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Scientific Aspects of Well Logging in Deep Ocean Drill Sites on Leg 48 - Biscay and Rockall Areas

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Scientific aspects of well logging in deep ocean drill sites on Leg 48 – Biscay and Rockall areas

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Downhole logging techniques are already widely used in the petroleum and mining industries. Despite strong recommendations, no logging has been attempted before in holes drilled on the continental margin areas where such techniques might reasonably be expected to produce worthwhile results. These logs will ideally be a complete and continuous record of the interval surveyed, will provide valuable correlative information against cores, back-up information for the seismic record, and will suggest general lithologies where no core exists.

This paper highlights and comments on the degree to which these logs succeed in their objectives and suggests alternative tools and techniques that might be used in the future. Recording the logs digitally at the well site has enabled the full interplay of computer techniques to be used to help in the analysis. Valuable additional information from the logs suggests re-examination and further analyses of the core material.

Introduction

Through the Institute of Oceanographic Sciences of the Natural Environment Research Council, the Department of Energy became aware that no downhole logging services were scheduled for boreholes to be drilled on Leg 48 of the Deep Sea Drilling Project.

In view of the expected valuable additional information to be gained by the use of such logging techniques, especially in sedimentary sequences the Department of Energy decided to fund such a project.

1. General conclusions and recommendations relating to logging surveys on Leg 48

(1) Downhole logging devices provide a very useful contribution to the information that may be gained from the Deep Sea Drilling Project. In particular, they provide:

(i) a continuous record of events with depth in the borehole;
(ii) a valuable correlative tool in conjunction with cores and physical properties measurements;
(iii) an inferred lithology when the core recovery is poor;
(iv) a tie for the seismic data;
(v) direct comparison of the physical property measurements with similar measurements recorded on the logs;
(vi) logging breaks which may have lithological and/or sedimentological significance;
(vii) suggestions for additional tests on core material to confirm inferences from the logs.

(2) A caliper survey (with a reliable range up to 16 in (40.65 cm) with the current size of drilled hole) should be run with each porosity tool.

(3) Where banding and interbedded sedimentary sequences are likely, logging tools with good thin bed resolution should be used.

(4) A simplified form of dipmeter suitable for through-drillpipe entry should be used, especially when a series of holes is planned within a restricted sedimentary environment.

(5) Shipboard scintillometer scanning of cores would provide a valuable additional correlative measurement for direct comparison with the gamma ray logs.

(6) Selected spectrometry tests should be carried out to determine which mineral assemblages are responsible for gamma ray anomalies seen on logs that are not directly related to clay mineral content.

(7) Core descriptions should have some form of hardness indicator which could be related to the caliper and other logs.

2. Equipment

(*a*) *General*

After consultation with logging service companies, and in the light of the special drilling techniques involved, a logging suite was chosen, bearing in mind the following constraints:

(i) the maximum internal diameter (i.d.) of the drill pipe available for tool entry into the open hole was in the range 4–$4\frac{1}{8}$ in (10.15–10.5 cm);
(ii) the drilled hole diameter – in most cases this was 10 in (25.4 cm);
(iii) the type of fluid in the hole for logging runs;
(iv) safety considerations.

In general, full-bore conventional logging tools could be used, and were preferred to slim hole, reduced-diameter tools. Additionally, there was some constraint as to the availability of tools for the duration of Leg 48.

The suite that was finally chosen consisted of combination tools as follows:

borehole compensated sonic/gamma ray/caliper/variable density log (BHCS/GR/CAL/VDL),
compensated neutron/formation density/gamma ray (CNL/FDC/GR),
induction 6FF40/spherically focused log/gamma ray/spontaneous potential (ISF/GR/SP),

and, as a back-up tool,

induction 6FF40/electric log/short normal/SP (IES/SP).

(*b*) *Log measurements*

(i) In the case of the CNL/FDC tool the maximum eccentralization available was 12 in (30.5 cm), and in holes over this size, application of the measuring device to the formation was usually unsatisfactory.
(ii) Owing to infill and bridging, tools were most often unable to reach total drilled depth.
(iii) The caliper device of the sonic tool suffered from partial and complete jamming, often rendering the absolute measurement values unreliable. In the enlarged holes the sonic, for the most part, reads fluid velocities.
(iv) For reliable results the VDL requires centralization within $\pm\frac{1}{8}$ in (0.32 cm) and this was seldom the case in practice. This log was included in the hope of detecting and confirming possible fracture zones in carbonates.

(v) Most of the recorded SPs were of limited use and there was evidence of magnetism and bimetallism. The SP measurement can, however, make a valuable contribution and every effort should be made to record a valid curve.

In spite of these difficulties in very adverse logging conditions which have reduced the absolute quantitative value of the logging measurements, the qualitative log values have provided a very valuable contribution in the form of:

(i) a continuous record of events with depth in the borehole;
(ii) a valuable correlative tool in conjunction with cores and physical properties measurements;
(iii) an inferred lithology when the core record is poor;
(iv) a tie for the seismic data;
(v) direct comparison of the physical properties measurements with similar measurements recorded on the logs;
(vi) logging breaks which may have lithological and/or sedimentological significance;
(vii) suggestions for additional tests on core material to confirm inferences from the logs.

(*c*) *Tool design*

One of the biggest problems encountered was the lack of a reliable caliper curve in conjunction with the logging runs. Ideally, a caliper should be run with each of the porosity combination tools.

Some thought should be given to a motorized spring feeler type of caliper in preference to the bow-spring design and preferably the caliper should have a reliable range, up to 16 in (40.65 cm) with the current size of drilled hole. Devices are already in use for logging using this approach in holes up to 21 in (53.3 cm) diameter.

(*d*) *Alternative logging devices*

In several boreholes, cyclic sequences of sedimentation were encountered which were well documented in the cores. In hindsight, it would have been useful to have selected a tool with good thin bed resolution – Laterolog 3 type or variable configuration type Guard Log, or, better, some modified type of microtool with small electrode spacing. This is recommended for further boreholes where banding and interbedded sedimentary sequences are likely to be met.

Geologists would no doubt be interested in a simplified form of dipmeter suitable for through-drill pipe entry especially when a series of boreholes is planned within a restricted sedimentary environment.

(*e*) *Additional shipboard equipment and measurements*

In view of the conventional continuous coring of boreholes it would be useful to have some form of shipboard scintillometer scanning of cores, which should prove a valuable additional correlative measurement for direct comparison with the gamma ray logs. This would be especially valuable in long sequences of similar lithologies where radioactivity levels (clay mineral percentages?) are changing.

Selected spectrometry tests should also be carried out to determine what mineral assemblages are responsible for GR anomalies seen on the logs, and which are not directly related to clay mineral content. Comparison of the GR curve with the SP often highlights such anomalies.

In particular cases the logs may infer an interbedded sequence of alternatively harder and softer rock material and it would be useful in core descriptions to have some form of comparative hardness indicator to confirm this.

TABLE 1. LOGGING SURVEYS

IPOD 401	IPOD 402A	IPOD 403
surveys: BHCS/GR/CAL/VDL ISF/SP/GR CNL/FDC/GR remarks: (1) no reliable caliper (2) all boundaries in site summaries recognized on logs in open hole (3) further subdivision suggested by well defined logging breaks	surveys: BHCS/GR/CAL IES/SN/GR CNL/FDC/GR remarks: (1) caliper jammed close below 2550 m (2) cycle skipping 2520–2551 m (3) hole washed out to 2551 m (4) unable to tie in logging markers for subunits 3A, 3B and 3C	surveys: BHCS/GR/CAL remarks: (1) no other logging runs possible owing to weather conditions (2) all boundaries in site summaries recognized on logs in open hole (3) part of log missing near TD (4) partial jamming of caliper device suspected (5) cross-plot techniques less effective
IPOD 405	IPOD 406	general
surveys: BHCS/GR/CAL ISF/SP/GR CNL/FDC/GR remarks: (1) maximum hole size exceeds 30.5 cm to 3222 m; logs less reliable quantitatively (2) onset of silicification clearly shown on logs (3) core/log match difficult due to poor core recovery	surveys: BHCS/CAL/VDL IES/SN/SP CNL/FDC/GR remarks: (1) GR failed on sonic run (2) rhythmicity on FDC/CNL curves to 3185 m owing to hole conditions (3) sonic–density cross-plots show good discrimination of all units and subunits (4) no GR taken through to sea bed	general (1) in spite of adverse borehole conditions, qualitative information from logs extremely valuable (2) can predict events with greater confidence when caliper considered reliable (3) in no case did logs reach total drilling depths due to infill and bridging

3. SUMMARY OF LOGGING SURVEYS

Surveys were run in boreholes IPOD 401, 402A, 405 and 406. In Site 403 only one logging run could be made (BHCS/GR/CAL) owing to deterioration in weather conditions and in Site 404 no logging runs were possible. Table 1 lists the logging surveys carried out. Figure 1 (*a*) shows the technique employed for logging with the drill pipe as a riser.

Owing to space restrictions, the more detailed description of logs from only one drill site is possible.

4. REPORT ON THE DOWNHOLE LOGGING RESULTS OF SITE 406

All depths quoted in this report refer either to depths marked on the logging runs with the density–neutron as the base log or their equivalent sub-sea bottom depths.

The following logs were run:

borehole compensated sonic/caliper (BHCS/CAL),
variable density log (VDL),
compensated neutron/formation density/gamma ray (CNL/FDC/GR),
induction 6FF40/electric log/short normal/SP (IES/SN/SP).

The gamma-ray log on the sonic run failed and the only gamma-ray available is that recorded on the density–neutron run.

The readings on the density–neutron log show a cyclic rythmicity down to 3250 m (356 m) with a period of about 10 m on the density log. The rythmicity continues down to 3585 m (691 m), but the period appears to change to around 6 m. These readings appear to be a function of hole conditions and are not related directly to lithology. The sonic log is less affected by these borehole conditions.

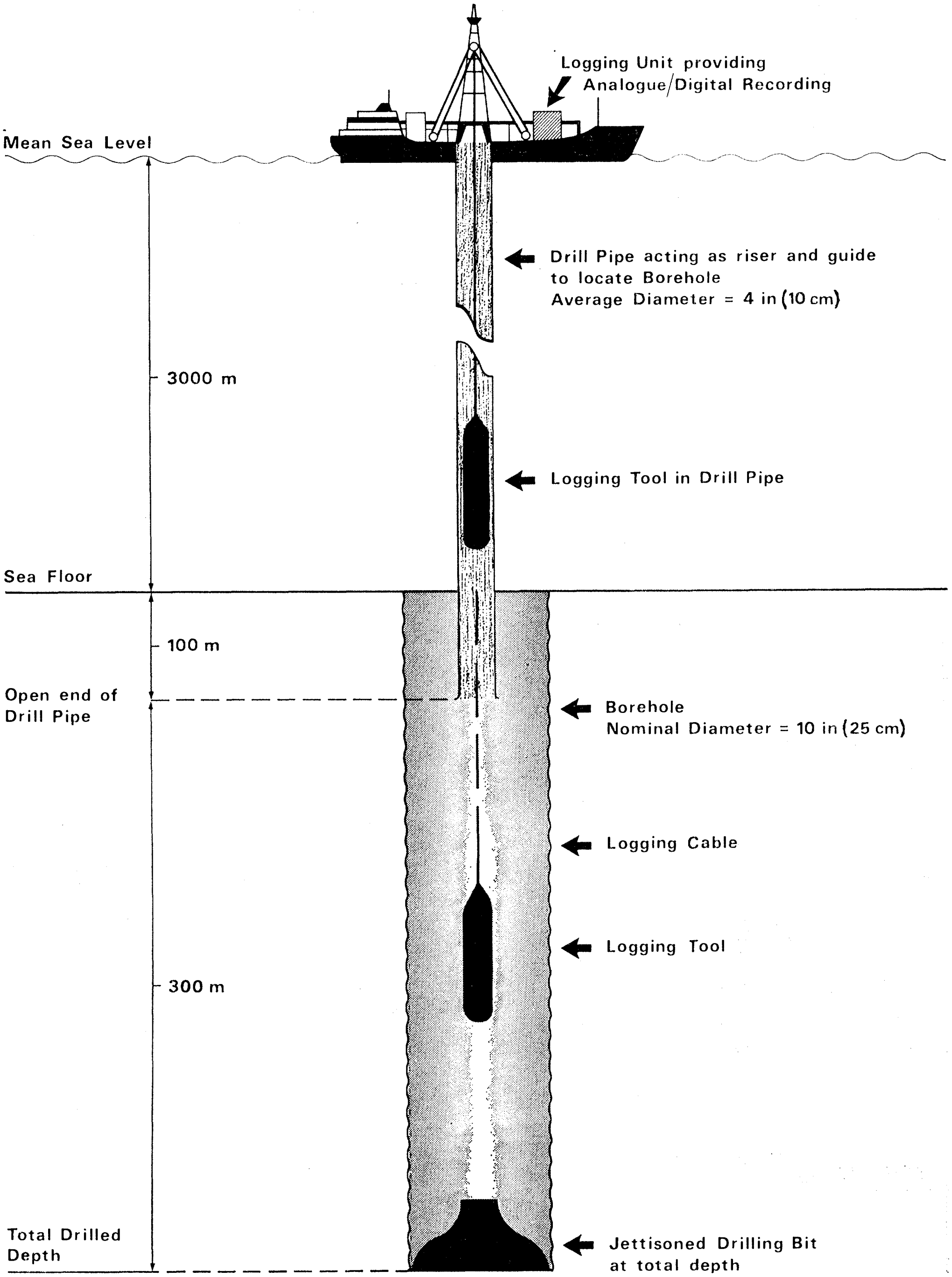


FIGURE 1. (*a*) Logging technique with the drill pipe as a riser.

In discussion of the lithological units and subunits, the information and depths have been used from the site summaries. Figure 1 (*b*) shows how well these match the logging results. Where depth discrepancies appear artificial, a double arrow marking is used. Other logging markers which may have lithological and/or sedimentological significance have been additionally marked in the depth column.

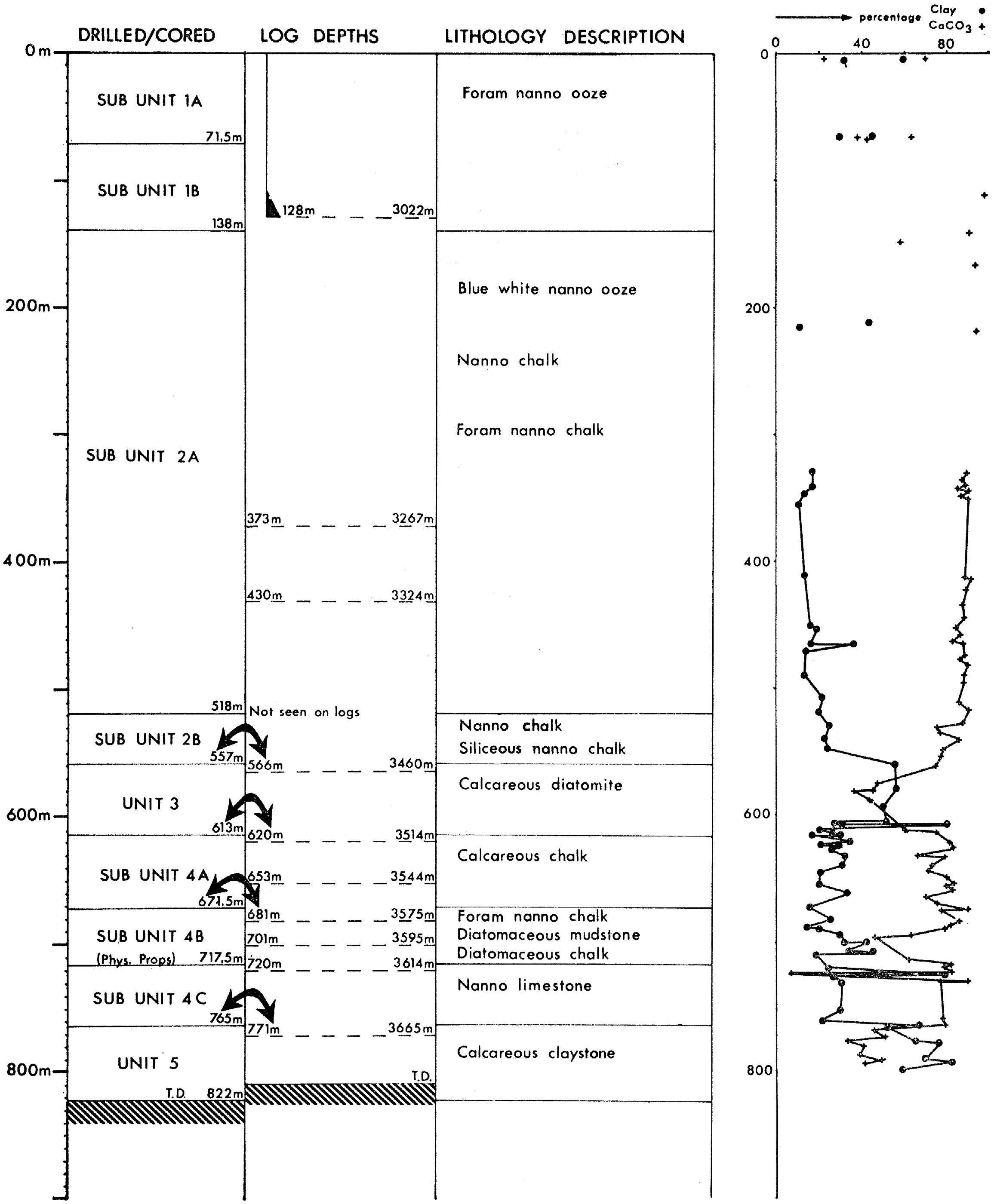


Figure 1. (*b*) Comparison of log with core depths at Site 406.

The SP suffers from magnetism and bimetallism and is of limited use. The physical properties log supports very well the Schlumberger logs throughout the section and ties the core–log correlations extremely well. Two of the most important physical properties measurements, the percentage of $CaCO_3$ and of clay, are included in figure 1(*b*).

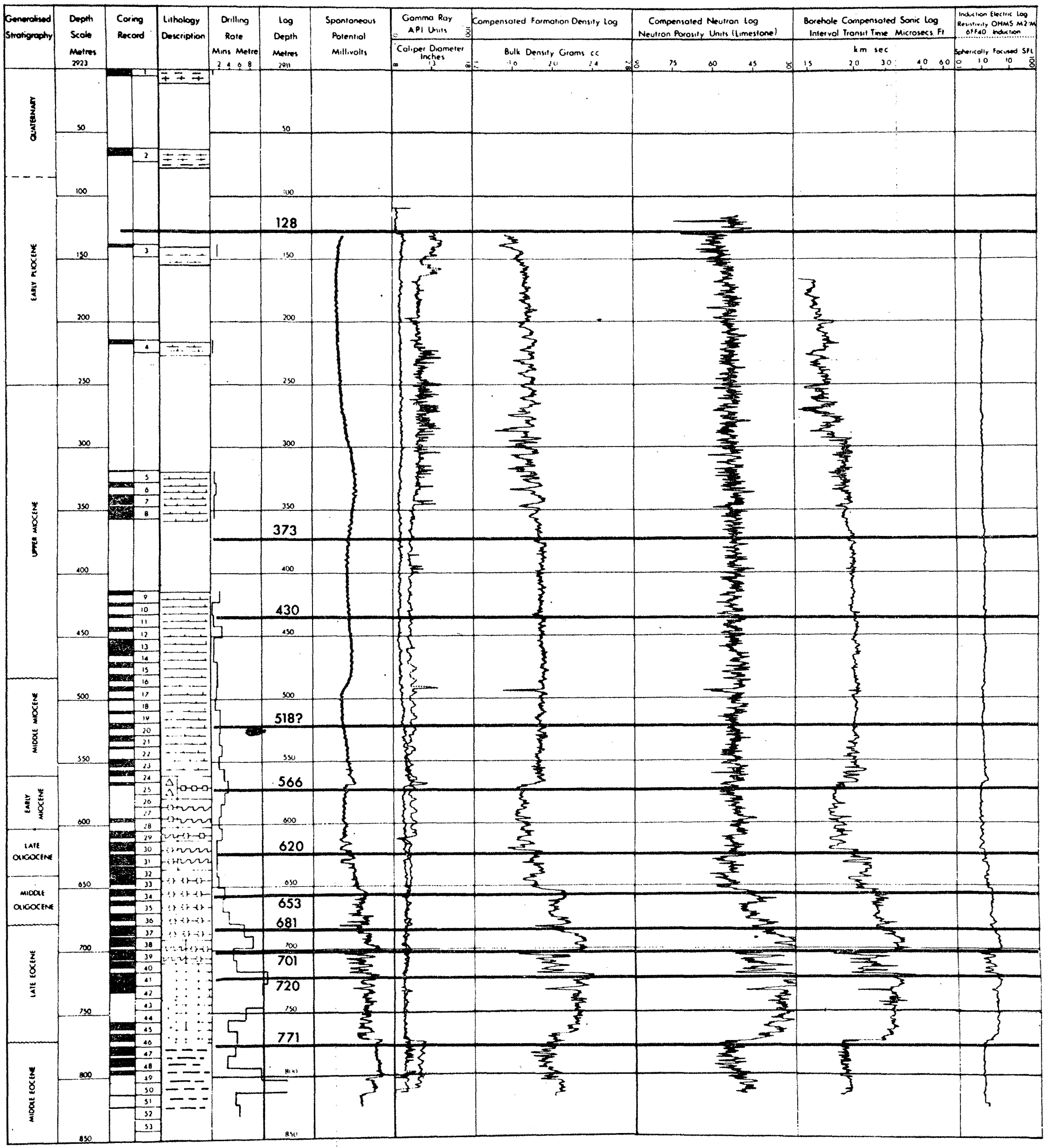


FIGURE 2. Composite of main logging curves depth matched against cores plus a generalized stratigraphic description.

Log interpretation

Figure 2 is a composite of the main logging curves depth matched against cores plus a generalized stratigraphic description. No gamma ray curve was available from entry into the drill pipe up to seabed. Entry into the pipe was recorded on the density–neutron log at 3022 m (128 m).

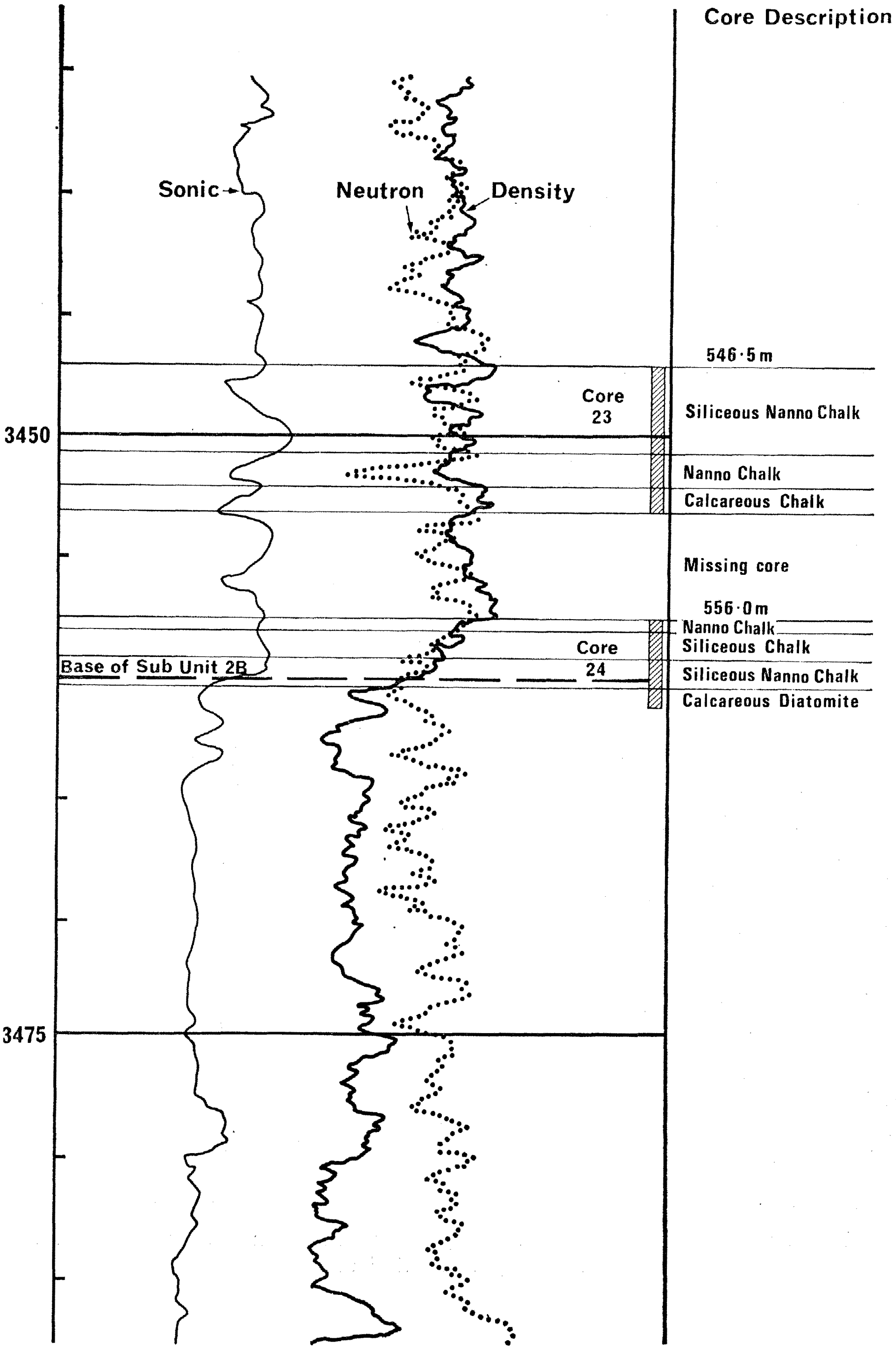


FIGURE 3. Density–neutron log and sonic curve of subunit 2B at Site 406.

Subunit 1A: 2894–2965.5 m (0–71.5 m)

No logs were recorded over this interval.

Subunit 1B: 2965.6–3032.9 m (71.5–138.0 m)

The only supporting evidence for the base subunit marker at 138.0 m appears on the short normal electric log at 3033 m (139 m). Although there is an increase in the density reading at the same depth, we are in a zone of too greatly enlarged a hole to count this as very reliable support. The sonic curve reads mainly fluid velocities down as far as 3058 m (in the range of 194–202 μs). No cores were taken over this subunit interval.

Subunit 2A: 3032–3412 m (138–518 m)

There is no evidence from the logs of any marked change of lithology or environment at 518 m.

On the sonic, there is a general trend of increasing velocity with depth down to 3267 m (373 m). From this depth downwards, the sonic plateaus at a steady value of 145 μs. This break is also supported by a relative deflexion on the density–neutron curves and an inflexion point on the SP, and so an event of some significance occurs here. Unfortunately, there are no cores covering this junction point.

The steady increase of velocity with depth is due to compaction effects (down to 373 m). Even though there is no marked change in lithology below 373 m, the density and sonic values stabilize and the formations become markedly more competent through to 430 m.

Some evidence of a further change in lithology occurs at 3324 m (430 m), where the sonic reading moves to a lower median value of 141 μs and the density reading moves to a slightly higher plateau. Again, there is no core recovery to help suggest the cause.

Subunit 2B: 3412–3451 m (518–557 m)

The base of the unit is well defined at 3460 m (566 m) and all the logs show this to be a major lithological break. Figure 3 shows the density–neutron log on a 1:200 scale with the sonic curve overlaid. The core descriptions have been transferred into the right-hand column for easy cross-reference. This figure shows that information from the logs supports the core observations and physical properties log very well. The most striking indication is the uniformly high $CaCO_3$ content and the sharp drop at the lower subunit boundary accompanied by a sharp increase in the silica content. The change in the cores is from conventional nanno chalk through siliceous nanno chalk to calcareous diatomite. The change is also well marked on figure 1 (*b*) in the physical properties column.

There is a high GR peak at 3461 m, which is not explained by an increase in the clay mineral content (smear slides show consistent average clay mineral content in the range 20–25 %) a concentration of a specific radioactive mineral may be the cause. As this peak lies within the interval covered by core 24 it would be interesting to run a scintillometer scanner over this core to check:

(*a*) that the peak is genuine,

(*b*) if confirmed, which radioactive isotope is present, by running a spectroscopic analysis.

Unit 3: 3451–3507 m (557–613 m)

The main lithology in this unit is calcareous diatomite ($CaCO_3$ 35–40 %, silica 50–60 %). The logs place the lower boundary of this unit at 3514 m (620 m) and marks a change to calcareous chalk – siliceous calcareous chalk deposition. On the physical properties log, there is a small transition zone on entering subunit 4A and then a sharp and continuing rise on the $CaCO_3$ content to around 80 %, at the expense of silica which drops to less than 10 %.

It is interesting to note the difference in velocity measured horizontally and vertically on samples especially at the base of the unit. Cores show the laminated–interbedded character of the formation from 610 to 613 m (core depths) which is less clear on the density–neutron logs due to hole conditions. Shipboard density measurements on samples over the same interval 610–613 m further show evidence of the interbedding and changing source material.

Subunit 4A: 3507–3565.5 m (613.0–671.5 m)

The physical properties log shows that the $CaCO_3$ content is uniformly high (*ca.* 75 %) throughout the section, and the main lithology is calcareous chalk. The density, sonic and resistivity values show this unit to be more compacted than unit 3 and with interbedding less important towards the base of the subunit.

An event of some significance occurs at 3544 m (650 m) and is seen on all the logs. Neutron porosity drops from over 50 % to 30 % and less, the density increases from around 1.8 g/cm^3 to over 2 g/cm^3, sonic velocities increase and resistivity shows a marked increase. All these factors point to a reduction in porosity.

This break aligns well with a similar one seen on the physical properties log at 645 m (core depths), and reinforces all the log observations made above.

There could be some further compaction of the strata from 3544 m downwards but, additionally, a cementation effect may be present. It is also interesting to note that the caliper begins to read undersize from this depth, indicating a build-up of mud cake, and shows the formation is less friable to the action of the drilling bit. Further investigation of the material in Core 33 may help to resolve the problem. Certainly, from the logs, this would appear to be a major hiatus. From 3544 to 3575 m (650.0–681.0 m) the lithology remains consistent and is mainly calcareous chalk and nanno chalk.

Subunit 4B: 3565.5–3611.5 m (671.5–717.5 m) (see figure 4)

The upper subunit boundary shows on the logs at 3575 m (681 m). From 3575 to 3595 m there is a continuation of the carbonate deposition of unit 4A, and this consists of Foram nanno chalk interbedded with calcareous chalk. There is a steadily decreasing porosity gradient throughout this interval, shown by all three porosity logs. At 3595 m there is a marked change in lithology. The break is well characterized on the physical property log at 693 m (cored depth), with a sharp drop in $CaCO_3$ content accompanied by an increase in silica to around 15 % (see also figure 1(*b*)). There is a continuing layered sequence seen also on the physical property log through to 3613 m.

Analysis of the core from 3595 to 3613 m (701–719 m) shows the reappearance of silica in significant quantities and core descriptions show interbeds of diatomaceous mudstone with calcareous chalk – siliceous calcareous chalk predominant. The fine detail seen in the cores is lost on the logs, which tend to average these events with a resolution of about 0.5 m. It would seem from the logs and physical property determinations that the interval 3595–3613 m could well merit a subunit status of its own.

The lower boundary of subunit 4B appears to have been changed on the physical properties log from that given in the site summary and, in this case, only the physical properties reference depth has been used.

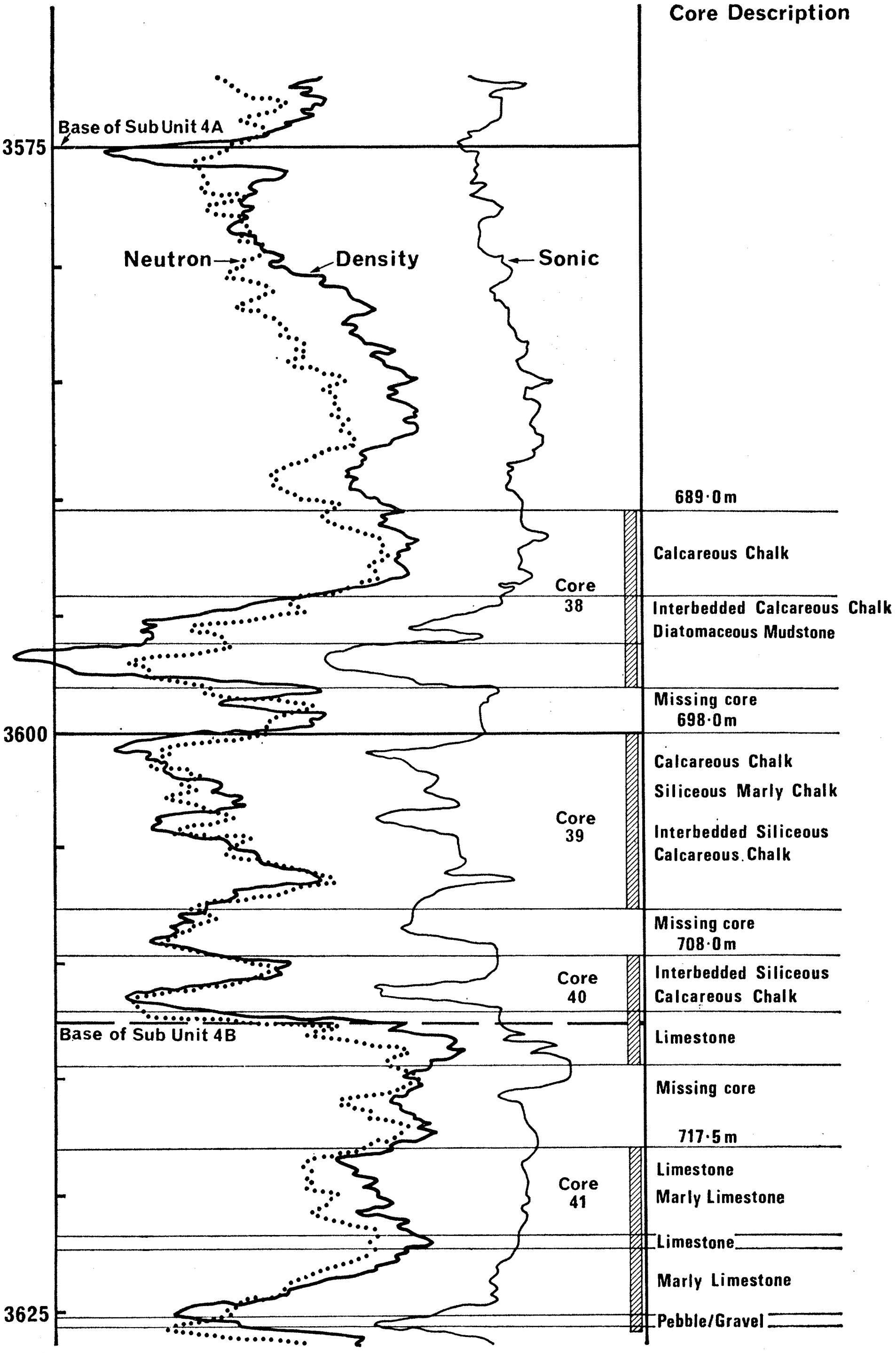
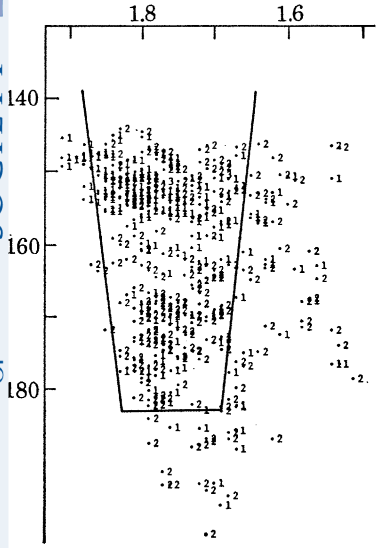
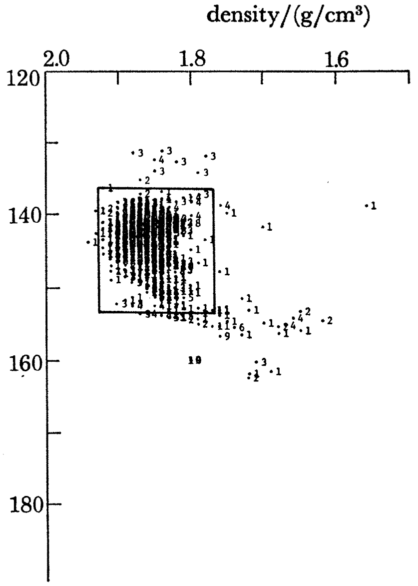


Figure 4. Density–neutron log and sonic curve of subunit 4B at Site 406.

Subunit 4C: 3611.5–3659 m (717.5–765 m) (see figure 4)

The logs mark the upper boundary at 3613 m (719 m) very clearly. Apart from a transition at the top, the remainder of the section shows remarkably uniform lithology and the sonic and resistivity curves read nearly constant values. The density–neutron readings are broadly similar but suggest an increase in porosity towards the base of the section – the lithology is limestone–marly limestone.





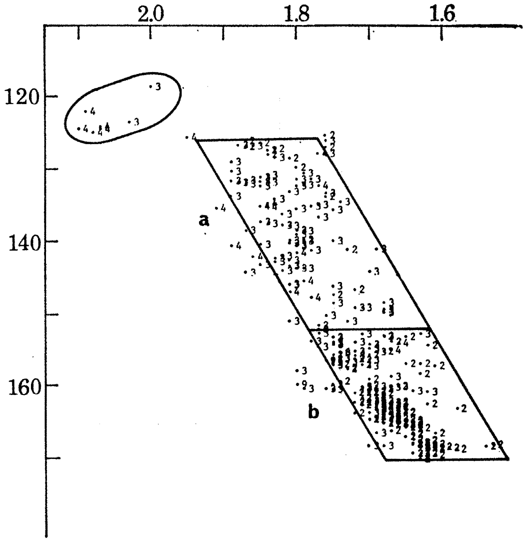


Figure 5. Density–sonic curve at 3125–3230 m (231–336 m) showing the scatter in the density values and a well defined trend towards increasing velocities with depth on the sonic.

Figure 6. Density–sonic curve at 3230–3462 m (336–568 m) showing a very consistent set of sonic readings where the curve plateaus. The scatter at the isolated g.r. peak of 3461 m is clearly shown by the values 6, 9 and 10 on the plot.

Figure 7. Density–sonic curve at 3459–3546 m (565–652 m) showing the two distinct lithologies of unit 3 and subunit 4A. This plot enhances the dramatic change in the character of the deposited material from 3544 m.

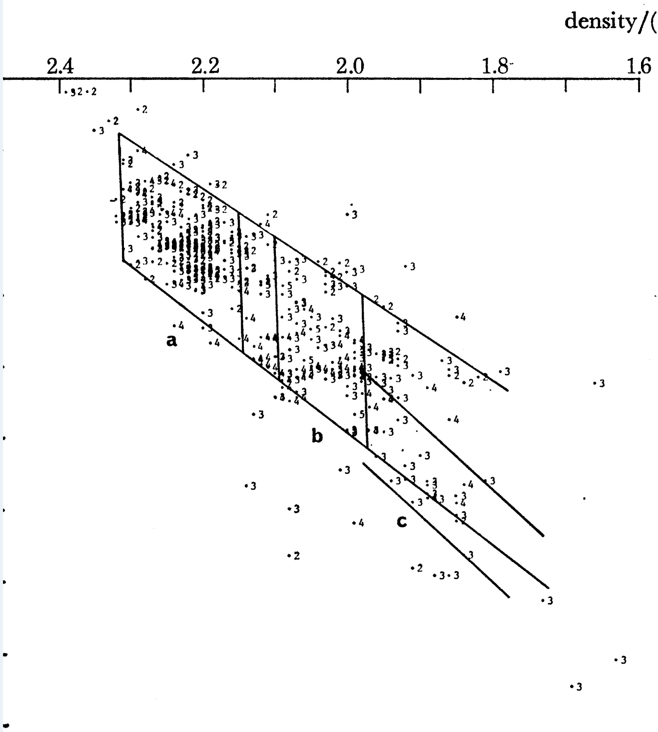
† 1 ft = 0.3048 m.

The single peak shown on all the logs 3625–3626 m is also seen on the physical property log and correlates with the basal section 6 of core 41, which contains the pebble bed.

The whole subunit shows a well developed undersized caliper with a $\frac{1}{4}$ in (0.64 cm) mud cake development, and exactly straddles the interval concerned. This confirms the competence of the formation to the action of the drilling bit and the homogeneity of the formation.

Unit 5: 3659–3716 m (765–822 m)

There is a clear and decisive break on all the logs to confirm the upper unit boundary at 3665 m (771 m). The GR moves to a much higher plateau of 32 API units, indicating an increase in clay mineral content and confirmed by the physical property log (see figure 1 (*b*)). The caliper takes on a 'ratty' appearance, although still indicating that many of the layers within the unit are permeable. The cores all confirm the increasing clay content (up to 95 %) and the $CaCO_3$ content drops on average to less than 40 %. The sonic shows a median value of 154 μs, indicating that the formation is still not normally compacted (in logging parlance a reasonable rule of thumb is that a true shale series should have a Δt of less than 100 μs to be considered normally compacted). Without a caliper on the density–neutron run, comments about the curves carry less weight. From the ‘ratty’ appearance of the sonic caliper, it is possible that readings are affected by hole conditions. The lithology is mainly calcareous claystone with many laminae and interbeds. The sonic values are rather uniform when seen on the 1:200 scale logs, but the density–neutron and caliper readings show the interbedded nature. The logs effectively bottom at around 3710 m.



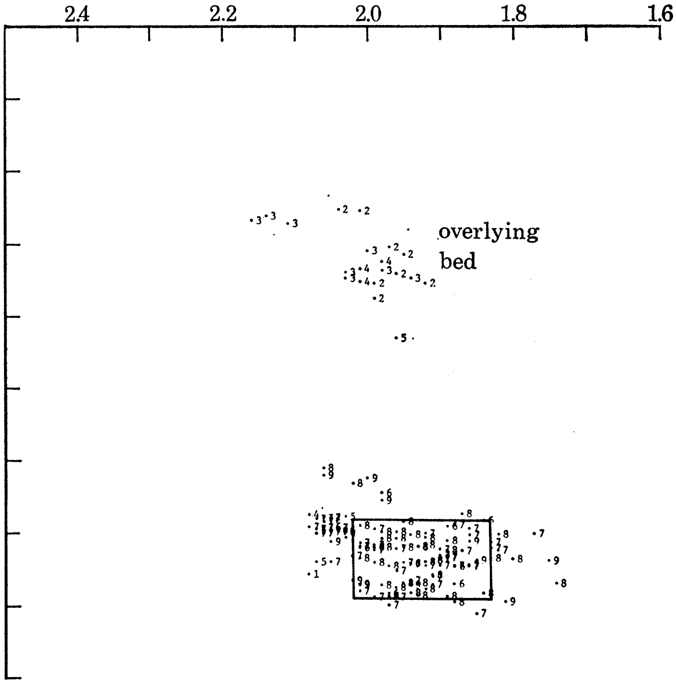


Figure 8. Density–sonic curve at 3545–3658 m (651–764 m) showing a completely new direction, thus confirming that a considerable hiatus occurs at 3544 m (650 m). There is considerable scatter in the alternating sequence from 3544 to 3612.5 m. The reappearance of diatomaceus material shows that its association is markedly different from that in unit 3. The transition points between subunit 4C and unit 5 are the only jarring note.

Figure 9. Density–sonic curve at 3658–3702 m (764–808 m) showing clearly the calcereous claystone lithology at the base with an abrupt shift of g.r. intensity from 3 s and 4 s to the diagnostic 7, 8 and 9 s of the basal unit.

Cross-plots

The cross-plots have been divided into convenient depth zones based on their logging characteristics followed by a final composite run over all zones to show the general pattern within the well. Several combination plots were run, including lithoporosity, density–neutron, neutron–sonic and density–sonic. Some of the plots gave unreliable results and only the density–sonic plots are described in greater detail.

Density/sonic ‘Z’ plot: g.r. relative intensity superimposed

This series of plots (figures 5–10) shows the more reliable discrimination of the sonic log compared with the density–neutron results, which are badly affected by hole conditions down to 3512.5 m.

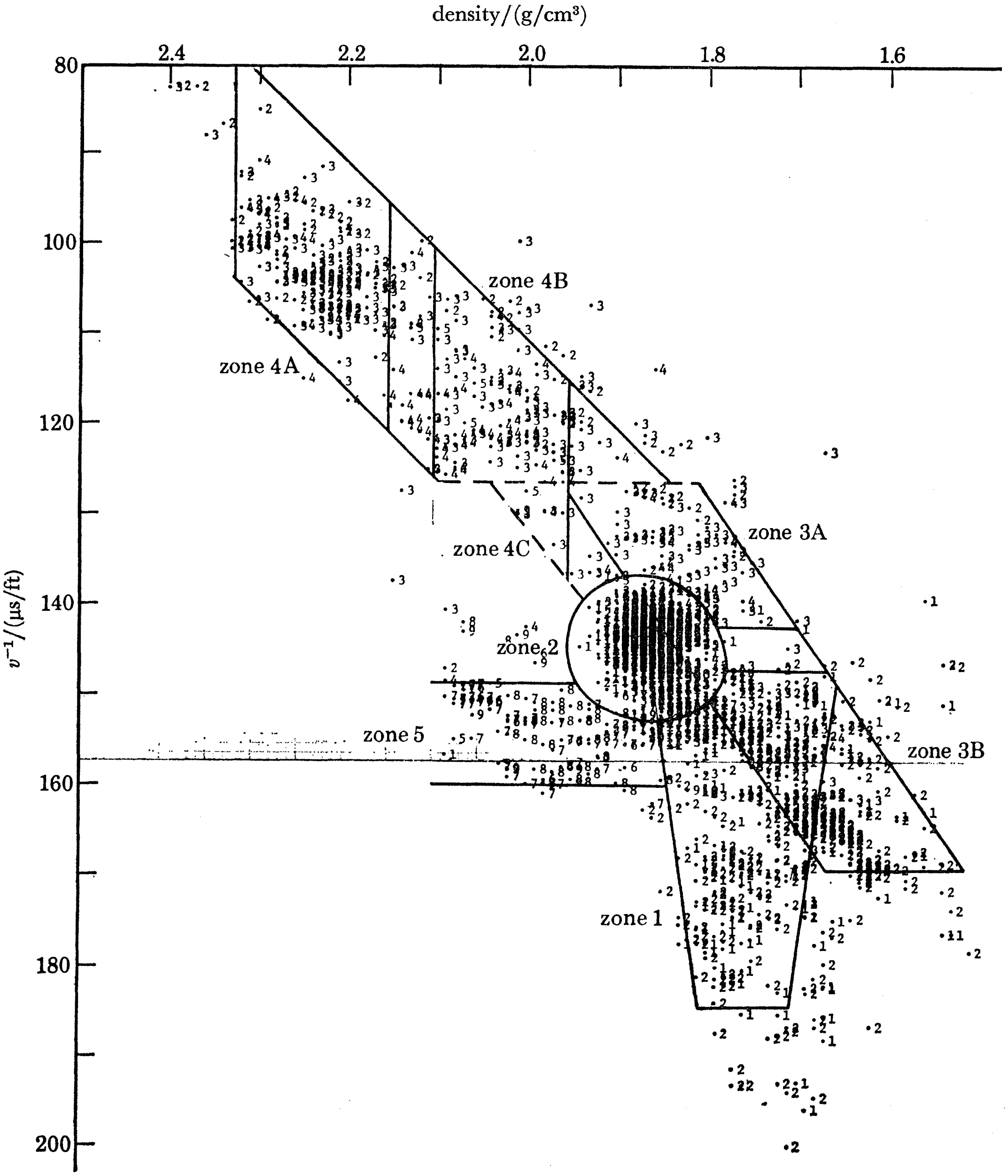


FIGURE 10. Density–sonic curve at 3125–3702 m (231–808 m) is a composite showing that practically all the major zones and units identified separately from the logs can be isolated within the plot.

CONCLUSIONS PERTAINING TO THE LOGS OF THE SITE 406

(1) The SP suffers not only from magnetism but also from bimetallism, and is of limited use.

(2) The density–neutron values are considered unreliable down to 3460 m (except in a general relative sense), where hole conditions are poor. Cyclicity is noted on the density–neutron curves down to 3512 m, due mainly to hole conditions.

(3) There is a general compaction effect seen on the sonic down to 3267 m and, from the remarks made in the basal calcareous claystone section, the rocks are still not normally compacted even at total depth.

(4) The density–sonic 'Z' plots show that cross-plotting techniques can prove extremely valuable in discriminating the main bulk lithologies encountered, especially when compaction effects are still apparent on the sonic.

(5) Two very distinct logging breaks are identified which could indicate some fundamental change in depositional environment and are not discriminated in the site summaries. These breaks occur, one at 3267 m (373 m), and another of greater importance at 3544 m (650 m). As core is available over both these depths, they are worthy of further study.

(6) There is a well developed interbedded sequence confirmed by all the logs from 3595 to 3613 m which could well deserve separate subunit status.

(7) Where the caliper is reliable we can make predictions with more confidence.

(8) The degree of accord between logs, cores and the physical property measurements is extremely good in this well.

(9) A gamma-ray recording through drill pipe to seabed would enable a better depth match with cores and should be adopted as a standard technique.

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