as a direct precipitate from sea water is not favoured since partial dissolution of aragonitic fossils on the sea floor (as documented by Schlager) suggests undersaturation of the bottom waters with respect to this polymorph of calcium carbonate.

Silica constitutes the next topic. Calvert presents a comprehensive survey of *Deposition and diagenesis of silica in marine sediments*. He notes that silica accumulates in marine sediments below waters of high biological productivity and in areas where volcanic products are widespread. He describes the solution-precipitation processes that turn opaline silica into chert. He furthermore notes that the concentration of dissolved silicon in interstitial waters of marine sediments is considerably higher than at the ocean bottom and there must therefore be a flux of silicon into the overlying waters. It is not unreasonable to suppose that this flux might be retarded when a siliceous ooze is suddenly buried by a turbidite or an ash bed. Could this explain the relationship between local silicification and redeposited horizons? Such a relationship may be observed in Deep Sea Drilling cores (e.g. Beall & Fischer, 1969) and on land (e.g. Garrison, 1967).

Results of Deep Sea Drilling have shown that only a small fraction of the siliceous oozes under the ocean bottom has been converted to chert; the rest is soft and unconsolidated. The exact mechanism of chert formation is still being worked out. Wise and Weaver, documenting the *Chertification of oceanic sediments*, illustrate the transition from opaline silica through disordered cristobalite lepispheres to quartz. They hold the 'maturation' theory of oceanic chert formation, that is, that the mineralogy of a siliceous rock is predominantly a function of its age. Wise and Weaver also stress the biological origin of most chert, even when recognizable siliceous remains are scanty. In describing the *Petrography and diagenesis of deep-sea cherts from the central Atlantic*, von Rad and Rösch also stress the 'maturation' theory. They note that the end product of quartz contains very few recognizable siliceous fossils yet its precursors are clearly biogenic. In contrast to Wise and Weaver and von Rad and Rösch, Lancelot proposes that the host sediments control the mineralogy of silica phases. His abstract is titled, *Formation of deep-sea chert: role of the sedimentary environment*. According to Lancelot, who worked with samples from the central Pacific, chert in clay-rich sediments comprises cristobalite while quartz is a primary precipitate in calcareous oozes, chalks and limestones. His complete account is published in the Initial Reports of the Deep Sea Drilling Project (Lancelot, 1973).

The next paper deals with cherts on land. Studying some Mesozoic radiolarites in the Othris Mountains of Greece, Nisbet and Price noticed that certain of the chert beds were graded and contained distinct intervals which were either structureless or parallel- and cross-laminated. The clay content of the radiolarites resembles the submarine weathering products of basalt; the tectonic position of the radiolarites suggests that they were originally deposited near the foot of a continental margin abutting a newly formed ocean. The title of their paper is thus, *Siliceous turbidites: bedded cherts as redeposited ocean ridge-derived sediments*.

Garrison gives us a general survey of *Radiolarian cherts, pelagic limestones, and igneous rocks in eugeosynclinal assemblages*. He stresses the effects that temporal changes in the carbonate compensation depth can have upon facies, and documents the biogenic nature of most sediments that lie upon or are interbedded with igneous rocks. He notes particularly the types of igneous rocks which underlie pelagic sediments and the nature of the contact. Reviewing occurrences from the Alps, Mediterranean and circum-Pacific regions, he presents models for the depositional setting of these sediments.

Boström discusses the *Origin and fate of ferromanganoan active ridge sediments.* These deposits are apparently formed through the expulsion of deep-seated magmatic fluids. Most of these sediments, having been formed on oceanic crust, will eventually be subducted or metamorphosed; ancient examples may, however, be sought in association with ophiolite complexes. Relevant in this connection are the *Pelagic sediments in the Cretaceous and Tertiary history of the Troodos massif, Cyprus* described by Robertson and Hudson. The basal member of the sedimentary series overlying the oceanic pillow lavas is constituted by the so-called *umbers* which are ancient analogues of active ridge sediments. The umbers pass up into radiolarian cherts which in turn give way to chalks. The general stratigraphic arrangement, albeit of differing age, resembles that in the Ligurian Apennines, as reviewed by Garrison.

Finally, Wendt demonstrates the occurrence of *Encrusting organisms in deep-sea manganese nodules.* The organisms comprise sessile arenaceous Foraminifera and may be found in depths as great as 5 km. Other organisms such as serpulids, corals, bryozoans and sponges commonly occur on nodules from seamounts. The sessile Foraminifera grow relatively rapidly, which suggests that nodules may, at certain periods, grow much faster than the average rates calculated from radiochemical analyses.

In conclusion it is clear that, with reference to pelagic sediments, the Recent is no skeleton key to the past. At the present time pelagic sedimentation is virtually confined to ocean basins. Clearly this was not the case during deposition of the Cretaceous chalks and those Tethyan Mesozoic pelagic facies which were laid down on continental basement. Such a setting, of course, gave them a favourable preservational bias. But even the true oceanic sediments that overlie ophiolites do not entirely correspond with what has been revealed by Deep Sea Drilling. The ascending stratigraphic sequence of pillow lavas, radiolarites, chalks (Cyprus, Ligurian Apennines) is not what one would expect to have formed on a spreading ridge moving below the calcite compensation depth. Before we rush to illustrate the close similarity between oceanic sediments on land and those under the sea perhaps we should look more critically at the differences.

REFERENCES

BADER, R.G. *et al.* (1970) *Initial Reports of the Deep Sea Drilling Project,* Vol. IV, pp. 753. U.S. Government Printing Office, Washington.

BEALL, A.O., JR & FISCHER, A.G. (1969) Sedimentology. In: *Initial Reports of the Deep Sea Drilling Project,* Vol. I (M. Ewing *et al.*), pp. 521–593. U.S. Government Printing Office, Washington.

BERGER, W.H. (1972) Dissolution facies and age-depth constancy. *Nature, Lond.* **236,** 392–395.

BERNOULLI, D. & JENKYNS, H.C. (1974) Alpine, Mediterranean and central Atlantic Mesozoic facies in relation to the early evolution of the Tethys. In: *Modern and Ancient Geosynclinal Sedimentation* (Ed. by R. H. Dott, Jr and R. H. Shaver), *Spec. Publs Soc. econ. Paleont. Miner., Tulsa,* **19,** 129–160.

BLACK, M. (1953) The constitution of the Chalk. *Proc. geol. Soc. Lond.* no. **1499,** 81–86.

CAYEUX, L. (1891) La Craie du nord de la France et la boue à Globigérines. *Annls Soc. geol. N.* **19,** 95–102.

FUCHS, T. (1877) Über die Entstehung der Aptychenkalke. *Sber. Akad. Wiss. Wien Math. Nat. Klasse,* Abt. I, **76,** 329–334.

FUCHS, T. (1883) Welche Ablagerungen haben wir als Tiefseebildungen zu betrachten? *Neues Jb. Miner. Geol. Paläont,* Beil. Bd. **2,** 487–584.

GARRISON, R.E. (1967) Pelagic limestones of the Oberalm Beds (Upper Jurassic-Lower Cretaceous), Austrian Alps. *Bull. Can. Petrol. Geol.* **15**, 21–49.

GARRISON, R.E. & FISCHER, A.G. (1969) Deep-water limestones of the Alpine Jurassic. In: *Depositional Environments in Carbonate Rocks, a Symposium* (Ed. by G. M. Friedman). *Spec. Publs Soc. econ. Paleont. Miner., Tulsa,* **14,** 20–56.

GÜMBEL, W. (1878) Ueber die im stillen Ocean auf dem Meeresgrunde vorkommenden Mangan-knollen. *Sber. bayer. Akad. Wiss.* **8,** 189–209.

GUPPY, H.B. (1885) Observations on the Recent calcareous formations of the Solomon group made during 1882–84. *Trans. Roy. Soc. Edin.* **32,** 545–581.

HANCOCK, J.M. (1961) The Cretaceous System in Northern Ireland. *Q. Jl geol. Soc. Lond.* **117,** 11–36.

HANCOCK, J.M. (1963). The hardness of the Irish Chalk. *Ir. Nat. J.* **14,** 157-164.

HARRISON, J.B. & JUKES-BROWNE, A.J. (1890) *The geology of Barbados* (being an explanation of the geological map of Barbados prepared by the same authors), pp. 64. Published by authority of the Barbadian legislature.

HAY, W.W. (1970) Calcium carbonate compensation. In: *Initial Reports of the Deep Sea Drilling Project,* Vol. IV (R. G. Bader *et al.*), pp. 672–673. U.S. Government Printing Office, Washington.

HEIM, A. (1924) Über submarine Denudation und chemische Sedimente. *Geol. Rdsch.* **15,** 1–47.

HEIM, A. (1958) Oceanic sedimentation and submarine discontinuities. *Eclog. geol. Helv.* **51,** 642–649.

HINDE, G.J. (1890) Notes on Radiolaria from the Lower Palaeozoic rocks (Llandeilo-Caradoc) of the south of Scotland. *Ann. Mag. nat. Hist.,* ser. 5, **6,** 40–59.

HSÜ, K.J. & ANDREWS, J.E. (1970) History of South Atlantic basin. In: *Initial Reports of the Deep Sea Drilling Project,* Vol. III (A.E. Maxwell *et al.*), pp. 464–471. U.S. Government Printing Office, Washington.

HUXLEY, T.H. (1868) On some organisms living at great depths in the North Atlantic Ocean. *Q. Jl microsc. Sci.* **8,** N.S., 203–212.

LANCELOT, Y. (1973) Chert and silica diagenesis in sediments from the central Pacific. In: *Initial Reports of the Deep Sea Drilling Project,* Vol. XVII (E. L. Winterer, J. I. Ewing *et al.*), pp. 377–405. U.S. Government Printing Office, Washington.

LOHMANN, G.P. (1973) Stratigraphy and sedimentation of deep-sea Oceanic Formation on Barbados, West Indies. *Bull. Am. Ass. Petrol. Geol.* **57,** 791. (Abstract.)

MAXWELL, A.E. *et al.* (1970) *Initial Reports of the Deep Sea Drilling Project,* Vol. III, pp. 806. U.S. Government Printing Office, Washington.

MOLENGRAAF, G.A.F. (1909) On oceanic deep-sea deposits of Central Borneo. *Proc. Sect. Sci. K. ned. Akad. Wet.* **12,** 141–147

MOLENGRAAF, G.A.F. (1915) On the occurrence of nodules of manganese in Mesozoic deep-sea deposits from Borneo, Timor, and Rotti, their significance and mode of formation. *Proc. Sect. Sci. K. ned. Akad. Wet.* **18,** 415–430.

MOLENGRAAF, G.A.F. (1922) On manganese nodules in Mesozoic deep-sea deposits of Dutch Timor. *Proc. Sect. Sci. K. ned. Akad. Wet.* **23,** 997–1012.

MURRAY, J. (1876) Preliminary report on specimens of the sea bottom. *Proc. R. Soc.* **24,** 471–532.

MURRAY, J. & RENARD, A.F. (1891) Report on deep-sea deposits based on specimens collected during the voyage of H.M.S. 'Challenger' in the years 1873–1876. In: *'Challenger' Reports,* pp. 525. H.M.S.O., Edinburgh.

NEUMAYR, M. (1887) *Erdgeschichte. Erster Band, Allgemeine Geologie,* pp. 653. Bibliographisches Institut, Leipzig.

NICHOLSON, H.A. (1890) Address on recent progress in palaeontology as regards invertebrate animals. *Trans. Edin. geol. Soc.* **6,** 53–69.

PETERSON, M.N.A. *et al.* (1970) *Initial Reports of the Deep Sea Drilling Project,* Vol. II, pp. 501. U.S. Government Printing Office, Washington.

ROTH, P.H. & THIERSTEIN, H. (1972) Calcareous nannoplankton: leg 14 of the Deep Sea Drilling Project. In: *Initial Reports of the Deep Sea Drilling Project,* Vol. XIV (D. E. Hayes, A. C. Pimm *et al.*), pp. 421–485. U.S. Government Printing Office, Washington.

SORBY, H.C. (1861) On the organic origin of the so-called 'Crystalloids' of the Chalk. *Ann. Mag. nat. hist.* ser. 3, **8,** 193–200.

SORBY, H.C. (1879) Anniversary address of the President (on the structure and origin of limestones). *Proc. geol. Soc.* **35,** 56–95.

STEINMANN, G. (1905) Geologische Beobachtungen in den Alpen. II. Die Schardtsche Überfaltungstheorie und die geologische Bedeutung der Tiefseeabsätze und der ophiolithischen Massengesteine. *Ber. naturf. Ges. Freiburg*, **16**, 18-67.

STEINMANN, G. (1925) Gibt es fossile Tiefseeablagerungen von erdgeschichtliche Bedeutung? *Geol. Rdsch.* **16**, 435–468.

SUESS, E. (1875) *Entstehung der Alpen*, pp. 168. W. Braumüller, Vienna.

THOMSON, C.W. (1874a) Preliminary notes on the nature of sea-bottom procured by the soundings of H.M.S. 'Challenger' during her cruise in the 'Southern Sea' in the early part of the year 1874. *Proc. R. Soc.* **23**, 32–49.

THOMSON, C.W. (1874b) *The Depths of the Sea*, pp. 527. Macmillan, London.

WALTHER, J. (1897) Ueber Lebensweise fossiler Meeresthiere. *Z. dt. geol Ges.* **49**, 209–273.

Spec. Publs int. Ass. Sediment. (1974) **1,** 11–48

Plate stratigraphy and the fluctuating carbonate line

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ABSTRACT

The most conspicuous feature of deep-sea sedimentation is the carbonate line, the facies boundary between calcareous ooze and pelagic clay. In any one facies regime, the carbonate line tends to follow depth contours, but on a global scale its depth range is considerable, about two kilometres. The topography of the surface described by the carbonate line is controlled by regional differences in carbonate supply, dissolution and, to some extent, redeposition. Supply and dissolution processes lead to geochemical fractionation, whereby carbonate is separated from other oceanic sediments. We identify basin-basin fractionation, bathymetric, latitutinal trophic, abyssal and diversity-related fractionation.

The palaeogeography and palaeobathymetry of carbonate deposits can be reconstructed using principles from plate tectonics and stratigraphy ('plate stratigraphy'), where information is available from drill holes. The reconstructions demonstrate that the carbonate line fluctuated in some areas during certain times, and stayed nearly constant in others. Arguments from plate tectonics provide clues on the variability of the fractionation processes which control the position of the carbonate line.

INTRODUCTION

The surface of Earth has several first order quasi-linear features which are controlled largely by elevation, such as the coast line, the snow line, the tree line, and the carbonate line, that is, the facies boundary between carbonate-rich and carbonate-poor sediments. Just as the migrating tree line and snow line tell the story of varying precipitation and temperature on land, the changing topography of the carbonate line contains information on the chemical climate of the sea and hence on the planetary environment. Oceanic environments are shaped by plate tectonics and its ramifications. To the extent that plate tectonics are responsible for sedimentation patterns through time and to the extent that plate-tectonic principles are applicable to deciphering the stratigraphic record, the science of stratigraphy becomes 'plate stratigraphy'.

In this essay we explore a number of relationships between deep-sea sedimentation and plate tectonics, focusing on the carbonate line and the regional and global controls which it reflects. We begin by discussing the present pattern of the carbonate line and then marshal evidence to show that this pattern varied through time, using palinspastic reconstructions derived from plate stratigraphy.

THE CONCEPTS 'CARBONATE LINE' AND 'COMPENSATION SURFACE'

Definitions

About one half of the deep ocean floor is covered by calcareous ooze, the other, deeper half, by sediment with only a few percent of calcium carbonate (Sverdrup, Johnson & Fleming, 1942, p. 977, Table 106). The boundary between the two facies regimes roughly follows depth contours over large areas (Fig. 1), owing to increased carbonate dissolution rates at depth (Murray, in Murray & Renard, 1891, pp. 277–279). The boundary has been called a compensation depth for calcium carbonate, generally abbreviated CCD, because rate of supply and rate of dissolution are approximately compensated at this level (Bramlette, 1961). Unfortunately, this term has occasionally given rise to a misconception that the level is a depth marker which, once established, is valid for all or most of the deep ocean. As both Arrhenius (1952) and Bramlette (1961) emphasized, this is not so. Instead, the surface defined by all local compensation levels (here called the carbonate compensation surface, abbreviated CCS) can display considerable topography near the equator in the Pacific and elsewhere (see Fig. 1). Arrhenius (1952, p. 190) introduced the term 'carbonate compensation line' to denote the facies boundary on the present sea floor; we use 'carbonate line' with a view to the snow line analogy (Peterson, 1966). The carbonate line, then, is the intersection between the carbonate compensation surface (CCS) and the sea-floor topography. We retain 'CCD' as a general undifferentiated term for both carbonate line and CCS.

Applicability

Like the snow line, the carbonate line is a statistical concept: from afar, the facies boundary appears quite well defined and seems to follow depth contours. On closer inspection, however, the line proves less distinct and merely denotes a probability limit: a few hundred metres above the line a surface sediment sample will probably be rich in carbonate; a similar distance below the line it will have none, or only a few percent, of carbonate. The sharpness of the carbonate line may be objectively defined, using the appropriate probabilities for finding carbonate, stated with respect to a given deviation from the line, say, 200 m above or below. This sharpness is a function of the relief of the compensation surface, of the relief of the bottom and associated redeposition processes, and of rate distributions of supply and removal of carbonate particles.

The zone which separates well-preserved from poorly preserved calcareous assemblages, the lysocline, is interpreted as denoting a marked increase in dissolution rate over a short depth interval at this level (Berger, 1971). In places, this level is well defined, as in the western trough of the South Atlantic, where it coincides with the boundary between Antarctic Bottom Water and North Atlantic Deep Water, and here the carbonate line also is well defined. A similar relationship between sharpness of lysocline and of carbonate line holds for pelagic areas with relatively low rates of supply, as on the East Pacific Rise, well south of the equator. The carbonate line is close to the lysocline here, providing for a distinct demarcation between carbonate and clay regime. Conversely, where the lysocline is indistinct and well separated from the carbonate line, as in the equatorial Pacific, the boundary between calcareous facies