

# SEDIMENTS FROM THE CENTRAL PHILIPPINE TRENCH

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## INTRODUCTION

The Philippine Trench is a furrow in the sea floor – approximately 1500 km long – off the Southern Philippines and Halmahera I. The Trench is considered an active depression of the Earth's crust, which according to MOROVA (1964) may be regarded as a modern geosyncline. The Philippines are mainly built up of igneous rocks and derived sediments. Recent volcanism and active fault zones are, moreover, important geological features.

The topography of the Philippine Trench is thoroughly described in KIILERICH (1959) and, besides in the papers quoted herein, also in IRVING (1951), FISHER & HESS (1963) and MOROVA (1964). Sections of the southern part of the Trench are dealt with by KOCZY (1956) and KRAUSE (1965).

NEEB (1943, p. 189 and 196) has carefully described size distribution, lime content, and sand mineralogy of samples from the Trench area collected by the Dutch Snellius Expedition (stations 260-272). Her studies show that the samples from the Trench proper are uniform, terrigenous muds. The sand grains are mainly derived from slightly metamorphosed, calc-alkalic, basic and ultrabasic rocks. The eastern part of Mindanao is suggested as the area of origin.

FREDRIKSSON (1959) investigated a 4 m core from the southern part of the Trench (approx. 5°N). The upper 3 m of the core is a homogenous, blue, clayey

silt, poor in lime. The lowermost 1 m consists of layers of sand, mostly composed of grains of fresh, basaltic andesite mixed with calcareous tests of shallow-water origin. These sediments are probably deposited by turbidity currents. Other features of the sediments of the core have been described by various authors. A general description was given by OLAUSSON (1960); the clay mineralogy was treated by FAVEJEE (1959), the Foraminifera by RAYMENT (1959), and the calcareous Algae by HORN AF RANTZIEN (1959).

In 1951, the Danish "Galathea Deep Sea Expedition 1950-52" under the leadership of A. BRUUN, collected a series of bottom samples from the Philippine Trench and its landward slope off Northern Mindanao. The sampling locations are indicated on fig. 1; the stations are indicated by G and the station numbers as recorded by BRUUN (1959). The samples were preliminarily described by BRUUN (1951, 1956, 1959), BRUUN & KIILERICH (1955), and KIILERICH (1955, 1956, 1957). ZOBELL & MORITA (1959) investigated the bacterial flora of the sediments.

The purpose of the present examination is to describe the sedimentary lithology and elucidate the processes of sedimentation in the Philippine Trench on the basis of the given material of samples. Lastly, it is intended to investigate whether the sediments have characteristics specific for hadal depths (e. i. deeper than 6000 m).

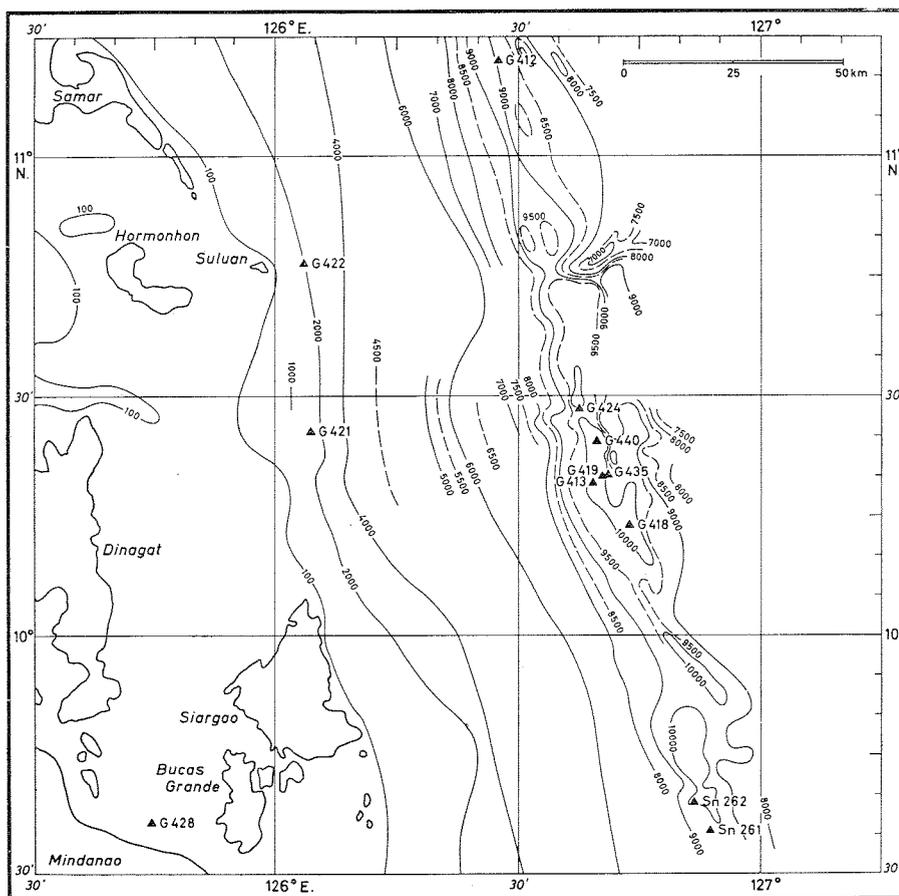


Fig. 1. The central part of the Philippine Trench with location of the samples. Depth contours in meters. Base map from KILLERICH (1959).

## METHODS

### Sampling:

Core samples were collected with a 1.7 m gravity corer with a PVA liner as described in KULLENBERG (1955, p. 89). According to experiments on gravity coring carried out by EMERY & DIETZ (1941), the core yield in soft sediments is about 60 % for short cores (<1.5 m) and approximately the same percentage for every section of core length. While drying, the length of the core shrinks about 20 %. It is, therefore, necessary to approximately double the depth of a feature, measured on the dry core, in order to obtain the true depth at the bottom. This approach has also been followed in the present investigation.

Grab samples were taken with a 0.2 m<sup>2</sup> Petersen grab, and trawl samples by trawls provided with a plastic bucket at the end and dredges along the sides (BRUUN 1959). The dredges were able to dig some tens of cm down into the bottom.

### Water content and size distribution:

In order to prevent flocculation of the clays, it was necessary to wash the salts out of the pores.

The chlorinity of the washing water was afterwards determined by titration. The original water content and the porosity of the sediments were then computed on the assumption that the chlorinity of the pore water was 19.2 ‰, like the bottom water of the Trench, and that the average density of minerals was 2.67. Repeated determinations of the water content agree within  $\pm 3\%$ . The samples were disaggregated in a Wiegner shaker for 18 hours using 0.002 M pyrophosphate as dispersing agent. With this method aggregates bigger than ca. 1.5  $\mu$  were effectively disaggregated, and delicate tests of microorganisms were not destroyed. The suspension was subsequently poured through a 60  $\mu$  sieve. The sand was dried, weighed and when possible sieved into grades. The size distribution of the silt and clay was measured by standard pipette analysis. Double determinations agree within  $\pm 1.5\%$ . Finally, the size fractions were often isolated by repeated decantation for mineralogical examination.

### Organic carbon:

Organic carbon (excluding carbonates) was determined by igniting the sample and weighing the

generated CO<sub>2</sub> in accordance with the method used by SPLITHOLST (1933). Microbiological consumption of some organic matter must have occurred after the sampling, and some volatile organic matter was probably lost during the drying of the core.

#### Carbonate:

The total amount of carbonate was determined by boiling the sample in 0.5 n HCl and absorption of the generated CO<sub>2</sub> in NaOH + BaCl<sub>2</sub> in an apparatus described by JACKSON (1964, p. 212). For small contents of carbonate (<2%) and 5 gr samples the precision was ± 0.5 %. Lime is given as weight % CaCO<sub>3</sub> of dry sample.

The calcite/aragonite ratio was determined by X-ray diffractometry as described by CHAVE (1954). Interference with the quartz 101 reflection caused some uncertainty in the delimitation of the aragonite reflections. Double determinations agreed within ± 5 %.

The Mg substitution in calcite was determined by an accurate measurement of d<sub>104</sub>. The Mg substitution was then read from the curves given by CHAVE (1952) and GOLDSMITH & GRAF (1958). The 104 reflection was in most cases divided into two peaks. The ratio between the heights of the peaks was used as a rough estimate of the ratio between the two types of calcite.

#### Classification of the sediments:

The classification of MURRAY & RENARD (1891) with amendments by OLAUSSON (1960) has been applied to the description of the pelagic and terrigenous sediments where organic components dominate.

For sediments in which tests of lime or silica constitute more than 30 %, the following rules have been applied: If a type of organism constitutes less than 10 % of the sediment, it will have no effect on the nomenclature. If it constitutes between 10 and 30 %, the sediment is called "rich" in the organism concerned. If the organism constitutes more than 30 % of the sediment, the latter will be named after the organism. The last two examples can be combined. If a sediment contains lime in undetermined or unspecified form, a general description such as "calcareous" for 10-30 %, "marl" for 30-60 % and "lime" for more than 60 % CaCO<sub>3</sub> has been used.

The classification of mineral terrigenous sediments by MURRAY and RENARD is partly based on colour (e.g. blue mud) and partly on depth of deposition. NEEB (1943) criticized this classification

by colour, and used instead a mineralogic, genetic subdivision of terrigenous muds. This is an acceptable classification, but it is very difficult to use in practice, especially in dealing with very fine-grained material. As shown by BAAS BECKING (1956), the blue colour that characterizes "blue mud" is an indication of reducing conditions. I prefer, therefore, to maintain the term "blue mud".

The classifications mentioned all contain vague indications of texture. In order to provide a basis for comparison, particularly with fossil sediments, a more precise textural nomenclature would be desirable.

In the following the size of the grains is described as follows: Stones > 20 mm > gravel > 2 mm > sand > 0.06 mm > silt > 0.002 mm > clay.

Size distributions are described by means of SHEPARD's triangular diagram, cfr. PETTIJOHN (1957, p. 24B). NB: clay is here defined as d < 2 μ instead of d < 4 μ. Mud is used as a short, informal term for coherent, soft, fine-grained sediments.

## DESCRIPTION OF SAMPLES

### Samples from the Trench:

G 412: 11°13'N, 126°21'E. 8990 m.

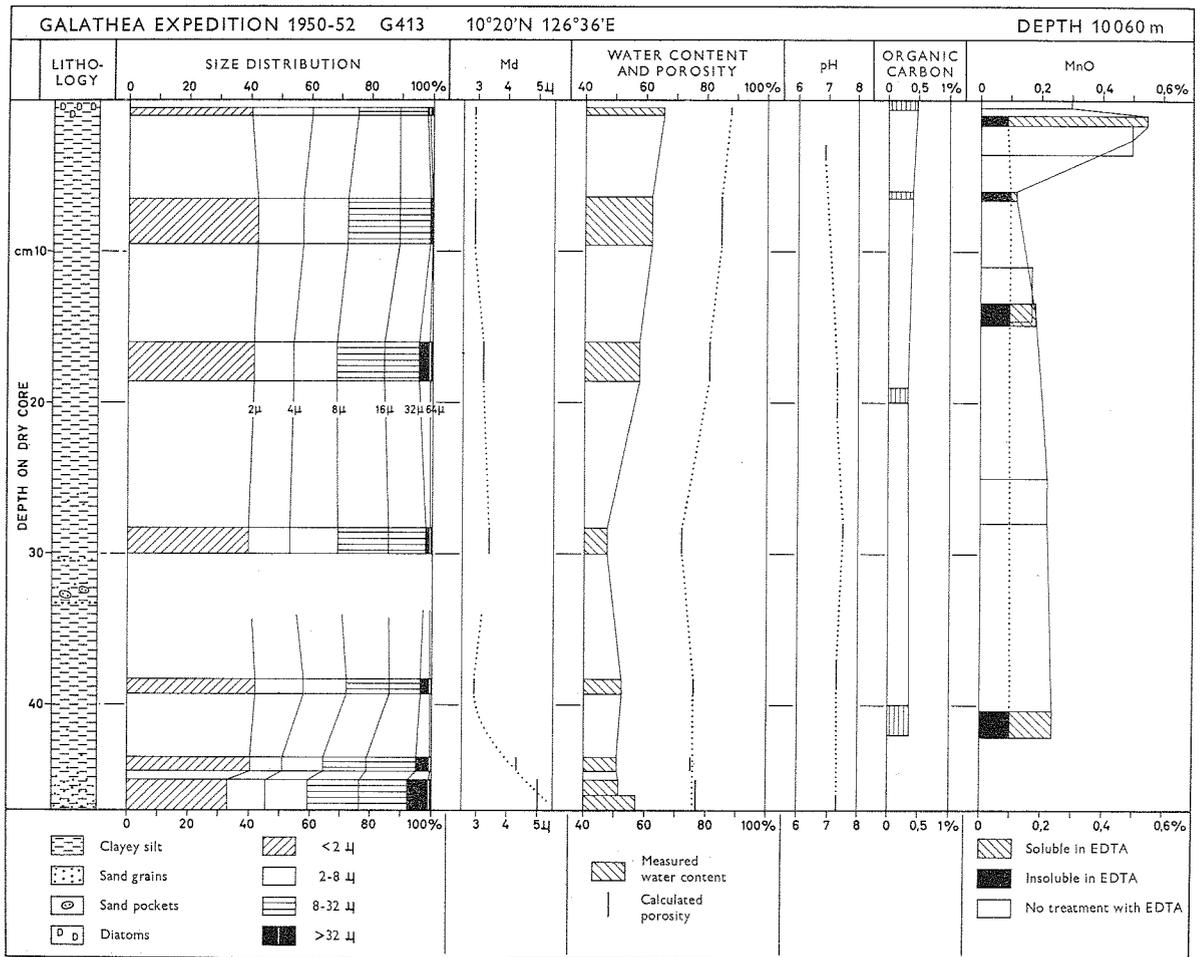
Grab sample. Mud with many mud pellets and a little sand. It contains some Globigerina and arenaceous Foraminifera. The sample is too small to allow a detailed analysis.

G 413: 10°20'N, 126°36'E. 10060 m.

G 440: 10°25'N, 126°40'E. 10020 m.

Core samples. Clayey silt with negligible amounts of sand grains, cf. figs. 2 and 3. The fresh samples are variegated bluish grey to dark grey, the dry samples are yellowish grey. Sand grains are partly dispersed in the mud, partly accumulated in a few very thin laminae and partly in 1-4 mm wide and 1-2 mm high elliptic pockets without mud matrix. No significant variation in the maximum grain size. The topmost 2-4 cm are rich in Diatoms and some bedding planes are covered with Diatoms and minor amounts of mineral grains, sponge spicules, fragments of wood, and amber. The grains from the Diatom layers are dynamically equivalent to coarse silt.

Remarks: The lime content is 0-0.3 %; regarding other chemical data see figs. 2 and 3, and table 3.



G 418: 10°13'N, 126°43'E. 10190-10150 m.  
 G 419: 10°19'N, 126°39'E. 10150-10210 m.  
 Trawl samples. Blue clayey silt with gravel and stones. The clayey silt contains very few sand grains. It is thixotropic. The fresh samples are bluish grey. The diameters of gravel and stones are between 2 and 160 mm. The stones and gravel are subangular to subrounded. About 80% is mostly fine-grained, often altered basic volcanic rocks, 15% grey lumps of semi-consolidated clay, cf. p. 13, and 5% sedimentary rocks, mostly calcarenites, calcareous sandstones and fragments of reef limestones, including two fragments of hermatypic Corals.

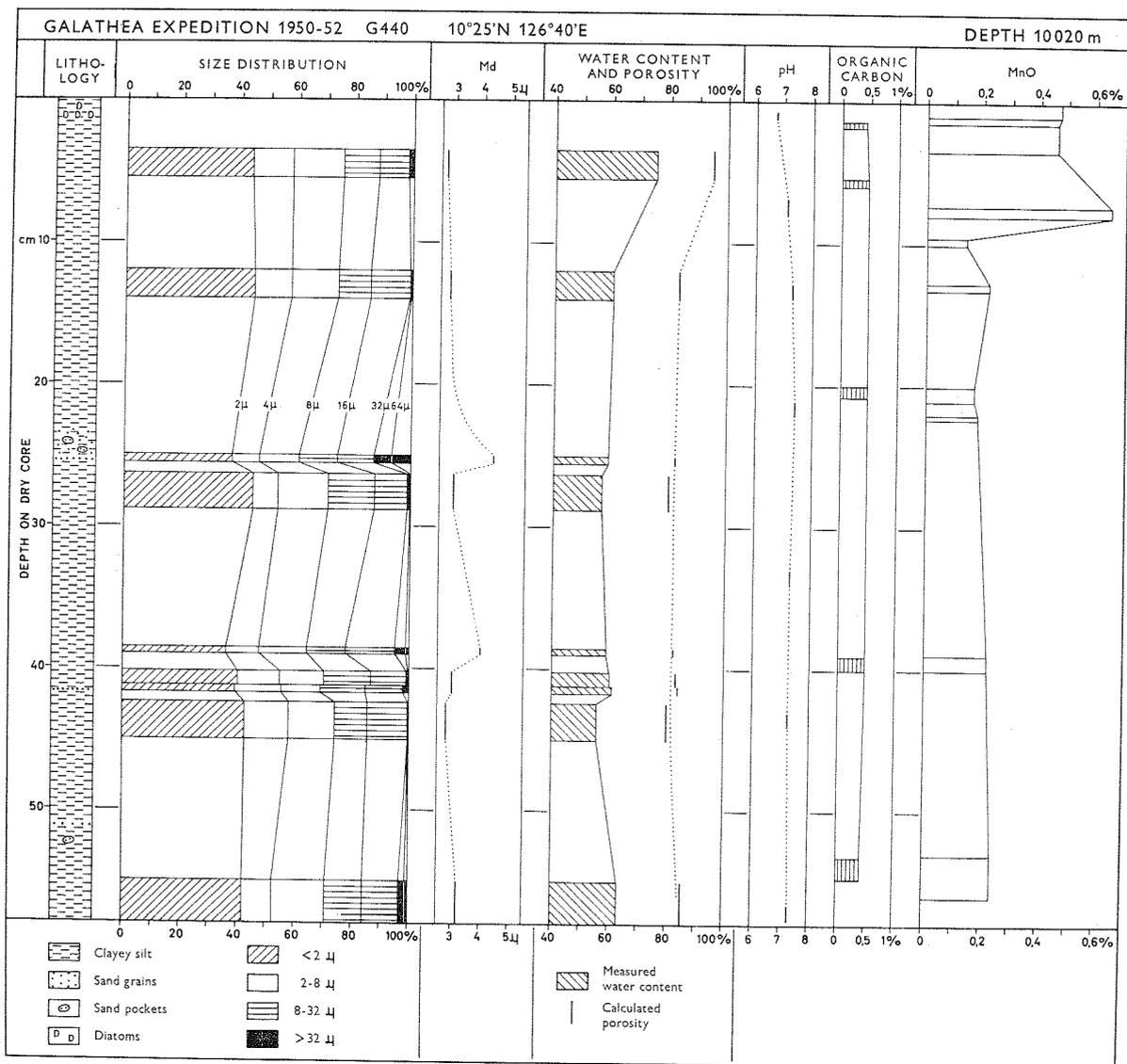
Remarks: Chemical data table 2. In bottles of mud with the original humidity preserved the water content is 62-64%, corresponding to a porosity of 82% from top to bottom. This indicates that the very porous internal structure is able to support itself to a depth of at least 15 cm, even if frequently shaken.

On a stone from G 418 three sea anemones are fastened in such a way that about half of the stone must have protruded over the surrounding mud.

G 424: 10°28'N, 126°39'E. 10120 m.  
 Grab sample. 6-8 cm clayey silt covering sand. Size distribution fig. 4. The clayey silt contains 9% sand grains, mostly mineral grains and diatoms and smaller amounts of mud pellets, calcareous and arenaceous Foraminifera, chitin fragments and chips of disintegrated wood. The fresh mud is brownish to bluish grey, the sand is olive green.

Remarks: Chemical data table 2. The curious size distribution of the sand has presumably come about by the mixing of approx.  $\frac{3}{4}$  well sorted fine sand with  $\frac{1}{4}$  normal clayey silt.

G 435: 10°20'N, 126°41'E. 9820-10000 m.  
 Trawl sample. Clayey silt with very little sand mixed with gravel and a few stones. The dry, clayey



silt is yellowish grey. About 50 % of the gravel is pumice in varying states of argillization, about 25 % fine-grained, often altered, basic volcanic rocks. 15 % is composed of brown or grey semi-consolidated clay, sometimes partly covered with a manganese crust, cf. p. 13. Loose flakes of 2 mm thick manganese crust were found. The remaining 10 % is made up of other sedimentary rocks, mainly coquina and reef limestones.

Remarks: Chemical data table 2. Fragments of shallow-water (<100 m) organisms have been found, i.e. the gastropods *Cerithopsis* sp. and some Vermetid, corals of *Porites* sp., some Acroporides and other corals of hermatype aspect, and the calcareous algae *Halimedeia* sp.

Samples from the landward slope of the Trench:

G 421: 10°26'N, 126°05'E. 1000 m.  
 Grab sample. Silty coral sand rich in Foraminifera. The dry sample is yellowish grey. Size distribution figs. 5 and 7. The sand grains are angular to sub-rounded. For composition of lime grains see table 1 and fig. 5. Planktonic and benthonic Foraminifera are of almost equal frequency. The majority of the carbonate grains in the silt and clay grade are irregular fragments. Spicules of calcareous *Spongia* and *Holothuria* occur in minor amounts. Lime content 66 %, water content 40 %.

Table 1. Composition of lime in sand fraction.

Station	Fraction mm	Fraction of whole sample %	Lime in fraction %	Corals <sup>1</sup> %	Foraminifera <sup>2</sup> %	Ostracods <sup>2</sup> and molluscs <sup>1</sup> %	Various <sup>2</sup> %
G 421 .....	>0,125	24	93	82	8	3	7
G 421 .....	—0,06	23	91	83	12	0	5
G 422 .....	>0,125	23	86	85	8	3	4
G 422 .....	—0,06	10	76	85	12	0	3

1. Aragonite. 2. Calcite.

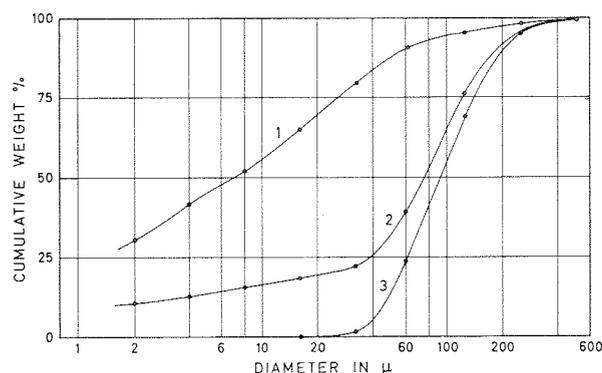


Fig. 4. Size distribution of G 424: 1) mud layer, 2) sand layer, 3) sand layer, if 25 % of clayey silt is removed from distribution 2.

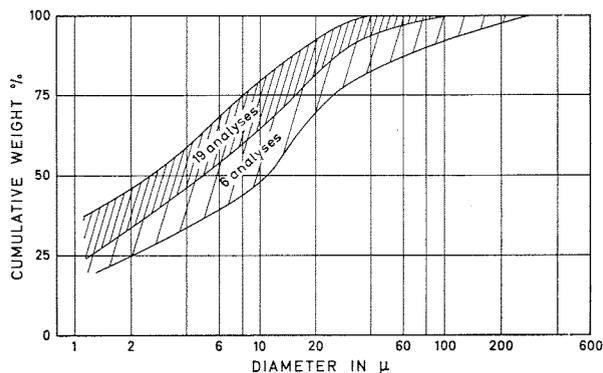


Fig. 6. Outline of size distributions of samples from Stations G 413, G 418, G 419, G 424 (mud layer), G 435 and G 440.

G 422: 10°47'N, 126°02'E. 2040 m. Grab sample. Coral sand-silt-clay. The dry sample is dusky yellow. For size distribution see figs. 5 and 7. The sand grains are angular to subrounded. For composition of lime grains see table 1 and fig. 5. Lime content 44 %, water content 50 %.

G 428: 9°36'N, 125°46'E (Candos Bay, Mindanao). 30 m. Grab sample. Clayey silt-marl. When fresh, greenish grey. It consists mainly of mud pellets. Size distribution fig. 7. The sand fraction is completely organogene. Apart from the pellets, Foraminifera (mostly Globigerina) and calcareous shells are important.

Remarks: Lime content 36 %, water content 67 %.

About 30 % of the carbonate is aragonite, about 25 % calcite with 12-20 mol % Mg, and the rest Mg-poor calcite.

## AN OUTLINE OF THE SEDIMENTS

### Lithology:

In fig. 6 a representative selection of grain distributions from sediments in the Central Philippine Trench is shown. In fig. 7 size distributions from stations Sn 251 and Sn 262 of the "Snellius" Expedition, G 428, the distribution of non-carbonate components in G 421, G 422, and some samples from the "Albatross" Expedition station 160 (FREDRIKSSON 1959) are given. NEEB (1943) employs a method of dispersion which does not disperse "clay casts", i.e. it overrates the sand grade as compared with the method used here.

In view of the fact that the stations here examined are scattered over a 30 km long area that may be extended to approximately 50 km if the Snellius samples are included, the texture of the sediments is amazingly uniform. We may, therefore, speak of the "typical size distribution" of the sediments of the Central Philippine Trench. This is characterized

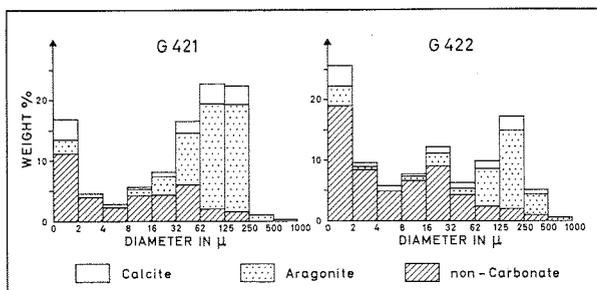


Fig. 5. Size distribution and mineralogical composition.

Table 2. Summary of the sediment samples from the Central Philippine Trench.

Sample	Water content %	Organic carbon %	CaCO <sub>3</sub> %	Md $\mu$	Clay %	Sand %
G 413	cf. fig. 2	0.47-0.32	0.07-0.30	3-3.5	ca. 40	> 1.1
G 412	65	—	0.13	2.7	41	1.3
G 418	62	0.47	0.13	4-8	30-40	4.0
G 419	55	0.41	0.16	4-10	27-30	5.4-1.4
G 424 <sup>1</sup>	59	0.48	0.12	7.0	32	9.0
G 435	45	0.17	0.11	3.8	42	0.2
G 440	cf. fig. 3	0.48	0-0.2	ca. 3	36-45	2.0-0.3
Clay lumps	41-39	1.15-1.49	0.1-0.2	1.6-2	50-58	0.2

1. The upper mud layer.

by 30-40 % clay, about 60 % silt and, generally, less than 5 % sand. The size distribution curve does not have any marked maximum. The trawl samples show, however, that accumulations of stones and pebbles occur, and sample G 424 proves that sands are present locally.

The water content of the samples varies generally around 60 %. Consequently, the internal structure of the sediment is relatively stable with a porosity of about 80 %. This hypothesis is strongly supported by the fact that the water content of samples stored in salt water is 62 %. Water contents which deviate essentially from 60 % must be due to special causes.

A particular question is, how the small pockets of loosely packed sand are formed.

Similar pockets are described from the Chile Trench by ZEN (1959, core 68-6). Sand pockets are very common in soft sediments in the Northern Mexican Gulf. They are formed by the action of digging animals in originally alternating sand and

mud layers (SHEPARD and MOORE 1955). Another possibility is that the pockets are the remains of sand tubes made by one or another organism. Pockets of sand may be observed in deformed clays with thin sand layers. Sometimes the sand layers are strongly thickened, forming pockets in the hinge zone of small folds. This suggests that the sand pockets may be mini "slump balls" as described by HADDING (1931).

Lumps of grey or rusty brown, stiff and rather dense clay have been found on all trawl stations (G 418, G 419, G 435). Apart from the colour the lumps are very much alike. Chemical data are given in table 2. The weight of the dry lumps is  $1.87 \pm 0.08$  g/cm<sup>3</sup>, while the normal silty mud only weighs  $1.43 \pm 0.07$  g/cm<sup>3</sup>. The lumps range in size from 10 to 1 cm. They are often tabular with rounded edges and consist of homogeneous silty clay with few grains bigger than 20  $\mu$  (fig. 8). The brown lumps are slightly cemented by limonitic matter. One lump shows closely spaced, parallel, rusty horizons. In a

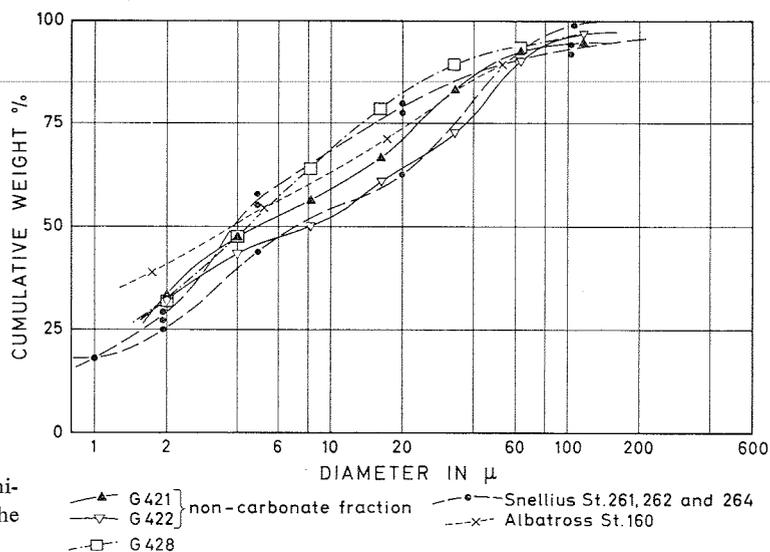


Fig. 7. Size distribution of samples from the Philippine Trench, collected by the "Snellius", the "Albatross" and the "Galathea" Expeditions.

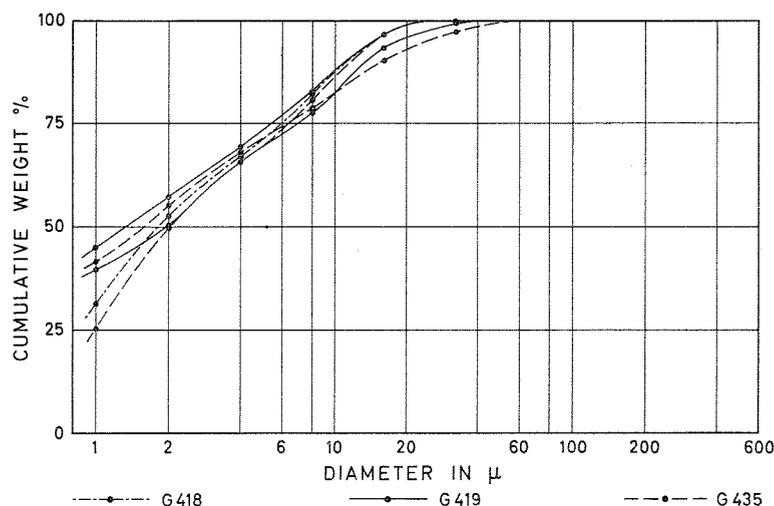


Fig. 8. Size distribution of lumps of dense clay.

few of the lumps one side is partly covered with a thin crust of manganese oxide. Another lump contains small manganese nodules (1 mm) dispersed in the clay. The water content is 39-41 %. If we assume that the original water content was 60 % and use the data on consolidation in HAMILTON (1959, fig. 4 and table 1), we can calculate the approximate load which would reduce the water content to 40 %. With an effective unit weight (i.e. unit weight ÷ bouyancy) of 0.33 g/cm<sup>3</sup>, a 15-20 m thick layer of sediments might cause the observed consolidation. It is, therefore, probable that the lumps have been lying in the mud as pebbles and that they have been transported as such from elsewhere. The mineral content does not differ significantly from the mud. The lumps greatly resemble pelagic red clay. It is, consequently, probable that they are derived from the eastern slope of the Trench. Limonitic, consolidated clays are exposed on sills between the Trench and the Sangihe Trough (NEEB 1943). Similar lumps have also been found in many other trenches (BEZRUKOV 1960, BEZRUKOV & PETELIN 1959). They have often been regarded as evidence of sliding.

#### Chemical composition:

Sampling and analysis: X-ray fluorescent diagrams were taken at different levels of the core samples and of average samples from G 418, G 419 and G 424. The relative height of the reflections from K, Ca, P, Ti, Mn, Cu, Cr and Zn were determined and compared. Except for manganese, cf. figs. 2 and 3, which will be discussed below, no significant variations were found in the composition. Consequently, there is reason to believe that the samples are rather uniform and that a chemical analysis of

one sample may be fairly representative of the whole material. A sample from G 413 (11-15 cm) was chosen and analysed. The result is shown in table 3.

The analysis is corrected for water and sea salt for comparison with analyses of consolidated sediments and crystalline rocks. The correction for sea salt is based on the assumption that the relation between the ions dissolved in the pore water is the same as for sea water. This may, of course, not be true.

The norm of cation is calculated according to the rules of the CIPW norm (BARTH 1962). The analysis is very close to sample S 154 in the Q, Fl, Px triangle of FREDRIKSSON (1959, p. 113).

Fredriksson's two analyses and my analysis of fine-grained, blue mud, formed by accumulation of terrigenous material, harmonize well, and some resemblance exists with an analysis of somewhat weathered andesite in BLANCK & OLDERSHAUSEN (1932). The chemical composition of the corrected analysis differs significantly from all types of eruptives mentioned in BARTH (1962, p. 58-59), which also appears from the norm calculation. We have reason to believe that the source of the sediment is weathered rocks of basaltic to andesitic composition.

Organic carbon: The amount of organic carbon is fairly constant, viz. around 0.45 %, corresponding to about 0.7 % of organic matter. In the bottle samples G 418 and G 424 we observe that this quantity of organic matter is sufficient to establish reducing conditions in the pore water. As a consequence it is reasonable to assume that blue mud is present at stations G 413, G 419 as well as G 440.

Distribution of manganese: The distribu-

Table 3. Chemical analysis of G 413 (11-15 cm).  
Analysed by M. MOURITZEN.

Content of	Air-dried. Salt liberated %	Corrected for salt and water %	Cation %	Norm of cation
SiO <sub>2</sub> .....	47.64	57.40	53.7	Q 24.7
TiO <sub>2</sub> .....	0.85	1.02	0.7	C 11.6
Al <sub>2</sub> O <sub>3</sub> .....	16.06	19.35	21.4	Or 11.5
Fe <sub>2</sub> O <sub>3</sub> .....	7.30	8.80	6.3	Ab 16.5
FeO .....	1.90	2.29	2.0	An 10.5
MnO .....	0.18	0.22		
MgO .....	4.66	5.61	8.0	En 16.0
	(0.27) <sup>2</sup>			
CaO .....	1.70	2.05	2.1	Il 1.4
	(0.07) <sup>2</sup>			
Na <sub>2</sub> O .....	1.51	1.82	3.3	Mt 3.9
	(1.75) <sup>2</sup>			Hm 3.7
K <sub>2</sub> O .....	1.58	1.90	2.3	
	(0.06) <sup>2</sup>			
Cl <sup>-</sup> .....	-			
	(2.35) <sup>1</sup>			
H <sub>2</sub> O <sup>+</sup> .....	9.0 <sup>2</sup>			
H <sub>2</sub> O <sup>-</sup> .....	3.5 <sup>1</sup>			
	100.38			

1. The determination of the water content was difficult as the clay quickly absorbs water from the air.
2. Salt = 4.25 %, calculated on the basis of the content of Cl (as oxides 4.5 %). SO<sub>4</sub><sup>-</sup> = 0.33 %, calculated on the basis of Cl<sup>-</sup>.

tion of manganese in the bottom is shown on figs. 2 and 3. A preliminary investigation seems to indicate that the observed variation of the content of manganese is due to a variation in the same which is easily soluble in a 5 % EDTA solution, while the content of relatively insoluble manganese is rather constant. The insoluble manganese is probably bound in mafic silicates. The soluble manganese is not part of a carbonate, but probably of some manganese oxide. The mineral content and, apart from manganese, also the total chemical composition is very uniform throughout the cores. It is, therefore, likely that a migration of manganese occurred during the diagenesis. This process has been imitated experimentally in blue mud stored in bottles.

A similar accumulation of manganese near the surface of blue muds has been investigated by e.g. MURRAY & IRVING (1895), BEZRUKOV (1960), HARTMANN (1964), BONATTI & NAYUDU (1965).

The diagenetic migration of manganese may preliminarily be explained as follows: ZOBELL & MORITA (1959) have indirectly shown that reducing conditions prevail in the pore water below a level

of a few cm from the surface of the bottom. This means that some manganese will dissolve as rather easily soluble manganous ion. When the underlying sediments consolidate, the pore water will slowly be driven upwards, carrying the dissolved manganese. When the pore water meets more oxidating conditions near the surface of the mud, the manganese will precipitate. Around sand tubes made by organisms which have been sitting in the bottom, and in this way have facilitated the interaction of pore water and the relatively oxygen-rich bottom water, we may find a cover of manganese oxide and small botryoidal manganese concretions. At the level of precipitation the concentration of manganese in solution will be very low, i.e., manganese will diffuse upwards from below and precipitate. The minimum of manganese content just below the level of accumulation is probably generated as a consequence of this process.

#### Mineralogy:

The sand grade: The sand grade is only significant in G 412, G 424, in some lumps from G 419, in the sand pockets in G 413 and G 440, and in the samples G 421 and 422 from the slope. The sand grade in G 421 and G 422 consists mainly of lime, which is discussed on p. 16. The sand in the Trench samples is rather uniform, predominantly angular to subangular, with only a few rounded grains. It is characteristic of the sand that the rock particles constitute 60-80 % of the grains even in the 125-60  $\mu$  grade. As a rule they are very cloudy, almost opaque. They consist of green, chlorite-like material held together by plagioclase or fine-grained, greyish weathering products.

The content of heavy minerals ( $d > 2.85$ ) is high, about 12 % in the 125-60  $\mu$  grade. The minerals consist chiefly of monoclinic pyroxene, epidote, and various alteration products which often contain fine-grained magnetite. In addition, green hornblende, biotite, and magnetite grains are often found. The light mineral grains include partly saussuritized plagioclase, generally with a refractive index somewhat above 1.54. Analcime constitutes 2-5 % of the fine sand, and quartz not more than a few percent. In accordance with NEEB (1943) we may conclude that the sand is very immature and mainly derived from strongly altered basic volcanic rocks.

In most of the samples of clayey silt half-disintegrated wood particles and silica organisms constitute a significant part of the sand grade.

The clay grade: The clay grade has been thoroughly examined with X-rays. A detailed description will appear on a later occasion. The clay mineralogy of the Trench samples, as well as the other samples, varies within rather narrow limits. About two thirds of the clay are mixed-layer minerals with montmorillonitic layers as the most important component. The mixed-layer minerals fall into two types: montmorillonite with 0-25 % non-expanding layers of a chiefly vermiculitic type, and montmorillonite-chlorite mixed-layer minerals. The ratio between the two components in the mixed layers varies considerably in the individual sample. Illite and chlorite are of about equal abundance, and the total amount of these two minerals hardly exceeds one third of the clay. It has not been possible to convert the chlorite X-ray spectrum into a chemical composition using the method of BRINDLEY and GILLERY (1956). Kaolinite, quartz and feldspar may occur in minor quantities. No diagenetic changes of the clay mineralogy in the uppermost meter of the bottom deposits could be demonstrated.

As the clay is in ion-exchange equilibria with sea water, the bulk of the montmorillonite clay minerals has  $Mg^{2+}$  as the dominating interlayer ion (= exchangeable ion).

Montmorillonite may be formed by weathering of igneous rocks and by leaching of illite and micas (GRIM 1953 and WEAVER 1958a). Weaver has found montmorillonite types with such a low "interlayer charge" that they are unable to absorb and, possibly, fix  $K^+$  from sea water in larger amounts. He has made it seem feasible that this type is formed directly by the weathering of basic igneous rocks. It is probable that the montmorillonitic layers in mixed-layer minerals examined have not – or only to a very small extent – absorbed  $K^+$  under formation of illitic layers. As the clay, furthermore, contains chlorite, it is quite reasonable to infer that it is mainly formed by the weathering of basic igneous rocks.

The next question is whether the mixed-layer structures found have been formed by weathering, through the influence of the ions of sea water, or by other diagenetic processes. Several authors, e.g. GRIM, DIETZ & BRADLEY (1949), PINSAK & MURRAY (1960), have postulated that montmorillonite has gradually been transformed into mixed-layer minerals and, possibly, later into illite and chlorite by diagenetic processes in the sea. As pointed out by WEAVER (1958b) this allegation has not been

proved, although it may partly be true. WILSHERE (1958) examined the alteration products of olivine and pyroxene normally described as "idding-site" (red types) and "serpentine" or "chlorophaeite", etc. (green types). He has shown that they consist of mixed-layer minerals with different pigments. On the basis of X-ray examinations the mineral has been identified as "smectite-chlorite". Smectite is montmorillonite in the widest sense. However, in his table 3, he states that in 12 out of 14 cases the mixed-layer mineral is contracted to about 9.7 Å, when heated to 500°, and not to a value between 9.7 and 14 Å, as might be expected if the mixed-layer structure had contained chloritic layers. All published facts point, on the other hand, to a montmorillonitic-vermiculitic mixed-layer mineral with  $Mg^{2+}$  as interlayer ion. In the last two cases the determination is correct. I, therefore, prefer to modify WILSHERE's conclusion as follows: montmorillonitic-vermiculitic and montmorillonitic-chloritic mixed-layer minerals may be formed by deuteric alterations and weathering of olivine and pyroxene of igneous rocks. Consequently, it is not possible to determine whether the mixed-layer structures in the examined clay have been formed primarily by weathering and/or in the sea water during diagenesis.

The lime component: The lime content of the Trench samples is generally low, about 0.1-0.2 %. As fig. 9 clearly shows that the sea water is undersaturated with lime below a depth of 4.000-4.500 m, this lime content is a problem. Part of the lime consists of more or less corroded tests of Foraminifera etc., but calculations show that the greater part is probably due to evaporation of the saline pore water rich in  $CO_2$ . It should, finally, be mentioned that local high amounts of lime (e.g. Sn 261, G 418 and G 419) may be due to slumping of allochthonous material.

As the lime is dissolved if it is carried down into the Philippine Trench (fig. 9), it might be appropriate to regard the lime component and the other components of the samples from the slope of the Trench separately.

From fig. 5 it is evident that in samples G 421 and G 422 the size distribution in the lime component is bimodal, and the proportions of aragonite and calcite vary remarkably, the aragonite amounting to 80-90 % of the lime in the sand grade but only to about 40 % of the lime in the clay grade.

The calcite occurs in two types: one with about 2-4 mol % Mg and another, more variable type, with

## SEDIMENTATION

The size distribution in G 421 and G 422 is bimodal both in the carbonate and non-carbonate components (fig. 5). This might indicate that the sediment of G 421 and G 422 is a mixture of material from at least two different source areas and of autochthonous benthonic and planktonic shell material. The size of the coral fragments and the rather fresh appearance of the grains suggest relatively short transportation. The coral reefs situated along the coasts of the Philippines are, undoubtedly, one of the source areas. The other areas must be the Philippines and the quiet bays behind the islands and the reefs. These areas mainly provide for the silicates, but also some lime is produced by erosion of limestone and by the organisms of the shelf. G 428 is a representative of such a source area. It is of interest that only between one fourth and one eighth of the carbonate in G 428 is aragonite; this is true also for the clay grade, taken separately.

Consequently, it is reasonable to explain the distribution of lime in G 421 and G 422 as a result of the mixing of coral sand rich in aragonite and fine-grained sediments, in which calcite is the dominant carbonate mineral.

It is significant that the size distribution of non-carbonate components in all three samples from the slope is clayey silt, poor in sand, with a size distribution very similar to that found in the Trench, cf. fig. 7.

It is very likely that the sediment material originally carried to the Trench area was fairly rich in lime. However, the sediments in the Trench are almost devoid of lime. This suggests that sedimentation below a depth of about 4500 m (cf. fig. 9) is so slow that the lime is dissolved before it is covered by new sediments.

Bedding planes covered with Diatoms have been found in the uppermost cm of the core samples. Owing to the presence of dynamically equivalent grains of amber and wood, the layers can not be explained by a possible mass death of Diatoms. The layers may have been deposited by a weak turbidity current which swept the sea-floor and in this way concentrated the Diatoms and the scarce grains of amber, etc. The current may have gradually lost its speed at the bottom of the Trench, thereby depositing the Diatoms, etc.

The sand layer at G 424 is rather well sorted with  $Md = 90 \mu$ . The occurrence of remains of sea organisms, dynamically equivalent with sand grains, shows that the sorting occurred in the sea.

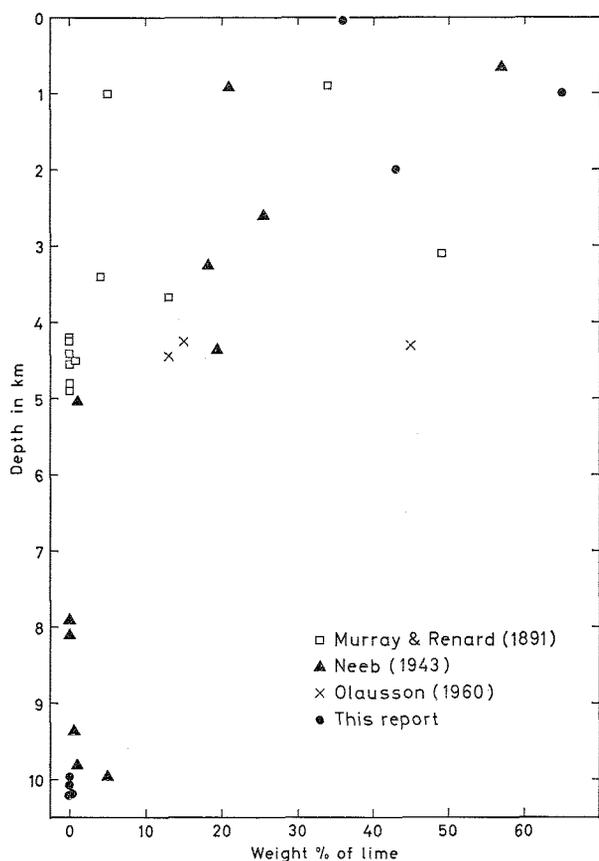


Fig. 9. The relation between depth and lime content of the samples from the Philippine Basin and the West Caroline Basin.

15-20 mol % Mg. In G 421 the ratio between the intensities of the X-ray reflections from the Mg-poor calcite and the Mg-rich calcite is about 1:2 in the sand grade and about 1:1 in the silt-sand grade. In sample G 422 about two thirds of the calcite contain 2-5 mol % Mg, and the rest 15-20 mol % Mg. No essential variation in the composition of the calcite can be detected in the different size grades.

The lime maximum of the sand grade is caused by accumulation of coral fragments and Foraminifera, the corals being composed of aragonite, cf. table 1.

Chemically precipitated calcite contains less than about 2 mol % Mg, while calcite formed organically in shells may contain bigger or smaller amounts of Mg (CHAVE 1952, 1954, GOLDSMITH et al. 1955). It is, accordingly, reasonable to assume that the calcite of the samples has been formed by disintegration of shells. The irregular shape of the grains suggests that the aragonite is also of organic origin, because aragonite precipitated in sea water is usually needle-shaped.

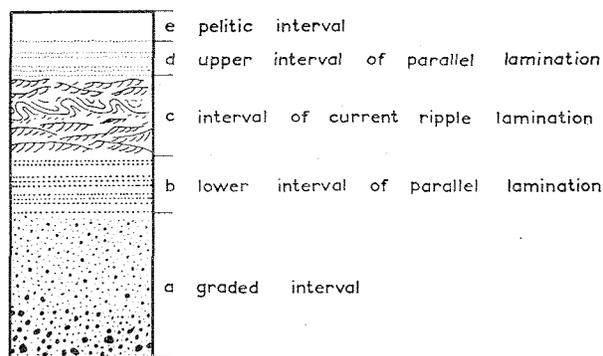


Fig. 10. The complete sequence of a thick turbidite, according to BOUMA (1962, fig. 8). By permission.

ZOBELL & MORITA (1959) have shown that the sand contains living fungous spores which could only germinate at pressures essentially lower than 1000 atm, i.e. the sand must have been deposited recently, geologically speaking. Nevertheless, it is covered by 8 cm mud. These circumstances suggest that the sand and the overlying mud have been deposited by a turbidity current, a theory which KILLERICH set forth in 1953.

The problem is now how the almost homogeneous mud in G 413 and G 440 (the core samples) has been deposited. The existence of sand pockets, sand laminae and the grading at the bottom of G 413 makes it improbable that sedimentation occurred grain by grain.

BOUMA (1962) has pointed out that a fully developed turbidite can be divided into five intervals (fig. 10). In the central part of a complete turbidite the whole sequence is developed, while in the peripheral parts only the upper intervals are present. A grading may exist in interval d and e, but it is very often absent. In consolidated sediments the thickness of d + e is 2-20 cm. The picture that we obtained of the sediments in the two cores corresponds well with interval d + e, if we assume that the material between two sand laminae is a turbidite. According to KUENEN (1963) turbidites are characterized by a sharp limit at the bottom and by the sand lying in a matrix of mud. This agrees with what we have found. Nevertheless, I have not been able to explain sand pockets by means of turbidity currents.

We have to conclude that the sediments of the locations G 413 and G 440 did most likely slide to their present situation, but deposition by a turbidity current can not be excluded. The sediments may also be slightly displaced turbidites.

All the scraped samples contain pebbles and stones, some of which come from shallow water, and

dense clay lumps which were probably formed at abyssal depths. We know that some of the bigger particles have protruded above the mud surface. The only agent which is able to transport stones and deposit them in this way is sliding (cf. SHEPARD 1964). A slide is also able to seize and transport the clay lumps presumed to be abyssal, and this offers a simple explanation of how the different components formed at very different depths have been mixed together in one deposit. Slides probably occur in the thixotropic mud deposited on the steep slopes of the Trench where earth-quakes frequently take place. Finally, it should be mentioned that NEEB (1943) records several places without recent sediments from steep parts of the western slope of the Trench off Southern Mindanao.

It should not be concluded that the whole area where scraping has been carried out is covered exclusively by slump sheets; the method of scraping may have destroyed evidence of other potential types of deposits in the samples.

KILLERICH (1955) has suggested that the sharp-edged stones were more or less formed in situ in fault zones. We have, however, good evidence that stones can be carried from very shallow water to the bottom of the Trench: the shelf off the coasts of Mindanao and Samar being very narrow, it is possible that stones pulled away by the surf may be carried beyond the shelf and deposited on deep water without showing any signs of attrition worth mentioning.

## CONCLUSIONS

The few samples are extraordinarily uniform considering the large area from which they have been collected. The description given by FREDRIKSSON (1959) and his collaborators of the "typical sediment" above the turbidites corresponds very well with what was found in G 413 and G 440. The same applies to NEEB's description of samples off Southern Mindanao. From our scattered and insufficient knowledge it, therefore, looks as if the sediments of the Philippine Trench are rather uniform on the whole, and that the examined samples are representative of large sections of the Trench. The sediments consist of uniform, non-calcareous, clayey silts, poor in sand, with local turbidites and slump sheets. The majority of the sediments is probably generated by disintegration and/or decomposition of basic igneous rocks, most probably extrusives. A glance at a map may convince one that the terrigenous sedi-

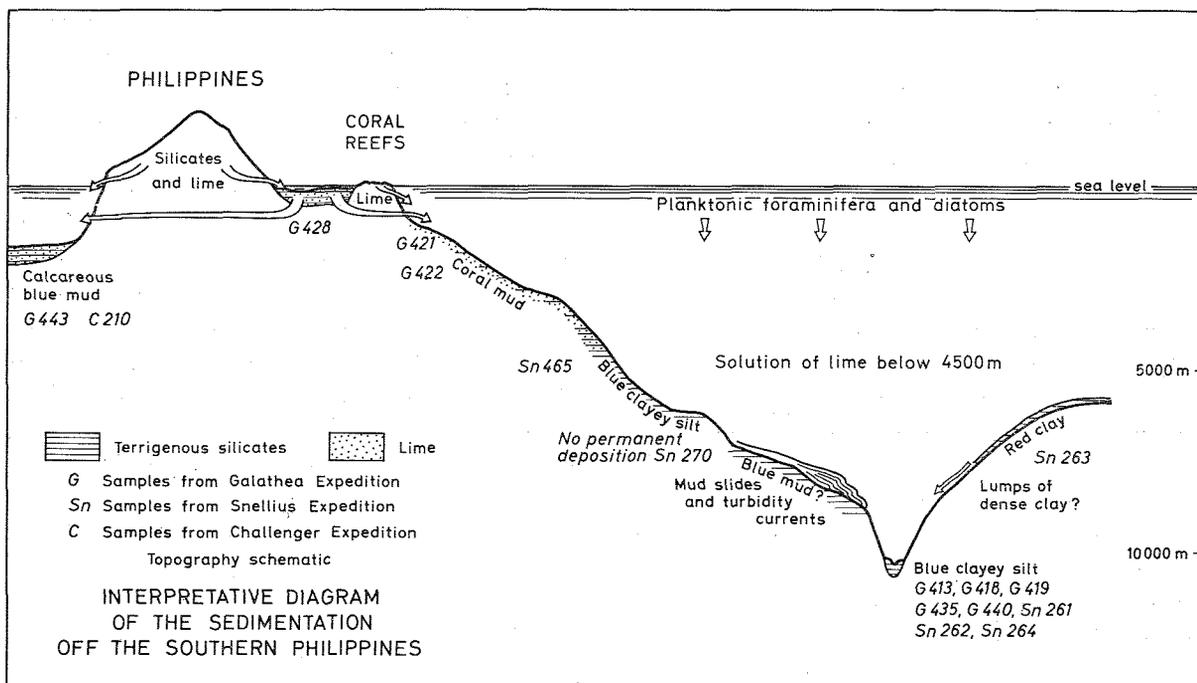


Fig. 11.

ments in the Trench area must be derived from the Eastern Philippines. This conclusion is in agreement with all facts found mineralogically and chemically.

Fig. 11 gives an outline of the processes of sedimentation off the Southern Philippines. As indicated above, the silicate minerals in the Trench area are derived from weathered rocks on the Southeastern Philippines. This area also produces some lime from raised coral reefs or the like, and this material is deposited in depressions in the shelf area (G 428) or carried over the coral reefs into the deep sea. G 421 and G 422 show that the terrigenous muds receive a considerable contribution of coral sand when crossing the reef. Owing to its grain-size the coral sand will, as a rule, be deposited immediately outside the shelf, where it constitutes 45-70% of the sediments, but smaller quantities may, at times, reach the bottom of the Trench, e.g. G 418, G 419 and FREDRIKSSON (1959). The uniform size distribution and composition of the non-carbonate fraction of G 428, G 421 and G 422 and all the samples collected from deeper levels than 4000-4500 m show that the fine-grained terrigenous silicates are spread all over the area, in accordance with the conclusion of NEEB (1943). The terrigenous sediments obtain a contribution of pelagic and benthic organisms. Lime is dissolved below 4000-4500 m and is lost for the sedimentation in the area. Some of the material originally deposited on steep slopes slides down into

the deeper parts of the Trench. The lumps of dense clay suggest that similar slides also occur on the eastern slope. East of the Trench slow sedimentation of red clay is taking place.

From the present material we have no reason to believe that turbidity currents starting in relatively shallow water have reached the Trench as proposed by BRUUN (1956).

It appears from the interpretation of the gravity profile of the Trench (HEISKANEN & VENING MEINNETZ 1958, p. 382) and the projection of the lower trench walls to intersection (FISHER & HESS 1963) that only a few hundred meters of sediments have been accumulated in the Trench. This result is surprising considering the very strong erosion on the Philippine Islands. However, it is partly explained by the fact that the potential source areas of the Trench - namely the regions that drain off to the Pacific Ocean or Leyte Gulf - cover only about 9000 km<sup>2</sup>. This is a small area compared with the offshore accumulation area which is about 50.000 km<sup>2</sup> (if delimited by the coast and the middle of the Trench). Another limiting factor is the dissolution of lime which considerably reduces the amount of sedimentary matter. A large amount of the material produced in the source area is coral lime, etc. which is dissolved if carried down into the deep parts of the Trench.

The combined result of the limiting factors is that very little material reaches the deep parts of

the accumulation areas, and this is one of the causes of the great depth of the Trench.

Apart from the relief which is a prerequisite for the development of a turbidity current, we have not found any properties specific for hadal depths.

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### SUMMARY

A description of sediments from the Philippine Trench and its landward slope off Northern Mindanao is given. The sediments of the Trench consist of very uniform, non-calcareous, blue, clayey silt

with occasional turbidite sands and slump sheets of mud with gravel and stones. The sand grade is mainly composed of disintegrated or decomposed basic extrusive rocks, and the clay is mostly made up of montmorillonitic mixed-layer minerals and smaller amounts of chlorite and illite. Re-sedimentation by sliding seems to be a normal feature in the Trench. On the western slope, coral sand rich in Foraminifera occurs above 4500 m; it has been generated by the mixing of fine terrigenous muds and coral sand. Apart from the slope which is a prerequisite for the development of turbidity currents, we have not found any properties specific for hadal depths.

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