NATURE VOL. 241 JANUARY 5 1973

Diachronous Deposits: a Kinematic Interpretation of the Post Jurassic Sedimentary Sequence on the Pacific Plate

B. C. HEEZEN
Columbia University, New York

I. D. MacGREGOR
University of California, Davis, California

H. P. FOREMAN
Oberlin College, Oberlin, Ohio

G. FORRISTAL
Shell Development Co., Houston

H. HEKEL
Geological Survey of Queensland, Brisbane, Australia

R. HESSE
McGill University, Montreal, Canada

R. H. HOSKINS
New Zealand Geological Survey, Lower Hutt, New Zealand

E. J. W. JONES
University College London

A. KANEPS
Scripps Institution of Oceanography, La Jolla, California

V. A. KRASHENINNIKOV
Geological Institute, Academy of Sciences, Moscow

H. OKADA
Kagoshima University, Kagoshima, Japan

M. H. RUEF
State Department of Ecology, Olympia, Washington

We have constructed a kinematic model which outlines the deposition of the units of the western Pacific seafloor on growing crust. The average northward component of motion for the Pacific plate has been 4.4 cm yr^{-1} from 100 to 30 m.y. BP and 2 cm yr^{-1} from 30 m.y. BP to the present.

BENEATH the thin (20 to 100 m) unlithified layer of brown clay on the floor of the western Pacific abyss is a thicker (300 m) sequence of chalk, chert and clay, and the boundary between the two layers is broadly time transgressive, varying in age from Early Cretaceous in the west to Late Cainozoic in the east. Because there has been a tendency to attribute a precise synchroneity to pelagic facies, this evidence of widespread and apparently systematic diachronism is significant. Evidence of the time transgressive nature of pelagic deposits has been accumulating since the beginning of the deep sea drilling product[1-3], and during Glomar Challenger's Leg XX we extended observations of this phenomenon to the oldest known areas of the Pacific crust[4,5]. We have now also a kinematic model of pelagic deposition for the time transgressive sedimentary sequences of the Pacific basin, which may be applied to the stratigraphic succession on any oceanic plate.

A Mid-Latitude Model for Deep-sea Pelagic Deposition

There are at least three principal sources of deep-sea pelagic sediments—the remains of living organisms, terrigenous detritus supplied as wind blown dust or suspended matter, and pyroclastic material. The biogenic remains are composed predominantly of calcareous and siliceous tests which dissolve as they sink to and rest on the ocean floor. The solution of the tests is controlled by a number of variables which result in effective compensation depths below which no calcareous or siliceous remains are found[6,7]. Thus the record of biogenic sedimentation on the ocean floor will depend on the depth relative to the appropriate compensation depth. By contrast the inorganic component may be found at all depths. Other variables such as plate motion and crustal subsidence are thus only important because they control the location of the plate relative to sources of supply, the pattern of oceanic circulation and depth relative to the compensation depths.

We propose that as new oceanic crust is formed in the rift valley of the Mid-Oceanic Ridge a blanket of light-coloured carbonate ooze is deposited on the new crust until the subsiding sea floor drops below the carbonate compensation depth. Subsequently a blanket of slowly accumulating abyssal clay covers the organic debris (Fig. 1).

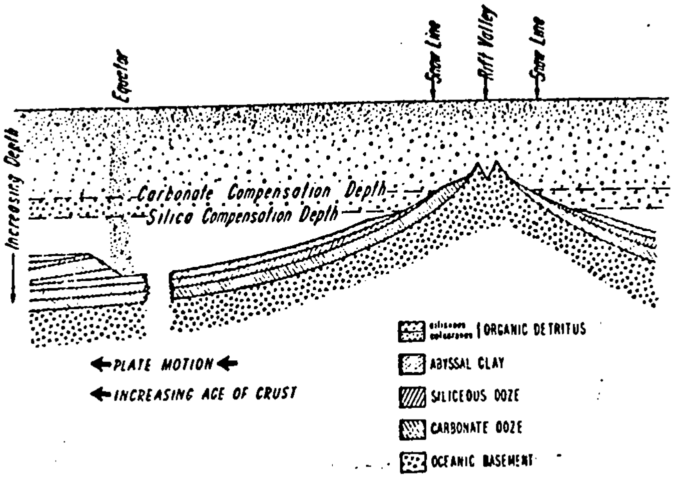

Fig. 1 Axially accreting model of oceanic sedimentation.

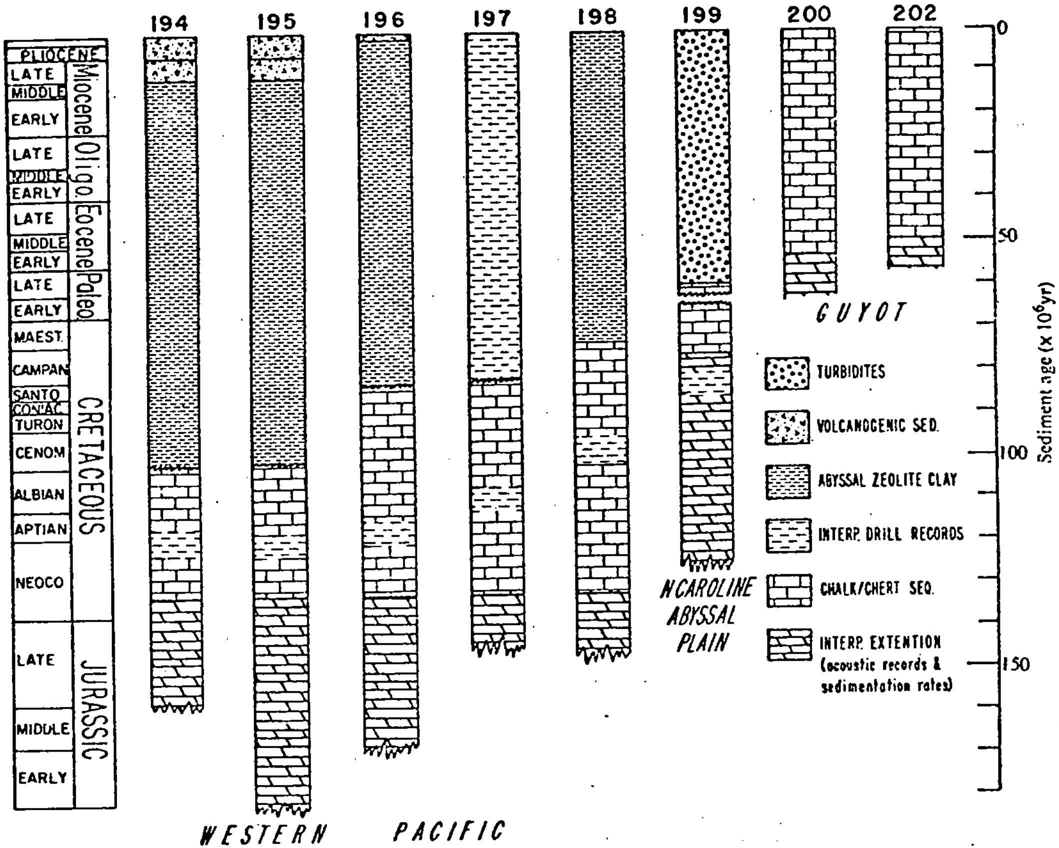

Fig. 2 Stratigraphic summary of Leg XX drilling.

The thickness and nature of the biogenic debris are determined by the depth difference between the compensation depth and the initial depth at the ridge crest, the rate of subsidence, and the type of biogenic sediments accumulating at any particular latitude. . In general, the compensation depth lies about 1,000 m below the ridge crest, and new crust subsides about 50 m $(\mathrm{m.y.})^{-1}$, allowing 20 m.y. of biogenic deposition before the onset of abyssal clay sedimentation. Sedimentation rates for pelagic biogenic oozes are less than 10 m $(\mathrm{m.y.})^{-1}$. Thus the basal calcareous layers can normally be expected not to exceed 200 m in thickness. Sedimentation rates for abyssal clay are generally significantly less than 1 m $(\mathrm{m.y.})^{-1}$. Thus Early Cretaceous (120 m.y.) crust formed under ideal conditions should have accumulated some 300 m of sediments consisting of 200 m of basal chalk and 100 m of overlying abyssal clay. Because the floor of the western Pacific is at least Early Cretaceous in age[3-5] we may compare the drilling results with the simple model.

Sediment Sequences in the Western Pacific

The sea floor of the western Pacific is covered by 5 stratigraphic units: a wedge shaped layer of Quaternary to Late Tertiary silty clay primarily of volcanic origin, thinning away from the Asiatic volcanic-arc source; a ~100 m thick layer of Tertiary to Cretaceous abyssal zeolitic clay; a sequence (±100 m) of Tertiary to Cretaceous cherts and chalks; an inferred earlier, thin abyssal clay a few tens of metres thick; and basal chalks, cherts, limestones and marls of Cretaceous age over 200 m thick (Fig. 2). Variations of this stratigraphy are seen in the Caroline Abyssal Plain, where Late Tertiary abyssal clays are intercalated with turbiditic calcareous oozes[4,5].

An Initial Comparison

The stratigraphic history may in part be explained as the normal sedimentary sequence expected to overlie a section of axially accreting mid-latitude oceanic crust. But the comparison of the mid-latitude model with the stratigraphic sequence drilled during Leg XX reveals serious discrepancies. Not only are the two chert/chalk sequences together nearly twice as thick as predicted but the span of time from the first chalk to the last chalk is closer to 50 m.y. than the 20 m.y. given by the model. The simple model outlined applies specifically to the mid-latitudes and the mid-ocean, and may be modified by considering additional sources of sediments.

Equatorial Model

Anomalously high surface productivity may be expected to push the compensation levels ("chalk line") to much greater depths (Fig. 1) and may increase significantly rates of biogenic accumulation[8]. The most notable example of chalk-line depression occurs in a narrow zone between the northern hemisphere and southern hemisphere current systems, beneath the narrow zone of equatorial upwelling. Crust that forms under the equator may accumulate a considerable thickness of biogenic sediments. The specific thickness of sediments will depend on the rate and direction of crustal drift and the age of the crust at the time of equatorial passage[9,10]. Crust drifting parallel to the equator may accumulate enormous thicknesses, particularly on young crust, but crust drifting north or south receives a thinner chalk whose thickness depends largely on the rate of drift.

A belt of siliceous ooze deposition lies between the equatorial zone of mainly carbonate deposition and the vast expanse of barren abyssal brown clay which floors the deep Pacific. The belt of siliceous oozes, at the margins of the Equatorial belt of high productivity, may be explained by the greater effective silica compensation depth, and allows us to predict the presence of siliceous units above and below ancient equatorial carbonates (Fig. 1). The resulting diachronous deposits of siliceous sediments would seem to be likely candidates for diagenetic conversion to bedded chert. Because the borders of the equatorial belts of carbonate and siliceous ooze are known to have suffered extensive fluctuations in the Quaternary, we may assume that alternation of thin siliceous and thicker carbonate oozes is an overall characteristic of equatorial deposition.

In practice there seems to be a depth below which the chalk line may not be depressed. At present this depth lies near 5,000 m. Ocean depth is a function of crustal age; a depth of 5,000 m generally corresponds to crust more than 50 m.y. old. Thus crust older than 50 m.y. at the time of equatorial transit might be deprived of an equatorial deposit, or the transit may be represented by siliceous deposits or by a thin sequence of carbonates.

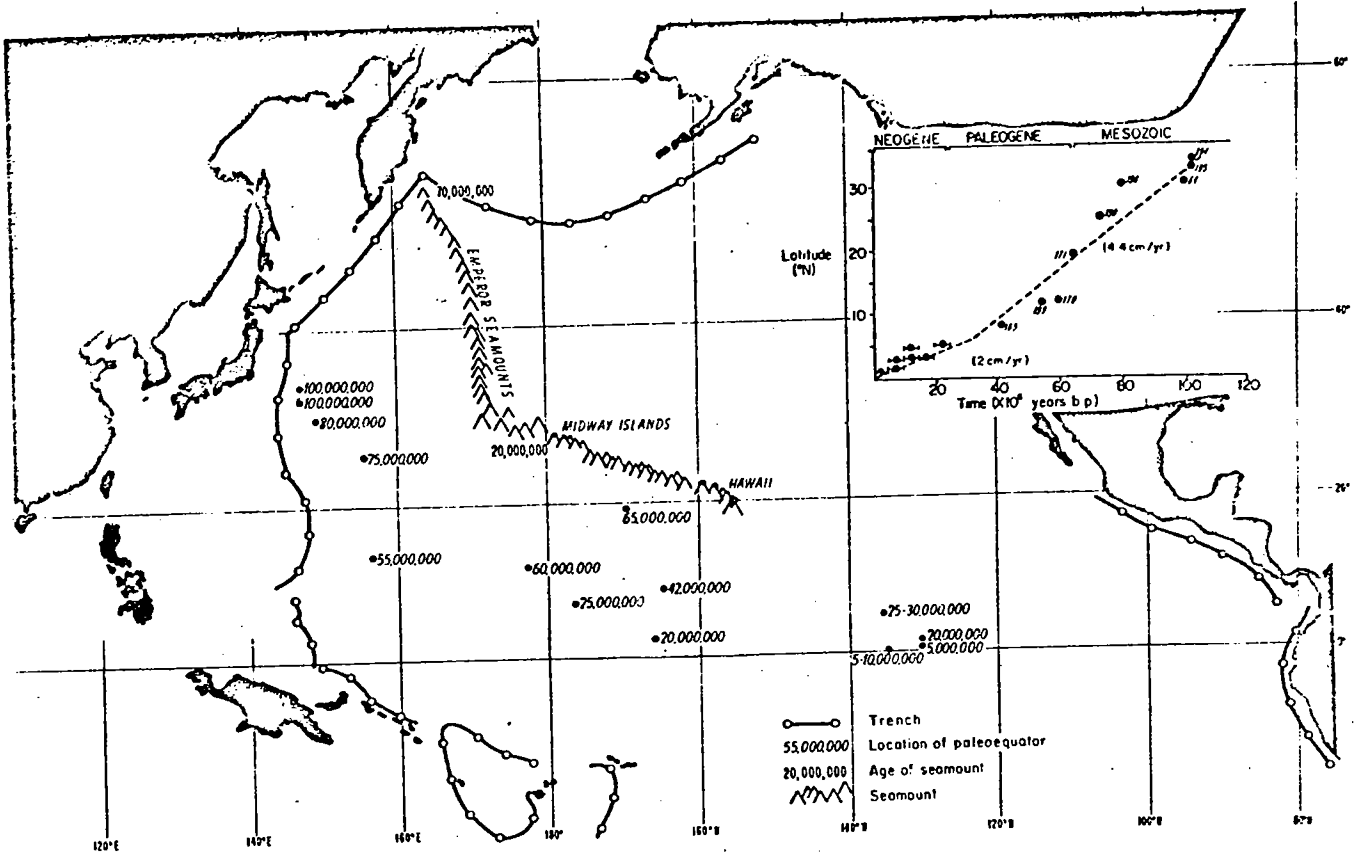

Fig. 3 Locations of palaeoequator in Pacific.

The age of the chert/chalk to abyssal clay boundary may thus be used as an index of the equatorial transit (Fig. 3). When combined with other evidence for equatorial transits[8-12] and the suggestion for a major change in the Pacific plate trajectory at about 30 m.y. (ref. 13), average northward components of plate motion of 2 cm yr^{-1} and 4.4 cm yr^{-1} are obtained for the Late Tertiary and the Early Tertiary to Cretaceous, respectively. Similar evidence of northward plate motion has been inferred from studies of the remnant magnetism of cored basalts and seamounts[9-12,14].

Thus, the mid-latitude and equatorial mid-ocean pelagic models, when combined, compare favourably with the drilling results of the northern Pacific. The Cretaceous chert/chalk sequence that lies beneath the Tertiary and Late Cretaceous abyssal clay in the northwestern Pacific records the earlier Mesozoic passage of the ancient Pacific crust beneath the equator. The Lower Cretaceous chert/chalk sequence that lies at the bottom of the northern holes apparently represents the initial basal chalk formed on new crust, and the abyssal clay that separates the 2 units records abyssal-basin sedimentation during the interval between the initial subsidence below chalk-line and the subsequent re-occurrence of chert/chalk deposition during the equatorial passage. The apparent success of the simple kinematic model in accounting for the stratigraphy of the western Pacific led us to examine more general implications of the model and to attempt a more analytical approach.

Analytical Model of Pacific Sedimentation

The following numerical values have been used in the calculation of the Pacific sedimentation models (Fig. 4): Crust formation at ridge crest at 3,000 m depth; compensation level at depth of 3,700 m; ridge crest subsides at rate of 35 m (m.y.)$^{-1}$; sediment accumulation rates of biogenic sediments at 10 m (m.y.)$^{-1}$; abyssal clay at 1 m (m.y.)$^{-1}$, and equatorial biogenic sediments at an additional 10 m (m.y.)$^{-1}$; zone of equatorial sedimentation 5° wide; trajectories of Pacific plate with a "westward" component approximately parallel to fracture zones, 259° and a northward component of 2 cm yr^{-1} from 0 to 30 m.y., and 4 cm yr^{-1} from 30 to 200 m.y.; and orientation of cross-sections at 79° intersecting 160° E at 0°, intersecting 160° E at 15° N, and intersecting 160° E at 30° N.

Basically the mathematics of the model is a simple book-keeping operation. We consider as an example a section perpendicular to the ridge crest. Whatever the relative motion of the equatorial zone, it may be described by its speed and width projected on the section. At each step in time, the sediments accumulated at each location are calculated from the appropriate sedimentation rates, and added to the sediment thickness already there. Isochrons may then be drawn through the thickness generated to produce a model geologic section. Several parallel sections based on the same parameters give a complete history of sedimentation and vertical traces may then be compared with a bore hole from any locality (Fig. 4).

A model has been calculated for a profile across the Pacific from the modern ridge crest off California to the Mesozoic crust off the Mariana Arc (Fig. 3) and may be compared with the gross lithic stratigraphy reported from Pacific deep sea drilling.

Summary of Pacific Stratigraphy from DSDP Data

The basic data are shown as vertical columns from drill holes projected to the lines of section (Fig. 4). Fig. 5 illustrates an interpolated summary of the distribution of the different major lithologies in the Pacific.

A comparison of the model (Fig. 4) with the observed stratigraphy (Fig. 5) and stratigraphic summary (Fig. 6) shows good agreement. The Pacific crust ages from east to west; an observation justifying a basic assumption of the model. The basal chert/chalk unit is time transgressive increasing in age from east to west. In the eastern Pacific the basal carbonate is about 50 to 200 m thick (or about 20 to 40 m.y. in extent) indicating a general agreement with the model. The basal chert/chalk is interpreted as that accumulated at the ridge prior to its submergence beneath the compensation depth. An upper chert/chalk unit which is only present in the western Pacific is also time transgressive, increasing in age from the equator northwards, and from east to west, and is interpreted as the biogenic oozes accumulated during the passage of the Pacific crust beneath the equator. The upper and the lower chert/chalk units merge in mid Pacific with the existence of a chevron pattern as predicted by the model. Two abyssal clay units are observed. The lower unit consists of a wedge-shaped horizon, whose upper and lower boundaries are time transgressive. The base of the lower clay is the chert/chalk sequence accumulated at the ridge crest, and the top, the chert/chalk sequence deposited during the equatorial crossing. The upper clay unit is only found in the northern Pacific wedging out to the equator in the south, and the younger crust to the east.

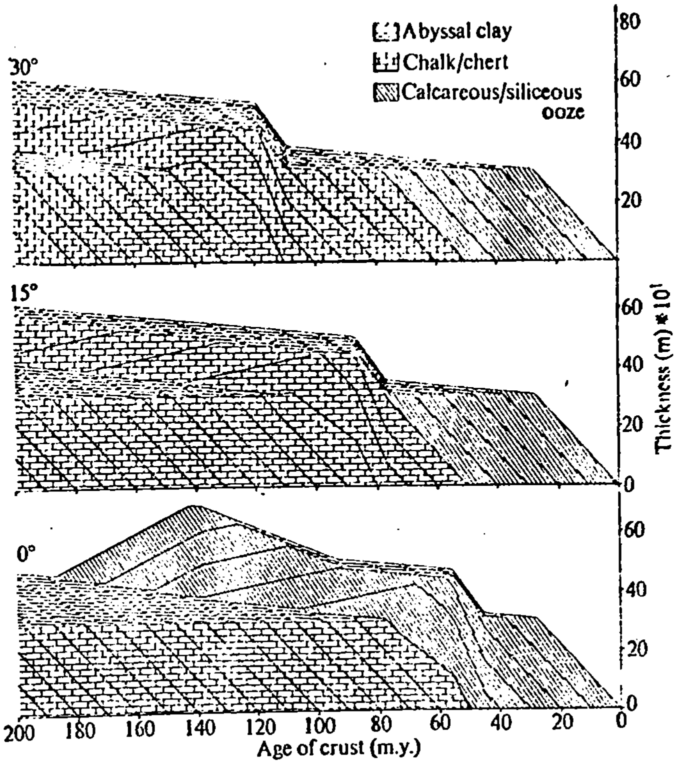

Fig. 4 Computed models of Pacific Ocean sedimentation history.

Other features observed in the data summary (Fig. 6) but not included in the model (Fig. 4) are that: Where the oceanic crust has passed marginal to a continental margin, positive area, or an extinct volcano we see the addition of turbiditic or volcanogenic sediments. Good examples are the wedge of turbidites along the west coast of North America[17–21], the turbidites filling the Caroline Abyssal Plain[4,5], and the wedge of wind blown volcanogenic debris east of the Asiatic arcs[4,5]. The presence of equatorial biogenic oozes along the whole length of the present equator, and the absence of this unit in any section south of the equator, and the onset of lithified chert/chalk sequences from calcareous and siliceous oozes at a crustal age of at least 50 m.y.

In general there is a close fit between the model and data summary both with respect to the distribution pattern, timing and thicknesses of the major lithologies. The fit is encouraging, and lends credence to the model as a useful first order approximation of the sedimentary history of the Pacific plate. Departures from the model should now illustrate smaller or more local events in the sedimentary history and add detail to the geologic history of the Pacific.

Acoustic Stratigraphy

The principal boundaries separating the lithologic units provide the strong contrasts in acoustic impedance necessary to create major reflectors of regional extent. Seismic reflexion profiling[22] has defined five acoustic units in the Pacific; an upper transparent layer lacking strong reflectors; a unit consisting of closely spaced strong reflectors known as the opaque layer; a lower transparent layer which is of smaller regional extent than the overlying layers; a lower opaque layer of limited extent; and basement, which, if smooth, is referred to as horizon B. The upper transparent layer corresponds to the abyssal clay in the west and central Pacific, turbidite sequences in the north and east, and unconsolidated biogenic oozes in drillings to the east and along the equator. The upper opaque layer corresponds to the thick chert/carbonate sequence of the western Pacific, the locally occurring lower transparent layer may correspond to the Cretaceous clay of deep sea drilling, and the lower opaque layer corresponds to the basal chert/carbonate in areas which having crossed the equator have acquired additional carbonates higher in the section.

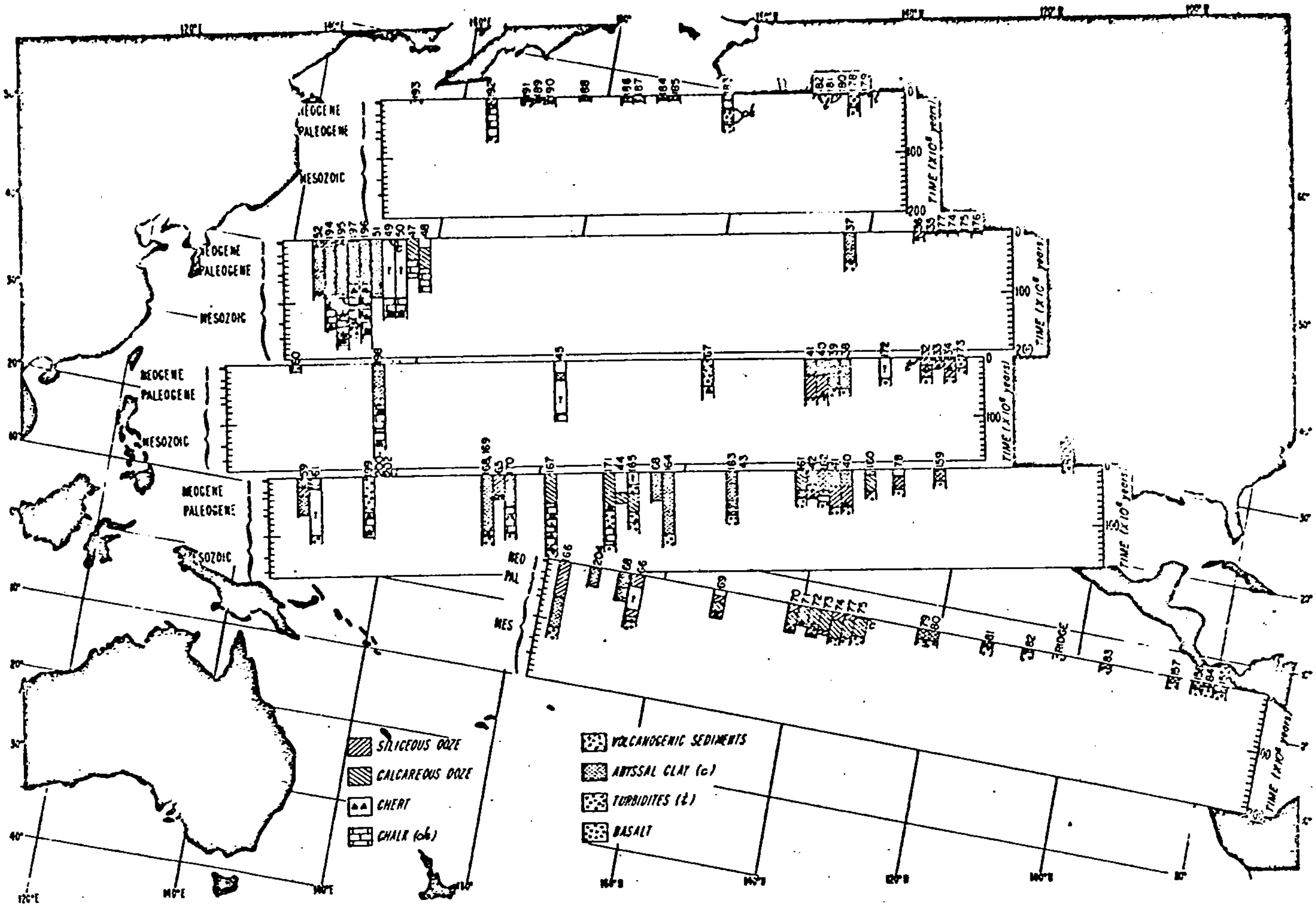

Fig. 5 Summary of drilling data from Deep Sea Drilling Project.

Previous interpretations of the acoustic records evidenced a strong preference for the synchroneity of acoustic boundaries (that is, lithic boundaries), suggesting Eocene or Late Maestrichtian ocean-wide, or even world-wide, horizons apparently resulting from synchronous global events.

The top of the opaque layer is, however, widely time transgressive. Thus the former assumption of synchroneity simply does not conform to the evidence from deep sea drilling and is in conflict with the kinematic model of lithologic stratigraphy. Similarly, the assumption that the opaque layer is a clastic wedge has been disproved by the drilling results.

The acoustic data, stripped of the synchronous time-stratigraphic interpretation, can be compared favourably to the kinematic model. The upper opaque layer evidently is a chert/carbonate sequence deposited at least in part under equatorial conditions. The area of the Pacific in which the upper opaque horizon is observed is that portion of the crust which has passed under the equator (Fig. 7). The limits of the upper opaque layer are the equator on the south, the subducting trenches on the west, and a line, marking the limit of crust created subsequent to the equatorial passage, on the northeast. The opaque layer is apparently thickest between 20° and 30° N, a fact which may be explained by a smaller northward component of drift of the Pacific crust in Early Cretaceous time, an effect similar to that recorded for Neogene time by the equatorial sediment bulge.

The upper acoustic opaque layer cannot be mapped in the northernmost western Pacific for the practical reason that the lower transparent layer pinches out a few hundred kilometres northwest of the Shatsky Plateau. This pinchout suggests that the basal carbonates merge with the equatorial carbonates and cherts, because the period of time separating the original generation of this crust and the equatorial transit of that crust was too brief to be represented by a layer of abyssal clay thick enough to be detectable by seismic reflexion profiling. Because the rate of abyssal clay deposition is so slow that a layer only 20 or 10 m thick is equivalent to 10 to 20 m.y., the true pinchout could be a considerable distance northwest of that shown by reflexion records. Thus somewhat northwest of the lower transparent layer pinchout would seem to have been formed very near the equator in pre-Hauterivian time.

The acoustic stratigraphy thus seems adequately accounted for by the kinematic model.

Certain further predictions can be made: First, on crust of a given age the total thickness of pelagic deposits should be markedly less in the South Pacific, which has yet to receive an equatorial contribution, than in the North Pacific where equatorial deposition has already produced an additional layer of carbonates; second, south of the equator cherts should be much less common than to the north.

Thus the new kinematic stratigraphy of pelagic deposits which predicts a characteristically diachronous behaviour of the acoustic upper opaque layer. The magnetic quiet zone has been explained as a period in the Cretaceous during which magnetic reversals did not occur[23]. Although this explanation may be true in part, no data have yet been presented in the literature in clear support of this assumption. The kinematic model predicts that the magnetic quiet is the locus of crust formed under the equator. If there was indeed a period without reversals during the Cretaceous its effect would be to widen the apparent intersection and introduce other details.

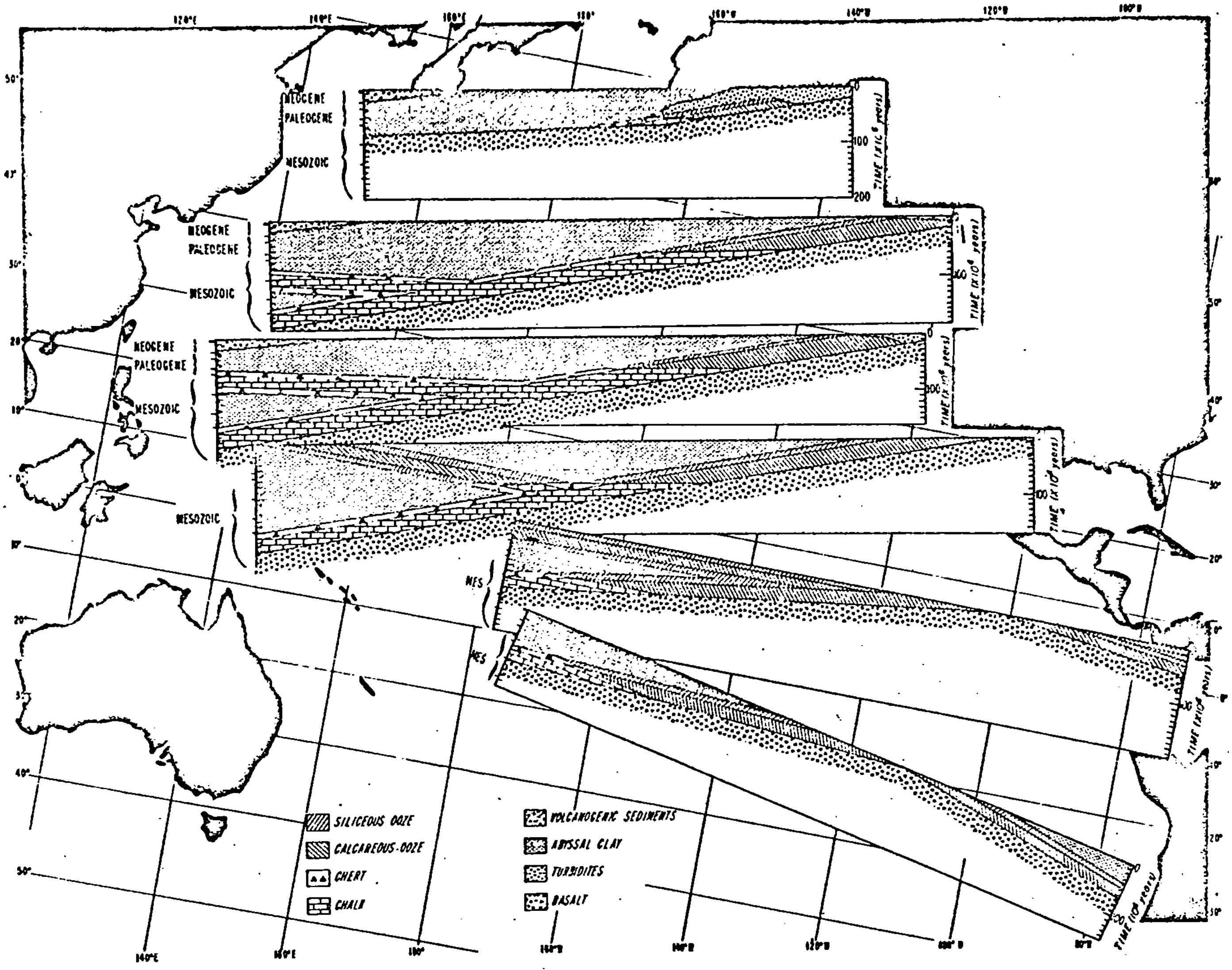

Fig. 6 Interpreted cross-sections showing sedimentary history of Pacific crust.

units can be applied to acoustic stratigraphy as well as to lithostratigraphy.

Magnetic Data

Stripe-like magnetic anomalies generated by east–west axial accretion are either absent or poorly developed in crust generated at the magnetic equator. A magnetically quiet zone has been mapped in the mid and high latitudes of the north central Pacific[23]. The zone which extends through the eastern Pacific from the present intersection of the magnetic equator with the axial rift valley towards the northwest Pacific (Fig. 7), lies somewhat east of the easternmost sites which sampled equatorial carbonates, and just east of the limit of

The Pacific crust is divided into two regions, one formed before and a second after the equatorial crossing. The boundary between the two is the "magnetic quiet" zone (Fig. 7). Similarly, the restriction of thick opaque layers to the western Pacific results in the correlation of this region with that portion of the Pacific crust that has passed beneath the equator, and thus received a double layer of biogenic sediment.

Diachronous Detrital Deposits on the Margins of the Pacific Plate

Evidence of crustal motions may also be derived from diachronous volcanic deposits near plate margins. A detrital wedge of volcanic debris is found within 1,000 km of the

Asiatic arcs in the northwest Pacific (Fig. 6). The shape and extent of the wedge is a function of two counter balancing effects, the amount and extent of distribution of volcanic debris and the westward subduction of the Pacific plate. Assuming that the rates of both processes have been essentially constant during Late Tertiary time, equilibrium should result and the shape of the wedge would stay essentially constant. Near the distal edge of the wedge (sites 194, 195, 196), Late Tertiary sedimentation rates are approximately the same. Thus the difference in thickness of the wedge between sites may be ascribed purely to the older age of the initial deposition surface at the western sites. With the above assumptions a value of about 8 cm yr^{-1} is obtained for the westward component of drift of the crust, that is, the subduction rate into the marginal trenches. This rate is of the same magnitude as the axial accretion determined for the past few million years by the magnetic stripes at the crest of the Mid-Oceanic Ridge.

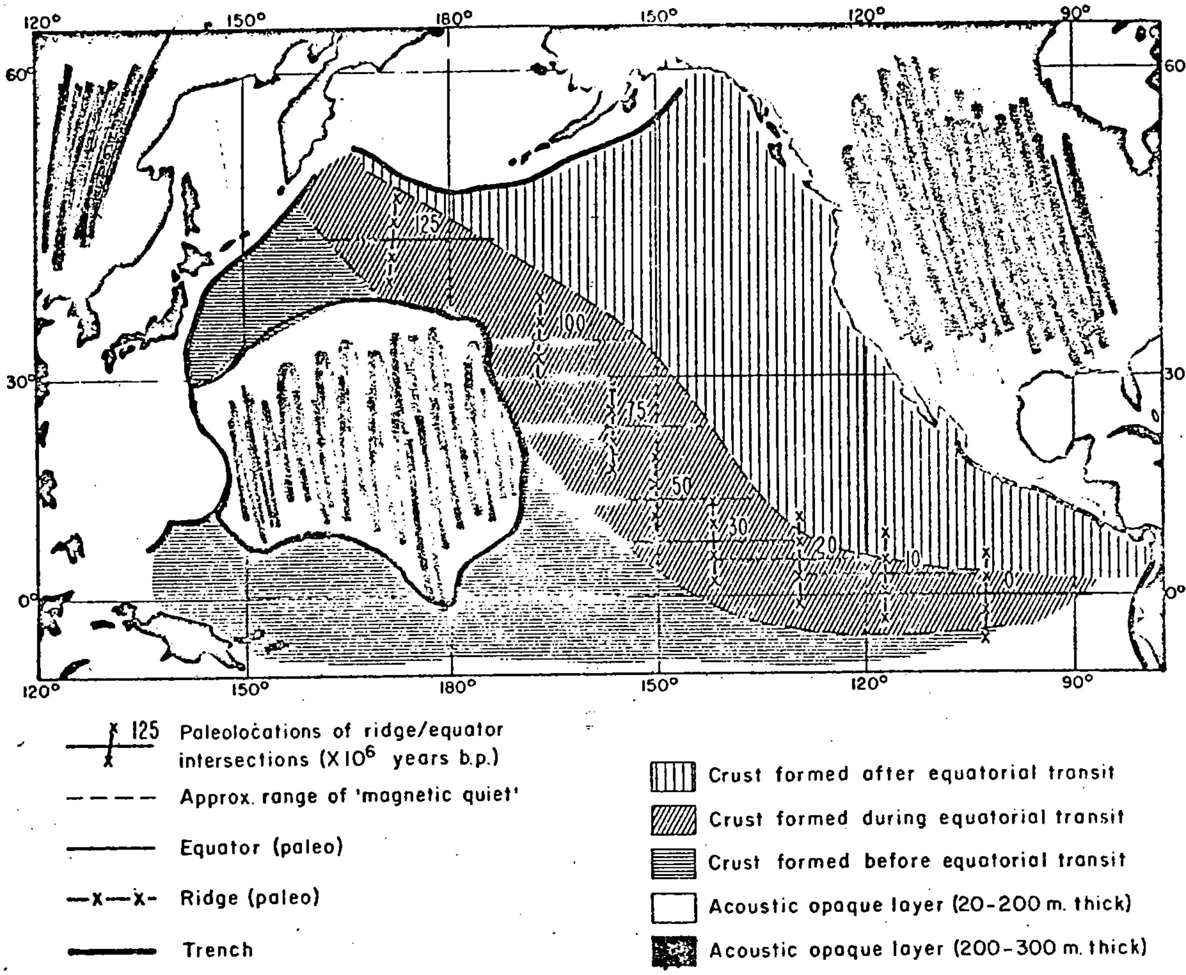

Fig. 7 Age structure of the Pacific crust.

By contrast other marginal detrital deposits may be synchronous, that is, the cut off of turbidity currents to the relict Aleutian Abyssal Plain by the blockage of the Aleutian Trench[24], or the commencement of turbiditic deposition on the Caroline Abyssal Plain by the creation of a source area in the Caroline Islands.

Whereas detrital sediments deposited in the deep sea may by means of some catastrophic mechanism be broadly synchronous, the characteristic litho-stratigraphy of pelagic deposits is broadly and systematically diachronous. The history of the Pacific plate has apparently been governed by a few simple and systematic factors: the carbonate and silica compensation depth, the gradual sinking of oceanic crust and the northward migration of the Pacific crust beneath the palaeoequator.

While we are gratified by the apparent close agreement of data and model we wish to emphasize the severe limitations of both. The model presented here has ignored both the theoretical effect of reversals in plate motion on bed thickness and possible evidence of such reversals. We have considered only a few changes in direction and rate of crustal drift and ignored possible changes in sea level or compensation depth.

In our opinion a relatively small number of additional holes drilled in the more ancient parts of the ocean would provide data for a greatly refined model. It would seem that even with only a few dozen better located, well sampled bore holes in the ancient Pacific plate we could, with the aid of a kinematic model, arrive at a rather detailed history of the Pacific since the Jurassic.

The Deep Sea Drilling Project is supported by the NSF and administered by the Scripps Institution of Oceanography. We thank W. A. Nierenberg, M. N. A. Peterson, N. T. Edgar and project staff for assistance.

Received July 14; revised August 29, 1972.

[1] Maxwell, A. E., Von Herzen, R., Andrews, J. E., Boyce, R. E., Milow, E. D., Hsu, K. J., Percival, S. F., and Saito, T., *Initial Reports of the Deep Sea Drilling Project*, 3 (National Science Foundation, 1970).

[2] McManus, D. A., Burns, R., Weser, O., Vallier, T., Von der Borch, C., Olsson, R. V., Goll, R. M., and Milow, E. D., *Initial Reports of the Deep Sea Drilling Project*, 5 (National Science Foundation, 1970).

[3] Fischer, A. G., Heezen, B. C., Boyce, R. E., Bukry, D., Douglas, R. G., Garrison, R. E., Kling, S. A., Krasheninnikov, V., Lisitzen, A. P., and Pimm, A. C., *Initial Reports of the Deep Sea Drilling Project*, 4 (National Science Foundation, 1971).

[4] Heezen, B. C., MacGregor, I. D., Foreman, H. P., Forristall, G., Hekel, H., Hesse, R., Hoskins, R. H., Jones, E. J. W., Kaneps, A., Krasheninnikov, V. A., Okada, H., and Ruef, M. H., *Geotimes*, 17, 10 (1972).

[5] Arrhenius, G., *Reports of the Swedish Deep-Sea Exped.* (Goteborg, 1952).

[6] Berger, W. H., *Science*, 156, 383 (1967).

[7] Peterson, M. N. A., *Science*, 154, 1542 (1966).

[8] Tracey, J. I., jun., Sutton, G. H., Nesteroff, W. D., Galehouse, J., Von der Borch, C. C., Moore, T., Lipps, J., Bilal Ul Haq, U. Z., and Beckmann, J. P., *Initial Reports of the Deep Sea Drilling Project*, 8 (National Science Foundation, 1971).

[9] Hays, J. D., Cook, III, H. E., Jenkins, D. G., Cook, F. M., Fuller, J. T., Gall, R. M., Milow, E. D., and Orr, W. N., *Initial Reports of the Deep Sea Drilling Project*, 9 (National Science Foundation, 1972).

[10] Winterer, E. L., Ewing, J., Schlanger, S. O., Moberly, R. M., Lancelot, Y., Jarrad, R. D., Douglas, R. G., Moore, T. E., and Roth, P., *Geotimes*, 16, 12 (September 1971).

[11] Winterer, E. L., *Bull. Amer. Assoc. Petrol. Geol.*, 56, 63 (1972).

[12] Winterer, E. L., *Bull. Amer. Assoc. Petrol. Geol.* (in the press).

[13] Jackson, E. D., Silver, E. A., and Dalryuple, G. B., *Geol. Soc. Amer. Bull.*, 83, 601 (1972).

[14] Francheteau, J., Harrison, C. G. A., Sclater, J. G., and Richards, M., *J. Geophys. Res.*, 75, 2035 (1970).

[15] Sclater, J. G., and Garrard, R. D., in *Initial Reports of the Deep Sea Drilling Project*, 7 (National Science Foundation, 1971).

[16] Vine, F. J., *Amer. Geophys. Union Trans.*, 49, 156 (1968).

[17] Creager, J. S., Scholl, D. W., Stewart, R. J., Fullam, T. J., Supko, P. R., Echols, R. H., Ling, H. Y., Worsley, T. R., Koizumi, I., Boyce, R. E., Grow, J. A., Lee, J. H., Ericson, A., Hess, J., Bryan, G., and Stoll, R., *Geotimes*, 16, 12 (November 1971).

[18] Von Huene, R., Kulm, L. D., Duncan, J. R., Ingle, J. C., Kling, S. A., Musich, L. M., Piper, D. J. W., Pratt, R. M., Schrader, H. J., Wester, O., and Wise, S. W., *Geotimes*, 16, 12 (October 1971).

[19] Van Andel, T. H., Heath, G. R., Bennett, R. H., Charleston, S., Cronan, D. S., Rodolfo, K. S., Yeats, R. S., Bukry, D., Dinkelman, M., and Kaneps, A., *Geotimes*, 15, 12 (June 1971).

[20] Hays, J. D., Cook, H., Cook, F., Fuller, J., Jenkins, G., Goll, R., Milo, D., and Orr, W., *Geotimes*, 15, 11 (April 1970).

[21] Winterer, E. L., Riedel, W. R., Bronnimann, P., Gealy, E. L., Heath, G. R., Kroenke, L., Martini, E., Moberly, R., Resig, J., and Worsley, T., *Initial Reports of the Deep Sea Drilling Project*, 7 (National Science Foundation, 1971).

[22] Ewing, J., Ewing, M., Aitken, T., and Ludwig, W. J., *Amer. Geophys. Union Mon.*, 12, 147 (1968).

[23] Hayes, D. E., and Pitman, W., III, *Geol. Soc. Amer. Memoir*, 126, 291 (1970).

[24] Hamilton, E. L., *J. Geophys. Res.*, 73, 4187 (1967).

DNA Replication Sites within Nuclei of Mammalian Cells

JOEL A. HUBERMAN, ALICE TSAI
& ROBERT A. DEICH

Departments of Biology, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139

DNA replication can occur throughout the nucleus and is not restricted to the inner surface of the nuclear membrane.

THE involvement of a membrane site in DNA replication was first suggested by Jacob, Brenner and Cuzin[1] in their "replicon" model for replication of bacterial DNA, but the evidence accumulated since then is inconclusive. In prokaryotic cells, co-sedimentation of DNA replication points and cell membranes has been demonstrated[1–4], and the origin of replication and the membrane found to be associated[5]. A lipid-free replicating DNA-protein complex from *E. coli* has been isolated[6] and it has been reported that only the origin, but not the growing points, of the *E. coli* chromosome is attached to membrane[7].

In cell fractionation experiments with mammalian cells it was also found that replication points, detected by pulse-labelling with ^{3}H-thymidine (TdR), are associated with the nuclear membrane (or some other large, light, hydrophobic cell structure)[8–11,13]. Association between replication points and the nuclear membrane has also been detected by electron microscope autoradiography of thin sections through pulse-labelled, unsynchronized HeLa cells. The label associated with the membrane apparently moved into the nuclear interior after a 1 h chase[13].

On the other hand, most electron microscope autoradiographic experiments suggest that replication can take place throughout the nucleus. For instance, Comings and Kakefuda[14] generally found grains located throughout the nucleus when unsynchronized human amnion cells were pulse-labelled for 5 min or more with ^{3}H-TdR and then sectioned and autoradiographed. When, however, cells that were supposedly synchronized at the beginning of S phase were pulse-labelled for 5 or 10 min, grains were found predominantly over the nuclear membrane. Comings and Kakefuda concluded that initiation of replication takes place on the nuclear membrane, whereas the replication occurs anywhere within the nucleus.

Somewhat different results were obtained by Blondel[15], using KB cells and pulse times of 2 min; Williams and Ockey[16], using Chinese hamster cells and pulse times of 10 min or longer; and Erlandson and de Harven[17], using HeLa cells and pulse times of 15 min. All three groups concluded, in agreement with Comings and Kakefuda[14], that during a large part of the S phase grains are produced over the entire nucleus, but they differed from them in finding a peripheral pattern of grains more frequently at the end of the S phase than at the beginning. A cell fractionation experiment by Kay *et al.*[18] also demonstrated association of late-replicating but not early-replicating DNA with the nuclear membrane.

Higher Resolution Autoradiography

Regardless of the time in S phase at which replication occurs close to the nuclear membrane, one important implication of