1. INTRODUCTION[1]

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CRUSTAL ACCRETION AND MAGNETIC STRIPES

Treatment of crustal problems in this volume is cast within the general frame of the theory of crustal accretion in linear belts, and of magnetic stripes as indices to the timing and patterns of such crustal growth. The oceanic basement is viewed as a volcanic complex, composed of hypabyssal intrusives, and a carapace of basaltic flows which may be interbedded with sediments. The authors have assumed that most of the oceanic crust is produced in this manner at the axis of the globe-girdling Mid-Oceanic Ridge, but as shall be shown below, Leg 6 produced evidence that oceanic crust may also grow at other sites—possibly associated with island arcs (Karig, 1970).

If it is assumed that the first basalts encountered in drilling, and the oldest sediments resting on them, are essentially contemporaneous with the basement, then deep sea drilling offers a means of measuring seafloor accretion which is independent of the approach through magnetometry. Obviously this assumption is not universally correct, for locally submarine volcanism distant from belts of crustal accretion must pour basalts over much older crust covered by sediments. Such volcanic aprons exist round the Hawaiian Islands and around countless other eruptive centers. Yet it would seem that they cover only a small fraction of the sea floor. Normally, seismic profiles allow recognition of sediments and of a well-defined base of the sedimentary sequence (*basement* or *Horizon B*) over hundreds of miles, and in such cases the authors are inclined to view these surfaces as true oceanic basement.

Legs 2, 3, and 5 of the Deep Sea Drilling Project crossed areas in which magnetic stripes had been mapped and models had been established for sea floor spreading. The results of Legs 2 and 3 (Peterson *et al.*, 1970; Maxwell *et al.*, 1970) were essentially perfect matches for the model based on magnetic stripes, while Leg 5 (McManus *et al.*, 1970) obtained much too young a date at one site—presumably by drilling into a younger eruptive center.

Leg 6 lay entirely outside the area of well-established and age-correlated magnetic stripes. Magnetics, corroborated in general by the drilling results of Leg 5, show progressive increase in crustal age westward, from

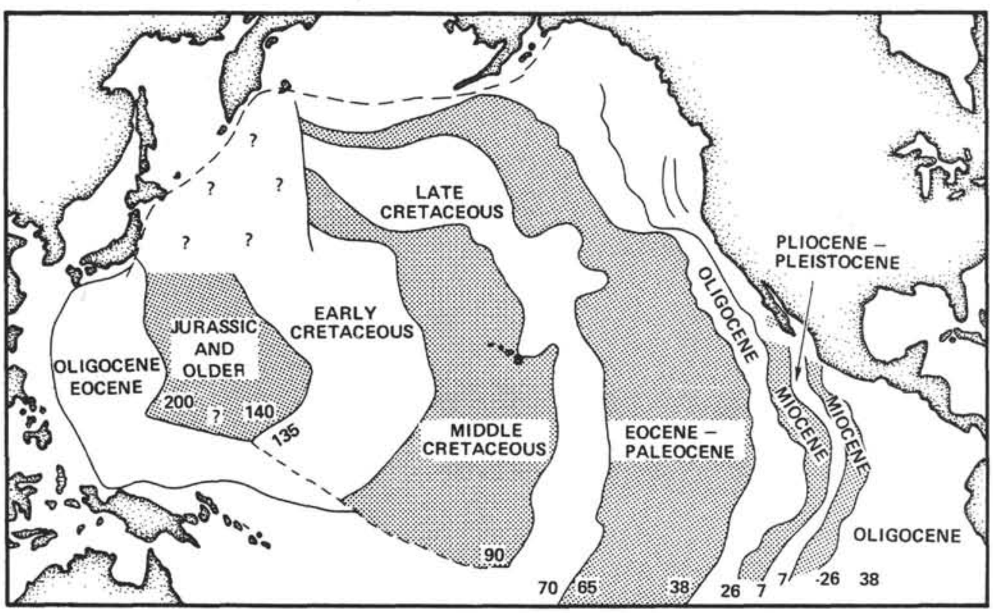

Figure 1. *Age of the oceanic crust in the North Pacific.*

[1] Lamont-Doherty Geological Observatory of Columbia University Contribution No. 1600.

essentially Holocene at the East Pacific Ridge to Lower Eocene some distance east of Hawaii. By simple projection of these drift rates to the west, the sea floor of the Pacific areas crossed by Leg 6 can be predicted to be Early Cretaceous and Jurassic, west to the trenches (Figure 1). This is compatible with the discovery of Lower Cretaceous (Albian) sediments on the Shatsky Rise by the *Vema* (Ewing *et al.,* 1966). If projection be extended still farther west, into the Philippine Sea, the crust there should be of Triassic or even of Paleozoic age–depending on the amount of crust which has been destroyed in the trenches.

On the other hand, this simple projection is a large-scale extrapolation, and certain characteristics–especially the rough bottom topography and the thin sediment cover of the Philippine Sea (Ewing, Ewing, Aitken and Ludwig, 1968) suggested young rather than old crust there.

Thus drilling in the Northwestern Pacific and the Philippine Sea held the promise of encountering early Mesozoic and perhaps even older crust, and of delimiting patterns of crustal accretion in what might be perhaps the largest remnant of the early Mesozoic sea floor left in existence; it also held promise of contributing to the knowledge of the opposite process–of the presumed destruction of crust in the oceanic trenches.

SEISMIC PROFILES

The development of the continuous seismic marine profiler has had an enormous impact on marine geology. Rock units devoid of reflecting surfaces appear clear or "transparent" on the paper record (since one can "hear" through them they are really "transaural"), whereas rock units containing many reflecting surfaces, and providing many echos, appear dark or "opaque".

Normally, the near-surface rocks show a stratified alternation of "transparent" and "opaque" seismic units, which can be traced over large distances. The seismic profiles thus reveal, by remote sensing, a stratigraphy, and in analogy with lithostratigraphic and biostratigraphic units the authors refer to these seismically defined bodies as *acoustostratigraphic units.* The reader may wonder whether a distinction between lithostratigraphic and acoustostratigraphic units is necessary since the reflective characteristics of a given sedimentary body are an expression of its lithic character. Practice has shown that such distinction is indeed necessary, for similar reflective character may be provided by a wide variety of totally distinct rock types, such as chert beds or nodules, volcanic tuffs in clay, turbidite sequences, etc.

The coupling of seismic profiling with drilling is of particular importance. The profiles provide the basis for working hypotheses of what may be found, in terms of thickness of sediments. The drill reveals the lithic character and local age of given acoustostratigraphic units. And, under the assumption that a given acoustostratigraphic unit maintains its age and character for some distance outward from a given drill site, the profiles may then be used to extrapolate the drilling results to the region round about.

For the Northwest Pacific Ocean, the prime source of published seismic profiles was Ewing, Ewing, Aitken and Ludwig, (1968). Over much of this vast region these authors had mapped a sequence of acoustostratigraphic units, named (from top to bottom) the *upper transparent layer,* the *upper opaque layer,* and the *lower transparent layer.* The top of the upper opaque layer was termed *Horizon A'*, implying a tentative correlation with *Horizon A* in the Atlantic: a unit initially and tentatively identified with the top of the Cretaceous on the basis of piston cores–and later Ewing *et al.,* 1969 (Leg 1)–shown to be a series of Eocene chert bed in the Bermuda Rise area. The base of the stratified acoustostratigraphic units, on a massive opaque unit, was termed *basement* where rough, and *Horizon B'* where flat and smooth–in tentative correlation with a similar surface in the Western Atlantic. The reason for this distinction was the observation that juvenile crust formed in the Mid-Oceanic Ridge normally shows high, rough relief, and the suspicion that the flat *B* surfaces represent either a secondarily truncated (peneplained?) basement surface, or a rough basement mantled by poorly stratified but reflective sediments (Ewing, Ewing, Aitken and Ludwig, 1968; Ewing *et al.,* 1969).

On the Shatsky Rise, additional reflecting horizons had been identified (Ewing *et al.,* 1966): a reflector within the upper transparent unit, termed α, and one below the upper opaque, termed β, in analogy to a widespread reflector in the Atlantic, identified by Leg 1 in the Cat Gap area as a Cenomanian radiolarian chert sequence (Ewing *et al.,* 1969).

These seismic profiles thus provided Leg 6 with a series of interesting targets, and with a number of specific problems, outlined as follows:

(1) What is the character and age of the acoustostratigraphic units in any one area?

(2) To what extent do the acoustostratigraphic units correspond to lithic units?

(3) How synchronous or diachronous are the acoustostratigraphic units, locally and regionally?

(4) What is the nature of *Horizon B'*?

THE PREPLANNED DRILLING PROGRAM

This published information, plus the store of unpublished data and personal experience at the command of the JOIDES Pacific Advisory Panel (Burns, Bonatti, Ewing, Maxwell, McBirney, McManus, Menard, Riedel and Rusnak) served as the basis for a recommended drilling program of six Prospective Sites on Leg 6. This would have been an acceptable drilling program, but for one factor which was not fully foreseen: chert turned out to be a very common constituent of these sediments, and terminated drilling at each of the recommended sites, generally far short of the objectives. Where chert or strongly lithified volcanic ash was encountered close to the sea floor it caused twistoffs (Sites 45, 46) or forced abandonment of the hole to avoid risk of such (Sites 49, 50, 52). Where chert was encountered at depths of 100 meters or more, it quickly dulled the bits and brought penetration to an end (Sites 44, 47, 48, 51, 59). For this reason the drilling program recommended by the Panel was completed, insofar as possible, in less than half the time alotted, and additional sites were drilled. Some of these, such as Sites 46, 48, 50 and 54, were supplementary to sites chosen by the Panel, whereas others–Sites 51, 55, 56, 57 and 58–were independent ventures; Sites 59 and 60 were initially on the Leg 7 program. The correspondence between the Prospective Sites chosen by the Panel and the sites actually drilled is shown in Table 1. The only Prospective Site not drilled is No. 16, one of the western

TABLE 1
Prospective and Drilled Sites, Leg 6

Prospective Site (Pacific Panel)	Drilled Site	Comments
11	44	
12	45	
	46	Supplement to Site 45
	47	
13	48	Supplement to Site 47
14	49	
	50	Supplement to Site 49
15	51	
16		Not drilled, in favor of 52
	52	
17	53	
	54	Supplement to Site 53
	55	
	56	Independent drilling venture in Caroline Ridge area
	57	
	58	
19	59	Originally scheduled for Leg 7
	60	

most guyots. Logistics (lack of beacons) forced a choice between drilling this site and drilling Site 51, another attempt to penetrate the sediments of the abyssal sea floor, which had not been accomplished further north. The decision, more fully explained in the narrative summary, was in favor of the latter.

THE ARGO SITE SURVEYS

The *Glomar Challenger* was extremely fortunate in being preceded, along the preplanned part of the cruise, by the R. V. *Argo* on its *Scan III* cruise; the *Argo,* under George Shor, conducted Site Surveys at DSDP Sites 44, 45, and the Shatsky Rise (47-51). Continuous seismic and magnetic profiles were made. The work at prospective drill sites also included some seismic refraction profiles, heat flow measurements, piston cores, and bottom photographs. Excellent seismic profiles were flown to the ship at Hawaii, as were magnetic data, maps made on shipboard, bottom photos, and reports and samples on the core, by R. K. Johnson and S. Einsohn. These data proved invaluable–not only the site surveys proper, but also the profiles between sites, which permitted additional drill sites to be staked and provided geological continuity.

Unfortunately drilling followed too closely on the *Argo's* heels to obtain seismic profiles from the *Argo Scan IV* cruise in the area of the Marianas and the Philippine Sea under D. E. Karig. However, Karig transmitted data on DSDP Sites 53, 59 and 60 by radio with sketches sent by facsimile, and by word-of-mouth.

The seismic profiles of *Scan III* and *Scan IV* which are applicable to the drilling cruise are reproduced in Part II of this report, as are other special data, and Karig's discussion of the geology of the Mariana Arc area.

CRUISE NARRATIVE

"The primary objectives of the deep-sea drilling program," as stated by the JOIDES Pacific Advisory Panel, "are the determination of the age and processes of development of the ocean basins." The panel further stated that "these long cores will also serve to provide reference sections for future studies in biostratigraphy, physical stratigraphy, and paleomagnetism. In addition, the cores will furnish new scope to studies of the physical and chemical aspects of sediment dispersal, deposition, and postdepositional changes in sediment."

Leg 6 began in Honolulu on June 11 and ended in Guam on August 5. The first site was on Horizon Ridge (Guyot). The following two attempted to test the age of the abyssal Pacific west of Hawaii. Four more were devoted to an investigation of the relatively thick and well stratified sedimentary sequence which caps the Shatsky Rise. Holes were drilled at two more sites in the deep sea floor of the westernmost Pacific.

The eastern Philippine Sea was drilled at two locations west of the Iwo Jima Ridge. Four sites were devoted to an investigation of the geology of the Caroline Ridge. One more was drilled in the abyssal Pacific east of the Mariana Trench, and a final site was drilled in the west wall of the trench.

A total of 34 holes were drilled at 17 sites (see Figures 2, 3). In all, 125 cores were taken, totaling 684 meters in length, and representing 27 per cent of the 2538 meters of hole drilled. Figure 3 summarizes the lithology of all sites drilled on Leg 6. Table 2 summarizes the statistics at each of the drilling locations on Leg 6. Site 51, with a water depth of 5980 meters, represents the deepest marine drilling attempted to date. Summaries of the drilling are presented in Tables 1 and 2.

Departing from Honolulu, Hawaii, on June 11, a course was for Horizon Ridge "Guyot" (a guyot is a flat topped seamount; this feature is a flat topped ridge, not a seamount) where Site 44 (Prospect II) was drilled on June 14. The hope was to penetrate the sedimentary cap to its base, in order to discover the time when the truncated volcanic foundation was first submerged and to determine what general history of subsidence may be reflected in the sediments. However, a series of chert beds or lenses in Middle Eocene pelagic ooze proved impenetrable, and on starting out of the hole the bottom hole assembly parted. A good sequence of cores through the Oligocene, Late Eocene and Middle Eocene provide new paleontologic and biostratigraphic data and a reference section for this mid-Pacific area.

The next aim was to date the acoustostratigraphic units and the oceanic basement in the deep basin between the Hawaiian Ridge and the mid-Pacific Mountains. Sites 45 (Prospect 12A) and 46 were drilled between June 17 and 25 with these objectives. Two major problems continued throughout much of the drilling and left the scientists far short of accomplishing their aims: (1) the upper opaque seismic layer (Ewing *et al.*, 1968) turned out to contain many hard beds–lithified

TABLE 2
Drilling Statistics for Leg 6

Site	Date	Water Depth (m)	Latitude (N)	Longitude	Penetration (m)	No. Holes	No. Cores	Total Core (m)
44	June 14-15	1478	19° 18.5′	169° 00.0′W	76	1	5	29
45	June 17-20	5508	24° 15.9′	178° 30.5′W	105	2	3	8
46	June 25	5769	27° 53.8′	171° 26.3′E	9	1	1	9
47	June 28-30	2689	32° 26.9′	157° 42.7′E	129	3	14	115
48	30-July 1	2619	32° 24.5′	158° 01.3′E	84	3	5	21
49	July 2-3	4282	32° 24.1′	156° 36.0′E	20	2	4	20
50	July 3	4487	32° 24.2′	156° 34.4′E	45	2	6	29
51	July 4-5	5981	33° 28.5′	153° 24.3′E	132	2	5	21
52	July 9-10	5744	27° 46.3′	147° 07.8′E	69	1	10	45
53	July 13-16	4629	18° 02.0′	141° 11.5′E	201	3	12	47
54	July 17-19	4990	15° 36.6′	140° 18.1′E	294	1	9	28
55	July 21-22	2850	09° 18.1′	142° 32.9′E	131	1	14	121
56	July 23-25	2508	08° 22.4′	143° 33.6′E	270	1	10	88
57	July 25-28	3300	08° 40.9′	143° 32.0′E	335	3	7	35
58	July 28-30	4503 4486	09° 14.1′	144° 25.1′E	173	4	4	14
59	31-Aug. 2	5554 5547	11° 46.8′	147° 34.9′E	135	3	7	19
60	Aug. 3-5	3717	13° 40.0′	145° 41.9′E	348	1	9	35
Totals 17					2556	34	125	684

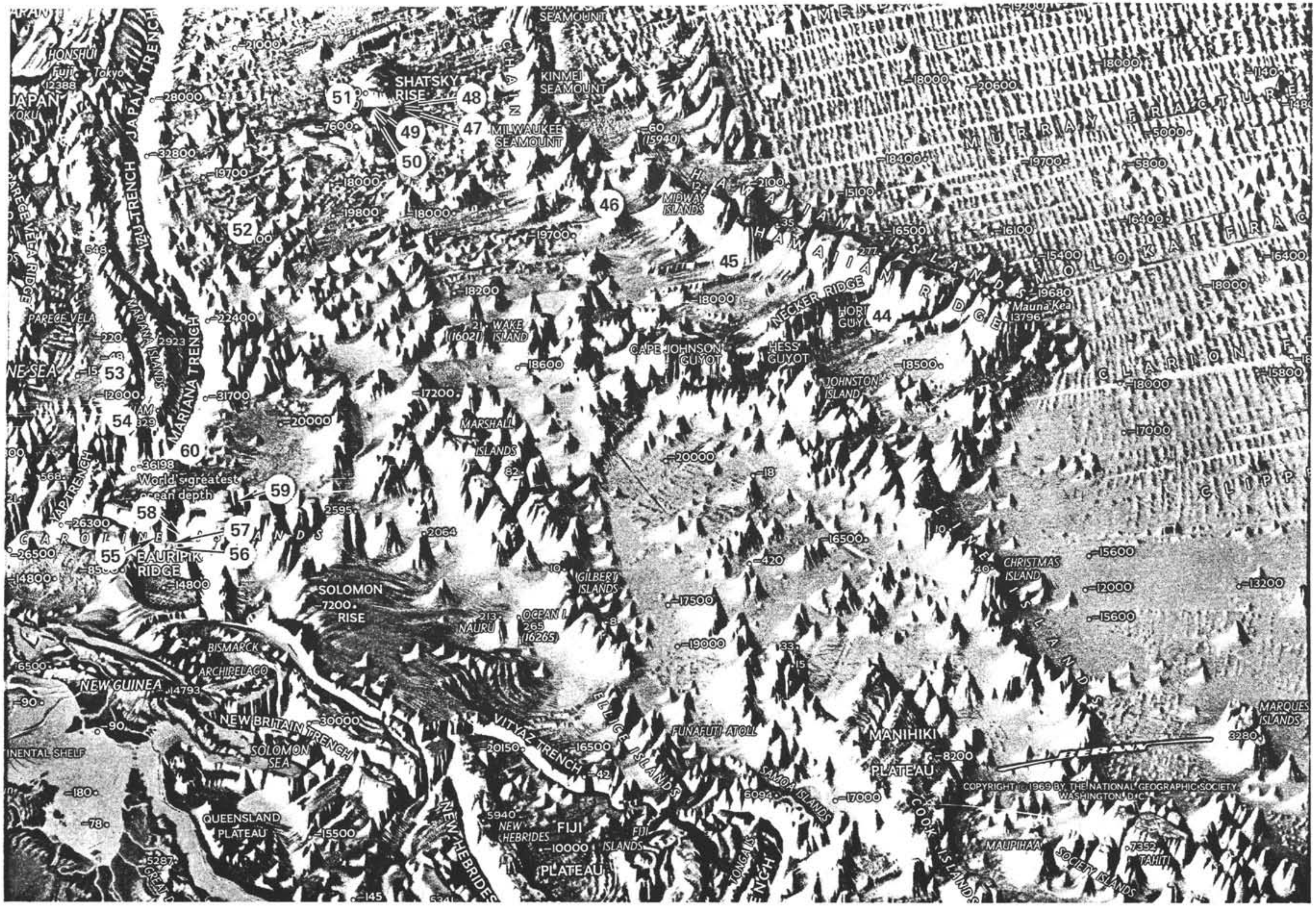

Figure 2. *Physiographic map of the Northwest Pacific showing locations of sites drilled on Leg 6. ©N. G. S.*

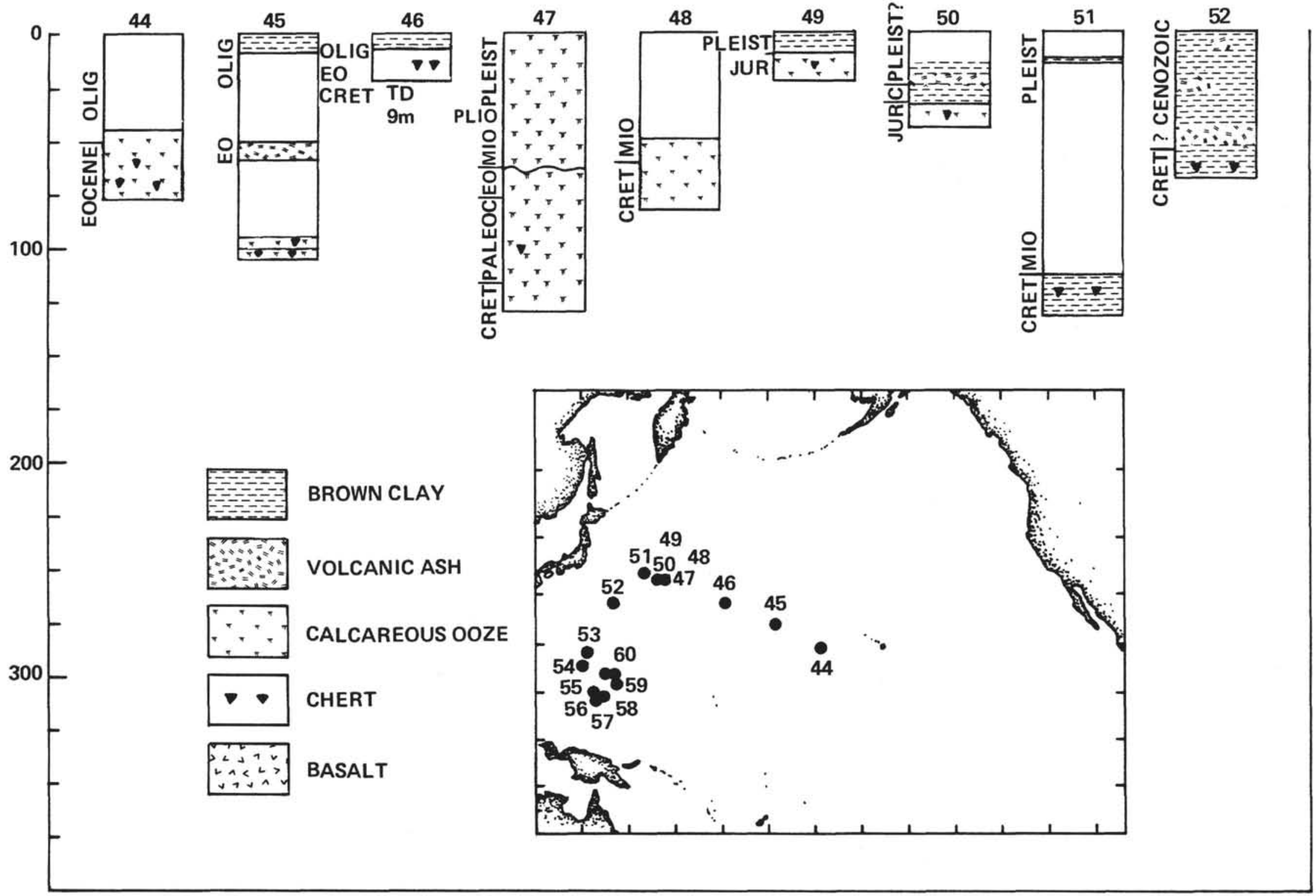

Figure 3. *Summary of lithology of holes drilled on Leg 6.*

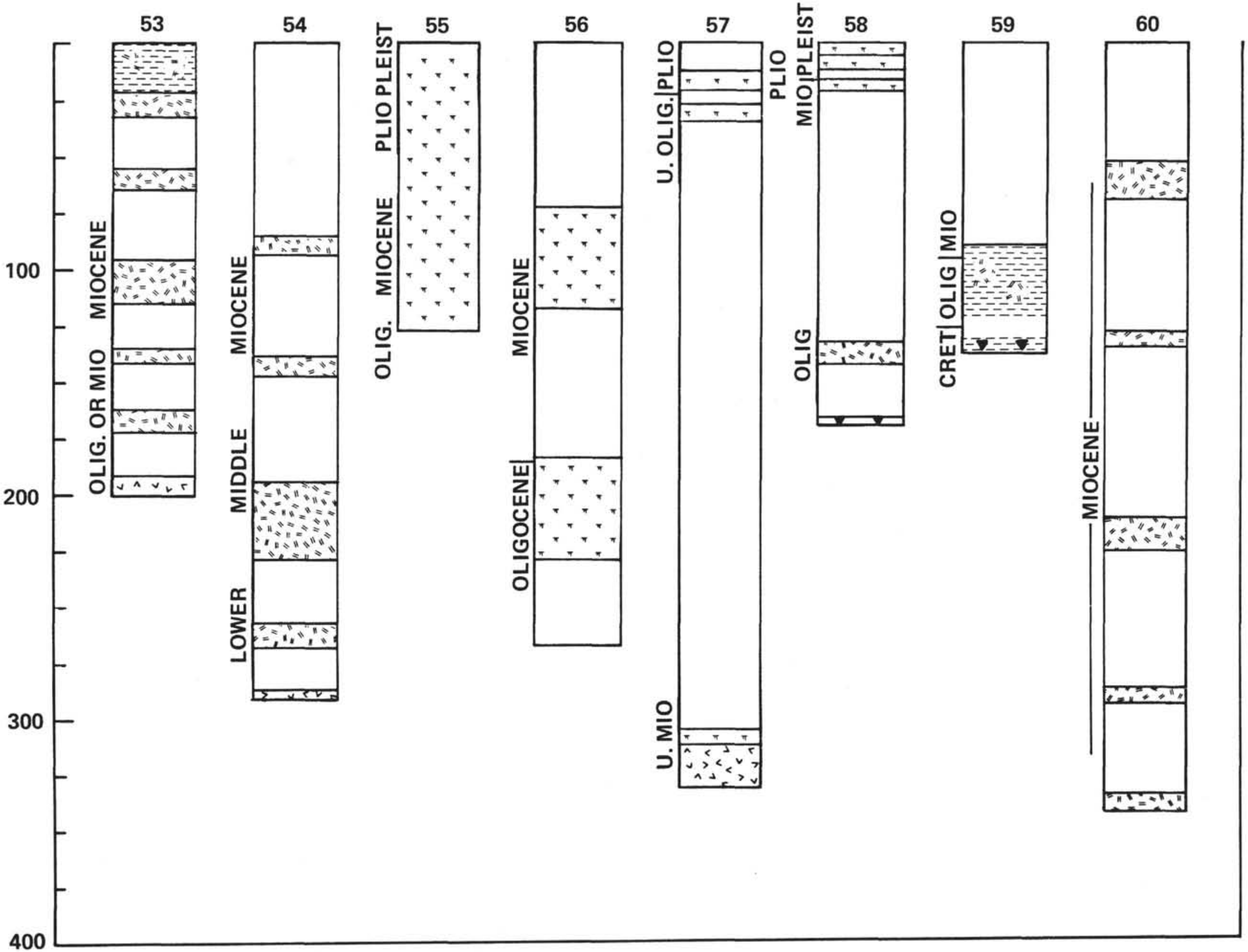

Figure 3. *(Continued).*

tuffs and chert, obstacles to drilling under any conditions; (2) in this area the amount of soft sediment cover over these hard beds is insufficient to bury the brittle bottom-hole assembly of drill collars and bumper subs, which, when thus unsupported, is likely to buckle and twist off.

Hoping that the upper opaque layer would prove amenable to spudding and drilling, the scientists staked Site 45 on an anticline and drilled two holes, both lost by twisting off. Hole 45.1 encountered Oligocene at the surface, Eocene and Mid-Cretaceous (Cenomanian) carbonate approximately at the base of the upper opaque at a total depth of 105 meters.

Site 46 was staked on a receded fault scarp, with the hope of spudding into the lower transparent layer and of penetrating to interface "B′", the lowest detectable seismic reflector in this area. It encountered a mixture of Oligocene-Eocene brown clay with Cretaceous chert and lithified ash, and was lost by twisting off.

The main result of drilling in the mid-Pacific was the determination in this area of the age and composition of the upper opaque layer. It ranges from Late Cretaceous (Cenomanian or post-Cenomanian) to Oligocene. Its lower part, possibly up to Maestrichtian, contains carbonates and chert, as well as lithified volcanic ash beds; its upper part here consists of interbedded brown clay and lithified volcanic tuffs and ashes. The source of volcanics is probably the Hawaiian Ridge to the north. Having failed to obtain information on the lower transparent layer, on Horizon B′, and on the oceanic basement, and having experienced three twist offs in as many holes, this area was reluctantly left for the Shatsky Rise, which held out promise of carbonate sediments and possibly better drilling.

The Shatsky Rise appears to be a persistent high, the crest of which accumulated a cap of up to 1 kilometer of sediment and has probably remained consistently above the carbonate compensation depth. It offered the promise of a most important biostratigraphic reference section for the whole northwest Pacific area. The oldest core in the Pacific (Albian) had been obtained here by *Vema*, from what are surely not the oldest sediments in the stratigraphic section.

From June 24 to July 5 four sites were occupied: 47, 48, 49, and 50–on the Shatsky Rise proper.[1] The hopes for one or two long stratigraphic sections were dashed since none of the holes reached a total depth of more than 129 meters, due to chert. Two–47 and 48–sampled the upper section on the crest, and yielded cores through Pleistocene, Pliocene, Miocene, Eocene, Paleocene and Maestrichtian chalk oozes with excellent biotas of coccoliths and foraminifera and, in the upper part, silicoflagellates, diatoms and Radiolaria. A major disconformity was noted between the Late Miocene and the underlying sediments (Early Eocene at Site 47, Middle Maestrichtian at Site 48). Both holes ground to a halt in the cherty chalks of the Late Cretaceous. The middle part of the sediment cap on the Shatsky Rise remained undrilled. The lowest sediments (above the enigmatic B′) were touch-sampled by the drill at Sites 49 and 50, on the west flank of the rise in an area of insufficient soft cover, and were found to be cherty chalk oozes of possibly Late Jurassic (Tithonian) to Early Cretaceous age. The basement or B′ layer remained undrilled, due to the extreme hazards of drilling hard rocks without adequate cover, but basalt and jasper pebbles in the lowest core at Site 50 may represent a basal conglomerate under the sediments.

Site 51 (Prospect 15), on the deep ocean floor at the western extremity of the Shatsky Rise, was drilled on July 4 to 5. A Cenozoic brown clay sequence, acoustically transparent, overlies chert and foraminiferal chalk of Cenomanian-Santonian age; which barred all further progress. The top of the upper opaque seismic layer is Cretaceous, older than at Site 45.

A major decision was faced here. Due to the limited penetration achieved by any one hole, more holes and more sites had been drilled than expected, and there were only three acoustic beacons left. Some hopes had been held out for delivery of beacons to Tokyo or Guam, possibly by July 15, and the decision called for concerned this delivery point. The ship could move either to Tokyo along the *Argo's* track, which showed more and more sedimentary (seismically transparent) cover toward the margin of the Japan trench, and thus offered tempting drill sites. Or it could move southward in the direction of Guam. In either case, only three more sites (assuming no beacon failures) could be drilled before obtaining new beacons. The alternatives were discussed with the scientific staff and the Drilling Superintendent, and the southward course was chosen. The reasons were largely logistic: the Japan alternative was attractive if beacons could be delivered by the 15th or 16th, but a delay in delivery would mean waiting off Yokohama, whereupon the *Challenger* would face the several days to travel to the Philippine Sea. It seemed wiser to avoid the risk of such time loss.

The choice of the next site posed another alternative. According to the original program, it should have been an unexplored seamount[2] (possibly a Guyot) for which no site survey had been made. The alternative was another hole in the abyssal floor sequence in order to get a third date on the top of the upper opaque

[1]Two prospective Sites 13 and 14, had been planned for the Shatsky Rise, *sensu stricto*.

[2]Prospect 16.

layer, which had yielded different ages at Sites 45 and 51, and to provide another chance at drilling the abyssal basement. The ideal could have been to drill both, but the shortage of beacons (only three left, and a minimum of two were needed for the holes in the Philippine Sea) permitted only one.

The merits of seamount and abyssal floor holes were compared. A hole in a guyot would have as its chief objective the dating of guyot subsidence in this area, in comparison to that at Horizon Ridge. But at Horizon there was not penetration to the critical objective, because of chert. A hole in the abyssal floor, closer to the trench than any of the others, might add substantially to the primary purpose of the Deep Sea Drilling Project "the determination of the age and processes of development of the Pacific Ocean basin." The decision was in favor of the abyssal test, and Site 52 was drilled.

Seismic reflection profiles (Ewing *et al.,* 1968) had revealed in this region an upper transparent unit, about 100 meters thick, overlying a 200 to 300-meter thinly bedded sequence (upper opaque layer). Sixty-five meters of brown clay, ash bearing and very poorly fossiliferous, were penetrated before encountering very hard drilling in lithified ashes and some chert–a unit which appeared in the acoustic profiles as a weak reflector within the upper transparent layer. Drilling was stopped here not because of a worn-out bit but because of the hazard of drilling such hard material with the drill collars and bumper subs only partly buried. A better designed (shorter and equally heavy) bottom hole assembly would have permitted further drilling into the underlying acoustically transparent material. The age relations of this sequence are most significant. The top of the Mesozoic lies somewhere between 30 and 64 meters, and the hard layers are equivalent to or older than the upper opaque layer of Sites 45 and 51. It is thus concluded that the upper opaque layer as defined by Ewing *et al.* is either sharply time-transgressive, or is a composite of different layers in different areas. The authors are inclined to think that it is a combination of both–a unit as complex as most lithostratigraphic units, broadly time-transgressive (older toward the trenches), but interfingering with transparent units at both top and bottom.

A series of continuous cores was obtained through the brown clay section, much disturbed by drilling.

At Site 52, another decision had to be made: whether to spend the remaining two beacons on further holes on the abyssal Pacific floor on the outside of the Mariana Trench, or on sites in the Philippine Sea before going on toward Guam and a new supply of beacons. The second alternative was chosen.

Leaving Site 52 on July 10, the ship steamed southward to cross the Mariana Trench into the Philippine Sea. Between Site 52 and the trench, the reflection profiles showed an upper transparent layer with the weak Cretaceous reflector that had stopped drilling at Site 52; an opaque layer below this, and under this yet another transparent zone not clearly seen at Site 52, resting on what presumably is basement. In the light of Site 52, the authors judge that the opaque layer, which was not reached by drilling is Lower Cretaceous and possibly older, and that the underlying transparent layer is of Jurassic or Triassic age. This may be the oldest sedimentary sequence encountered along the track. It extends to the edge of the trench, where sediments vanish against rough basement.

The Philippine Sea (along with the other seas forming the western margin of the Pacific) poses major problems of genesis. If the Pacific crust has grown only at the crest of the East Pacific Ridge, then these western seas should be bottomed by the oldest Pacific Crust, and should represent the oldest oceanic areas in existence today, dating back to the very beginnings of Mesozoic time if not to the Paleozoic.

Yet, the thinness of the sediments as revealed by seismic refraction and seismic reflection measurements and implied by the roughness of bottom topography, suggested a young rather than an old crust: a young crust such as postulated by Wegener, but not easily accounted for by the particular concepts of drift and sea floor accretion which are dominant today.

This then was a significant problem which the scientists hoped to solve by drilling. Yet another reason for drilling on the continental side of an island arc system arises from the problems of relating ancient mobile belts) known mainly through their sedimentary record in geosynclines) to present day mobile belts (known chiefly through their topography, volcanism and seismic activity).

Seismic reflection profiles had shown that most of the Philippine Sea has too little sedimentary cover for present day drilling techniques. However, the western flank of the Iwo Jima Ridge (or inner Mariana Ridge) is buried under a thick sedimentary apron, wedging out toward the west. These sediments cover a rough basement, and lap out against the flanks of buried basement hills.

Two sites were drilled in this setting, Sites 53 (July 13-16) and 54 (July 17-19). Both were staked on the flanks of such buried hills, and encountered rather similar geology. In both cases, the sediments are of dominantly pumice ashes of mixed andesitic and basaltic composition, containing an abundant admixture of coccoliths and other planktonic skeletons.

The underlying basement is basalt at both sites. At Site 53, the basalt is interbedded with pinkish and brownish limestone, veined and baked, of Oligocene or possibly early Miocene age. A series of down-hole logs was obtained at Site 53, but at Site 54, a piece of basalt that dropped out of the last core had lodged in the drill pipe, and prevented passage of logging tools and sinker bar.

The Eastern Philippine Sea appears to be built very much like Guam where basement is a massive volcanic (mainly basaltic) flow complex, Eocene and Oligocene or earliest Miocene in age. Superimposed on this basement are locally thick aprons of Miocene pyroclastics, chiefly of andesitic composition. It is not certain that the basalt outpourings represent the flow-carapace over an age-equivalent ultramafic crust below, for they could mantle a yet unsampled sequence of older sediments and a still older crust beneath.

The program in the Philippine Sea depended not only on geological matters, but also on logistic ones: Sites 53 and 54 were drilled with the last remaining beacons, and Site 54 was the rendezvous at which new beacons were delivered by the *Ran Annim* out of Saipan.

Once again a major decision was faced: whether to continue drilling in the Philippine Sea, or whether to return to the Pacific, outside the island arc.

At this reconnaissance stage of oceanic drilling there seemed little point to drill more holes in the pyroclastic apron explored at Sites 53 and 54. Most of the Philippine Sea seemed to lack sufficient sediment to be drilled, and the great sedimentary sequences near the Philippines lay too distant from the next port (Guam) to be considered. A small patch of sediment west of the Parece Vela Ridge, reported by Ewing *et al.*, (1968) at 16°N latitude, was tempting but the distance to this site and the uncertainty of finding enough sediment there forced a decision against it, and attention was turned once more to the ocean outside the Mariana Arc.

The *Glomar Challenger's* experiences to the north, as well as the reports of other ships equipped with profilers, provided information that east of the Mariana Arc the amount of soft sediment cover over the upper opaque layer was generally less than the minimum required for spudding in. However, the total thickness of sediments increases toward the equator, in part, presumably because of greater organic productivity in the equatorial upwelling belt. Also, the existence to the south of shallower areas above carbonate compensation depth–the Caroline Ridge, the Eauripic Ridge, etc.–assured more expanded carbonate sequences. Here hope was to pursue the elusive goals of the Pacific drilling farther north: to penetrate and date the stratigraphic sequence to the oceanic basement.

The ship left Site 54 on July 19, on a course slightly east of south, and crossed the Mariana Trench on the night of the 21st.

A thin veneer of 10 to 50 meters of sediment overlying a smooth, opaque basement at the southern trench margin, slowly thickens southward to the base of the Caroline Ridge proper.

The north flank of the Caroline Ridge rises in a series of remarkable benches or terraces, with very steep "rises" up to several hundred meters high, and flat basement "steps" mantled with sediment. The thickness of sediment is variable on any one of these steps, generally least at its outer edge, and reaches 0.2 seconds or more on the intermediate steps. While various possible modes of origin of these steps were considered, the scientists ultimately concluded that they represent a series of essentially vertical block faults, progressively down to the north. In the central part of the ridge some faults are downthrown to the south, producing there a pronounced horst-and-graben structure.

Site 55 was staked on July 21 on the fourth of these fault steps along the track, in what appeared to be a sequence of over 200 meters of sediment on a smooth B′ type "basement." The sediments were ash-rich carbonate oozes, mainly of Miocene age; the Oligocene had just been reached at a depth of 131 meters on July 22, when winds associated with a marked atmospheric depression centered slightly to the southeast threatened to blow the ship off the hole. Falling barometer pressure and current reports from weather flights suggested that this small cyclonic depression might develop into a typhoon. The hole was, therefore, abandoned, and the ship headed east, in order to get behind the storm. The center was passed during the night of the 22nd and Site 56 was commenced on the afternoon of the 23rd, but the winds and swell to the rear of what rapidly grew into typhoon Viola hampered operations for several days.

Holes 56 and 57 both had the same prime objective as 55: to explore and date B′ or basement. Basement was reached at 56, but the bit seemed incapable of drilling into it. At 57, basement yielded two magnificent cores of a fresh, doleritic basalt under unaltered Upper Oligocene sediments. It is believed that this basalt is representative of the basement in this area, and that the smooth surface B′ on seismic reflection profiles may be of volcanic origin in other places as well. A logging program was carried out at Site 57.

This work on the Caroline Ridge had brought a surprise: the crust here appeared to be young, much more closely related to that of the Philippine Sea than to that of the old western Pacific.

The next concern was to find the boundary between this portion of young crust lying outside the island arcs and the Pacific crust proper. Therefore, the ship left Site 57 on July 28, on a northeasterly course, to cross the eastern extension of the flat area which had been crossed between the trench and Site 55. After dropping over the last fault scarp the sediments thinned to 0; then sediments appeared again along the track, but with a different character, showing more discrete reflectors. When these sediments thickened to 0.18 seconds, along the track, there was a decision to drill them, and the beacon for Site 58 was dropped on July 28.

The section here turned out to be of the same general (mainly Miocene) age as that of Sites 55 to 57, but of a somewhat different sedimentological character: the site is located in the mouth of a submarine valley system, the branches of which extend to some of the Caroline Islands (Faraulep Atoll and Gaferut Island) and banks. These shallow areas have contributed pebbles and granules of basalt, volcanic glass, skeletal matter (corals, algae, echinoids, shell debris, large foraminifera), and consolidated limestone, since Miocene time. Such clasts occur in two distinct ways: as pebbles in the ashy nannofossil oozes, and as well-sorted carbonate sand. Presumably the transport of clasts occurs by turbidity, and, possibly, other currents and mud flow in a manner similar to that in which Bahamian debris had been contributed to deep water sediments in the Cat Gap area off the Bahamas since Cretaceous time—as at Sites 4 and 5, Leg 1 (Ewing *et al.,* 1969). The special reflective character of the sediments at Site 58 is presumably due to these sands and pebbly zones.

A hard basement was reached at 173 meters, but no core was recovered. Another hole was spudded, specifically to obtain a basement core; but, during retrieval of a first core, sands and gravel (possibly mainly pebbles suspended in the rising column of drill water) packed around the drill pipe and flooded 230 feet up the inside, sticking the drill string. In the end, it proved necessary to shoot off the lower bottom hole assembly at the second bumper sub. An abundance of chips of fresh porphyritic basalt in the upper bumper sub makes it highly probable that basement here is of the same type as that at Site 57, and confirms the conclusion that Site 58 was drilled in the Caroline crustal province.

Site 58 was left on July 30, on a northeastward coarse in search of old Pacific crust.

The projected track was over a rugged area that forms a kind of outlying bastion of the Caroline Ridge, onto the smooth and deeper floor of the Pacific, where the *Argo (Scan IV)* had passed on its way from Guam. On hand was a sketch of the *Argo's* Site Survey 19A, forwarded by facsimile, in an area that appeared to offer enough sediment cover for drilling, and that seemed to belong to the old Pacific crust.

At this time, the seismic profiler, which the ship had been totally dependent upon since Site 53, broke down. The ship therefore headed directly for the *Argo's* prospect 19A, geologically blind except for the bottom topography revealed by the precision depth recorder. At the northern edge of the rugged area, two asymmetrical ranges, fine illustration of a fracture zone, were crossed before reaching the flat abyssal floor at a depth of nearly 3000 fathoms. Having found a place near the *Argo* line by dead reckoning, Site 59 was drilled on July 31 to August 2. Unfortunately, there were no more massive diamond bits for an all-out attempt at deep penetration. The stratigraphic section here contains Upper Tertiary brown deep-sea clays, overlying a condensed section of Paleocene and Eocene clay with traces of chalk, lying on Cretaceous cherty brown clays with beds of lithified ash. The sequence is clearly of the old Pacific type, comparable to that seen farther north at Sites 51 and 52. Thus, the boundary between the young and old oceanic crust in this area seems to lie between Sites 58 and 59, and the authors are inclined to place it along the fracture zone at the northern edge of the mountains between these sites.

Penetration to greater depth was stopped by extremely rough drilling, presumably due to the chert. Tools were retrieved, with the expectation of finding the bit badly damaged, but this was not the case. The scientists debated the possibility of drilling another hole here in the hopes of penetrating deeper, but felt that Leg 7, which would pass through this area, would be able to do this more effectively with a better bit than any that were left. With one more beacon and two more drilling days remaining, the possibilities of either drilling a geologically blind hole in the Pacific ocean floor or crossing the trench axis to drill the *Argo's* prospect 18A, on the west wall of the trench east of Guam was considered. The site near Guam was attractive chiefly as a base for insight into the history of the Mariana Trench and the outer island arc; and this was chosen as the last drill site.

Karig's sketch of the *Argo's* profile (Prospect 18A), transmitted earlier by facsimile, showed a thick sequence of sediments (no basement visible), containing an unconformity. The sediments above this unconformity thin rapidly from west to east, that is, down dip, by a progressive pinching out of beds at the base (a case of "down-dip overstep"). The *Glomar Challenger's* profiler, which began to operate marginally as the ship steamed on to the drill site (in response to heroic labors by the electronics staff), confirmed parts of this picture.

Hole 60.0 was drilled to 348 meters, in a sequence of Miocene pyroclastics, chiefly pumice ash with an admixture of planktonic fossils, and interbeds of resedimented volcanic sand. The unconformity was probably penetrated, without a major change in age or rock type. No evidence of a shallower episode was encountered.

Drilling became progressively slower with depth, due to increasing consolidation. The hole was abandoned in

Lower Miocene pyroclastics the night of August 4 to 5, in order to meet the scheduled arrival time at Apra Harbor, Guam, on the morning of August 5.

Site 60 is thus, essentially, a counterpart to Sites 53 and 54, drilled in a pyroclastic apron of similar age extending east from the center (Mariana) Arc.

In retrospect, an eventful and exciting voyage of exploration had been completed. Thirty-four holes had been drilled at 17 sites, and 125 cores had been recovered and processed with an aggregate length of 684 meters. Site 51 set records as having been drilled in the deepest water attempted to date (5981 meters), and having required the longest drill string ever lowered from a floating platform.

Regarding scientific achievements, it is necessary to differentiate between those immediately apparent, those which will emerge from the work of the shipboard scientists and the onshore laboratories over the next few months, and those which will appear yet later, chiefly from work on the 684 meters of core, subsequent to the concise report. The authors deal only with the first of these categories.

(1) The primary charge was to contribute to the understanding of the origin and history of the ocean basins. They found parts of the northwestern Pacific to date back at least to the Late Jurassic, and to represent the oldest part of the Pacific ocean, perhaps the oldest truly oceanic area left in existence. Unfortunately, technological limitations–the need for 100 meters + of comparatively soft sediment at the surface, and the inability to penetrate much chert–crippled the efforts to determine the character and age of the oceanic basement in this old region.

In abrupt contrast to this old province, the crust of the Philippine Sea and possibly that of the Caroline Ridge appears to be young, roughly Oligocene. At least, this is the age of lavas underlying the sediments, and the authors are inclined to the view that the regional outpouring of these lavas corresponds to the creation of new basement or the thorough remodeling of old basement beneath these areas. The contact of the old and new crustal provinces lies along the north-south portions of the Mariana Trench, and, southeast of Guam, along the fracture zone bordering the general Caroline province against the deep Pacific Ocean floor.

(2) These observations pose geometrical problems of sea-floor growth. On the one hand, it is conceivable that a counter-clockwise extension of the East Pacific Ridge once encircled the northern Pacific on the north and west, and that the young crust of the Philippine Sea and adjacent areas was developed from this now defunct part of the Mid-Oceanic Ridge

On the other hand, it seems conceivable that new oceanic crust was (and perhaps still is) formed not only by axial accretion in the Mid-Oceanic Ridge, but also by other processes and at other places.

(3) The young oceanic crust (basement) being formed by volcanic processes in the Mid-Oceanic Ridge shows a rough topographic surface. This has led many geologists concerned with the interpretation of oceanic seismic reflection profiles to limit the term basement to a reflective layer which shows no coherent reflections and *which has a rough surface.* The older parts of the Atlantic and Pacific show large areas in which the sediments are underlain by "opaque" appearing material with a smooth, flat surface, and this was termed "Horizon B" in the Atlantic and "Horizon B′" in the Pacific (Ewing *et al.,* 1968). Conceivably this could represent either a peculiar sedimentary mantle over a rough basement, or a widespread surface of planation prior to deep submergence, or a true volcanic oceanic basement formed in a manner distinct from that grown in the Mid-Oceanic Ridge; or, perhaps, a kind of plateau volcanism on the ocean floor, subsequent to and mantling an older basement.

On the Shatsky Rise, Hole 50 came nearer to sampling this old B′ than has any hole drilled to date. The recovery of a basalt pebble and a piece of jasper suggests (but does not prove) that in this area B′ is the surface of a volcanic complex.

On the Caroline Ridge (Sites 55 to 58) the sediments are underlain by a young B-type surface, and this is the surface of prophyritic basalt flows. Thus it is shown here that B-type surfaces can be of volcanic origin. It remains to be seen whether these young lavas of the Caroline Ridge are underlain by equally young ultramafic crust, or whether they only mantle on older crust.

In the field of sedimentology, the most impressive generalization that has come out of Leg 6 is one concerning the development of chert: back to sediments of Oligocene age, opaline skeletons tend to be common and well-preserved. In the Cretaceous, on the other hand, they are rare; most of these old siliceous skeletons are calcitized or represented by crude quartz molds. Correspondingly, chert was uniformly encountered in Cretaceous and older sediments, but (with exception of Site 44) not in the Tertiary. This does not wholly correspond with the experiences in the Atlantic, where Eocene cherts are widespread. Nevertheless, these observations in sum-total indicate (1) that the formation of chert is normally a late diagenetic process, and (2) that most Mesozoic or older oceanic sediments are very cherty.

Eventually data from Leg 7 will contribute more to the problem of the origin of cherts, to the problem of carbonate compensation depth, and to a variety of other sedimentary phenomena.

In the field of paleontology and biostratigraphy, Leg 6 has provided the first essentially complete stratigraphic sequences in pelagic carbonate facies for the northwest Pacific realm. At various sites Radiolaria are associated with coccoliths and foraminifera, and it will thus be possible to cross-correlate radiolarian zones with those of the calcareous fossils. The Tertiary Radiolaria of the Shatsky Rise area show assemblages distinct from the better known tropical ones, and may represent a boreal province, allied to the California faunas. The foraminifera and coccoliths do not show such a pronounced biogeographic differentiation, though the Late Tertiary Shatsky Rise nannofossil assemblages appear somewhat impoverished.

In another kind of retrospect, the participants have behind them sixty days in which men—of radically different backgrounds and talents (seamen, drilling crews, scientists, technicians, engineers), of different nationalities (American, Russian, British), and attached to a multitude of different organizations—combined their efforts and worked in harmony. Thus, they functioned as an operating arm or, and supported by, the Scripps organization, with the help of the *Argo's* Site Surveys, aided by the recommendations of the JOIDES committees, and under sponsorship of the National Science Foundation. This voyage shall always be a happy memory.

EXPLANATORY NOTES

Responsibilities of Authorship

In the chapters which follow the authorship of Part 1: Shipboard Site Reports, was essentially a joint effort of the shipboard scientific party with responsibility on board (listed alphabetically) as follows: Background, Strategy, Objectives and Conclusions—A. G. Fischer, B. C. Heezen; Nature of Sediments—R. E. Garrison, A. P. Lisitzin, A. C. Pimm; Physical Properties—R. E. Boyce, A. C. Pimm; Paleontology—D. Bukry, R. G. Douglas, S. A. Kling, V. Krasheninnikov.

Further, in Part III: Cruise Leg Synthesis, certain members have made the primary contribution. In recognition of their effort and also to facilitate the answering of questions relating to this work, the initials of the primary author(s) have been placed after the subtitle of the appropriate section. All contributors to a particular chapter in Part III are listed under the chapter heading.

The scientific editing and compilation of this volume were the responsibilities of A. C. Pimm, who was ably assisted by the Deep Sea Drilling Project scientific division.

Survey Data

Presite survey data collected by the Scripps Institution of Oceanography vessel *Argo* is given in Chapters 19 and 20 of Part II of this volume, under the authorship of the respective Chief Scientists. Geophysical profiles and survey data for each site are given in Chapter 19.

The *Glomar Challenger* underway data (between sites) is given in Chapter 21, Part II.

Shipboard Scientific Procedures

These are described fully in Appendix II, pages 452 to 490 of Volume II Initial Reports of the Deep Sea Drilling Project.

A detailed account of the methods used in Physical Property Measurements is given as Appendix II of this volume.

Shore Laboratory Studies

Methods used in the Shore Laboratory Studies are in many cases given or referenced in the relevant chapters. Methods used in the Deep Sea Drilling Project shore laboratories for grain size, carbon carbonate, and X-ray diffraction determinations are given in Appendix III of Volume IV Initial Reports of the Deep Sea Drilling Project.

Biostratigraphy

The biostratigraphic framework used for Leg 6 is given in Appendix I of this volume.

Data Presentation

The data obtained from each site during Leg 6 are presented in this report in the following manner:

(1) site data and main results;

(2) background objectives and strategy;

(3) operational data;

(4) nature of sediments;

(5) physical properties;

(6) conclusions;

(7) graphical presentation of the Hole Summary data followed by a Core Summary which is displayed in four parts—lithologic description, physical properties, paleontological summary, and core photographs; and finally where conditions warrant a Section Summary. Lithological symbols and explanation of text used in the graphical displays are given as Figure 4.

Depth Information

In the process of staking a drillsite, a sounding in standard units (tau = 1/400 sec travel time) is obtained from the precision depth recorder. This sound is converted to

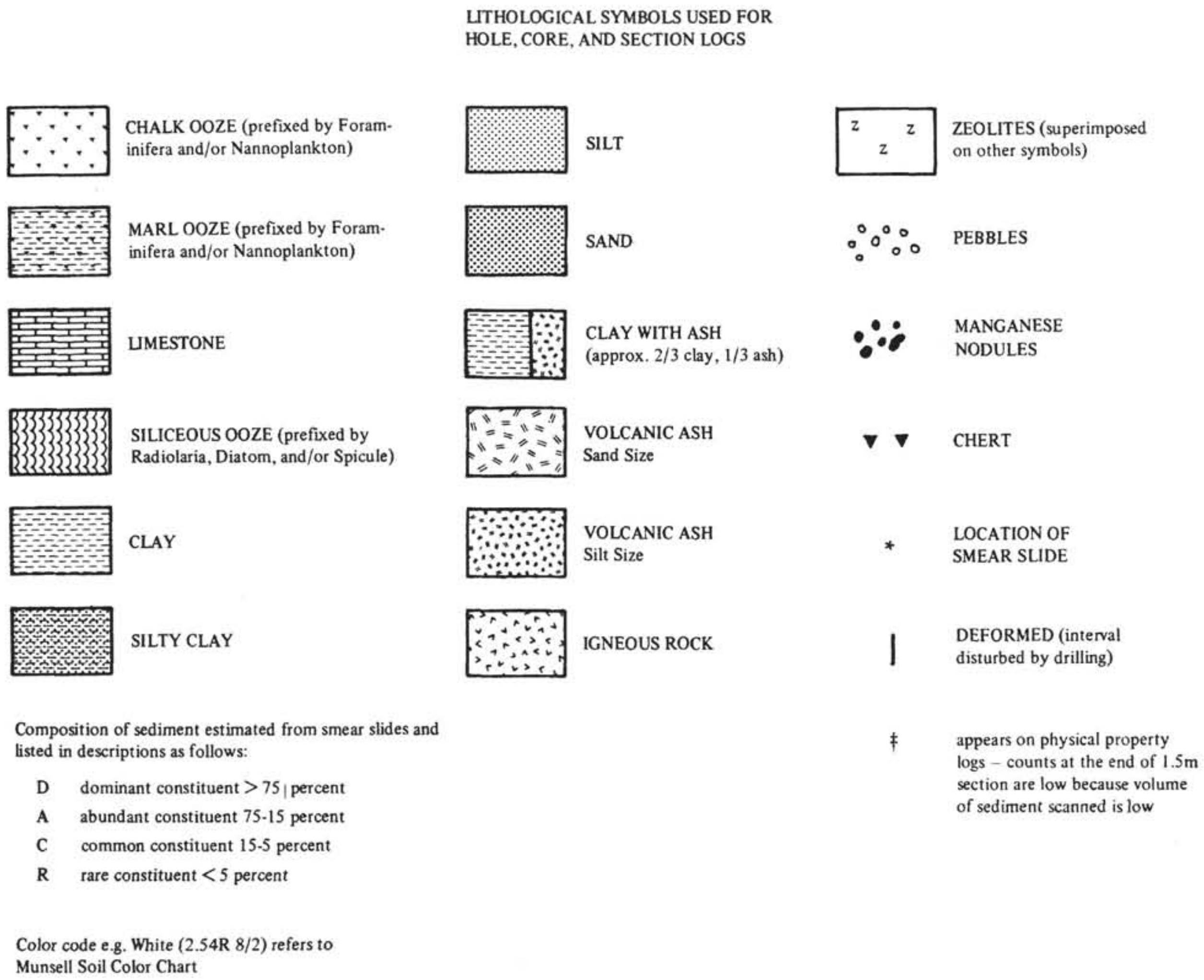

Figure 4.

water depth in meters by use of Matthews' tables, converted to feet, and brought to derrick floor height by the addition of 52 feet. It is used as a guide to the drillers. A second depth figure, in feet from the derrick floor, is obtained by the drillers, when bottom is felt by the drillpipe, and this is used as the basic water depth figure. This figure also may be in error–partly because of pipe stretch, partly because the surficial sediment is commonly very soft and watery, and may not be recognized by the driller.

The subsea level depths given in this report are corrected by subtracting the height of derrick floor above sea level (33 feet), and are given in meters.

REFERENCES

Ewing, M., Saito, T., Ewing, J. I. and Burckle, L. H., 1966. Lower Cretaceous sediments from the northwest Pacific. *Science,* **152** (3723), 751.

Ewing, J., Ewing, M., Aitken, T. and Ludwig, W. J., 1968. North Pacific Sediment Layers Measured by Seismic Profiling. *Geophysical Monograph No. 12.* The Constant Upper Mantle of the Pacific Area. American Geophysical Union, Washington, D. C. 147.

Ewing, M. *et al.,* 1969. *Initial Reports of the Deep Sea Drilling Project, Volume I.* Washington, D. C. (U. S. Government Printing Office).

Karig, D. E., 1970. Ridges and basins of the Tonga Kermadec Island Arc System. *Geophys. Res.* **75**, 239.

Maxwell, A. *et al.,* 1970. *Initial Reports of the Deep Sea Drilling Project, Volume III.* Washington, D. C. (U. S. Government Printing Office).

McManus *et al.,* 1970. *Initial Reports of the Deep Sea Drilling Project, Volume V.* Washington, D. C. (U. S. Government Printing Office).

Peterson, M. N. A. *et al.,* 1970. *Initial Reports of the Deep Sea Drilling Project, Volume II.* Washington, D. C. (U. S. Government Printing Office).