AN ABSTRACT OF THE THESIS OF

Kenneth Lloyd Russell for the M.S.
(Name) (Degree)

in Oceanography presented on May 2, 1969
(Major) (Date)

Title: CLAY MINERAL ORIGIN AND DISTRIBUTION ON ASTORIA FAN

Abstract approved Redacted for privacy
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Clay minerals from sediment samples obtained on Astoria Fan were analyzed by X-ray diffraction. Clay minerals are defined for the purpose of this study as crystalline phyllosilicates less than two microns in equivalent settling diameter. The clay minerals are subdivided into the five common families: montmorillonite, chlorite, vermiculite, illite, and kaolinite. One X-ray scan of a magnesium ion saturated, ethylene glycol treated sample was sufficient for the identification of all the clay minerals.

A typical Recent hemipelagic sediment contains about 40 percent montmorillonite, 30 percent illite, and 30 percent chlorite. Neither kaolinite nor vermiculite is detectable in these samples. These concentrations are similar to those reported for Columbia River sediments.

The surface sediments have an identical clay mineral assemblage from the head of Astoria Canyon to the outer edge of the fan

approximately 250 kilometers offshore. All of the Recent sediments in piston cores from Astoria Fan are the same as the surface sediments on the fan. This similarity indicates an unchanging source during Recent time and a lack of any visible marine diagenesis after burial.

X-ray traces of Pleistocene clay minerals are distinctly different from those of the Recent. One can use this change in clay mineralogy as a time marker across the fan. Presumably the Pleistocene clays were formed under different weathering conditions caused by different climatic conditions.

CLAY MINERAL ORIGIN AND DISTRIBUTION ON ASTORIA FAN

by

Kenneth Lloyd Russell

A THESIS

submitted to

Oregon State University

in partial fulfillment of
the requirements for the
degree of

Master of Science

June 1967

APPROVED:

Redacted for privacy

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Date thesis is presented May 2, 1967

Typed by Kay Smith for Kenneth Lloyd Russell

ACKNOWLEDGMENT

The writer is indebted to Dr. Kenneth Deffeyes for his guidance and encouragement with this project.

Thanks are extended to Dr. John Byrne for initial help with the research and to Dr. Moyle Harward for assistance with X-ray techniques.

The help of Dr. LaVerne Kulm and Dr. Keith Oles in editing the manuscript is greatly appreciated.

The author wishes to express special thanks to his wife Rosalie without whose aid and encouragement this project could not have been completed.

This project would have been impossible without the financial support of the Office of Naval Research, contract Nonr 1286 (10).

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CLAY MINERAL ORIGIN AND DISTRIBUTION ON ASTORIA FAN

I. INTRODUCTION

General Statement

Clay minerals are defined for this study as crystalline phyllosilicates having an equivalent settling diameter of two microns or less. This is a working definition which is quite suitable when all analyses are carried out by X-ray diffraction. The crystalline phyllosilicates are divided into five familes: montmorillonite, vermiculite, chlorite, illite, and kaolinite. Each of these families is defined in a later section.

This study was undertaken in order to (1) map lateral and vertical distributions of the clay minerals, (2) determine the origin of the clay minerals on Astoria Fan and the transporting agent, and (3) study marine diagenesis of clay minerals.

Previous Work

Griffin and Goldberg (1963) have studied the general clay mineral distribution for the entire Pacific Ocean. However, no detailed studies have been made of clay minerals in the northeast Pacific. McAllister (1964), Taggart and Kaiser (1960), and Griffin (1962) have done studies similar to this one on the sediments of the Gulf of Mexico.

Biscaye (1964b, 1965) and Berry and Johns (1966) carried out similar studies on Recent sediments of the Atlantic Ocean.

Menard (1955) did a regional bathymetry study which included the area now called Astoria Fan (Figure 1). Menard pointed out that the fan began at the mouth of Astoria Canyon. He also noted the existence of the channels across the fan. Hurley (1960) published a bathymetric chart with compilations of all bathymetric data up to that time. A newer bathymetric chart, which is used here (Figure 1), was compiled by McManus (1964).

Menard (1955) discussed hemipelagic deposition versus turbidity current deposition. He concluded that turbidity current deposits were dominant in the construction of fans. Hurley (1960) also studied some cores from Astoria Fan for evidence of the transporting media. A more complete stratigraphic study by Nayudu (1964, 1965 with Enbysk) pointed out a correlation between the sediment location and its color. Nayudu (1964) also suggested that the Pleistocene to Recent boundary could be detected by a faunal change. Work by Fowler and Duncan (1967) established that this boundary could be located precisely by observing the ratio of Radiolaria to Foraminifera.

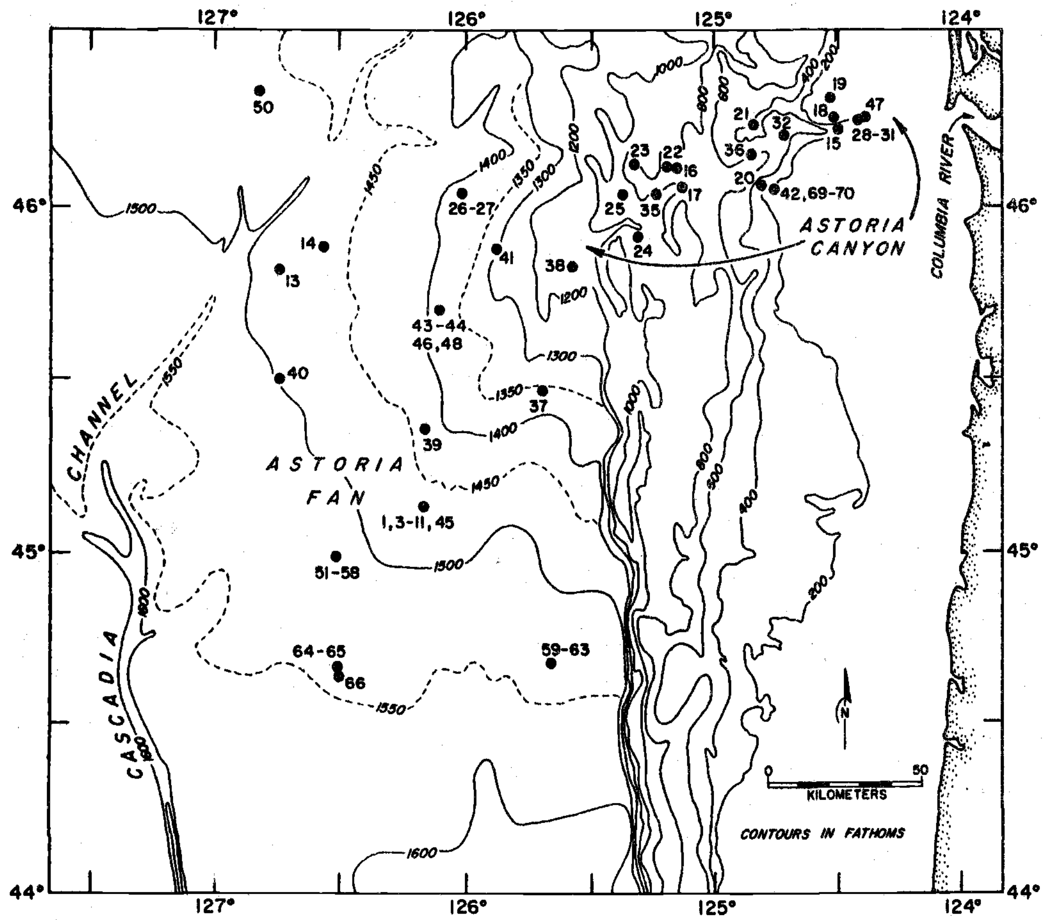

Figure 1. Index map showing sample locations and bathymetry.

II. SAMPLING

Sediment samples used in this study were obtained from piston cores in the Oregon State University collection (see Appendix). Samples approximately 4 cm long were taken from the top or near the top of 28 cores. The depths given in the appendix are to the tops of the 4 cm intervals. Five cores were sampled more extensively in order to study the vertical distribution of the clay minerals. A total of 32 samples were taken for this purpose. Most of the 28 cores analyzed were from Astoria Fan but six came from Astoria Canyon. Other samples include four from pipe dredge hauls in Astoria Canyon, three from grab samples 416 kilometers upstream in the Columbia River, and two from short cores taken 30 kilometers upstream of the mouth of the Columbia River.

The cores were sampled while still in their original moist condition. The samples were never allowed to dry until the final slide had been prepared. Sediment samples were of sufficient size to yield 5 grams of clay.

Sample Preparation

Jackson (1956) has described in great detail the techniques for preparing sediment samples for X-ray analysis of the clay minerals. By using his techniques one can extract the maximum amount of information from each sample. However, when using his techniques one requires as much as a week's work to process a few samples. One of the first objectives of this research was to find a compromise technique which gave the desired information but allowed more samples to be handled in a shorter time. The technique finally developed is a considerable modification of Jackson's work.

In order to prepare a clay sample for X-ray analysis, both organic matter and calcium carbonate must be removed. These constituents were removed simultaneously by placing the sample in a beaker with 50 ml of water, 10 ml of 30 percent hydrogen peroxide, and 10 ml of Morgan's Solution. (Morgan's Solution is a common reagent used by soil scientists. It contains 82 grams of sodium acetate and 27 ml of glacial acetic acid diluted to one liter and is a weak buffer at pH 5.0). This reagent mixture dissolves both organic matter and calcium carbonate but is believed to have no marked effect on the clay minerals. The hydrogen peroxide reacts with visible bubbling and frothing as long as organic material remains. One can watch the solutions and add hydrogen peroxide as necessary to remove all of the organic matter. Excess hydrogen peroxide was destroyed by heating for one hour at 80°C.

The clay minerals were removed from this solution by centrifugation and were rinsed twice with Morgan's Solution. This rinsing removed the residues of the organic decomposition and the last traces of sea salt. Griffin (1962) emphasized the importance of salt removal and used a chloride test to check for sea salt. A chloride test on the solution from the second rinse with the present technique always showed the absence of chloride ions. Finally the samples were placed in beakers with 50 ml of 2 percent sodium carbonate solution. They were stirred with a magnetic stirrer for five minutes at high speed. This stirring, coming after the hydrogen peroxide treatment, was sufficient to disperse the clays.

The dispersed sediment was washed with 0.01 percent sodium carbonate solution into centrifuge tubes in order to separate the clays from the larger particles. Jackson (1956) presents graphs of the settling velocity of the clay minerals based upon calculations using Stoke's Law. His calculations are valid if the suspension is in 0.01 percent sodium carbonate solution. Everything which remained in suspension after centrifugation for three minutes at 850 rpm had an equivalent settling diameter of 2 microns or less. The sediment was resuspended in the 0.01 percent sodium carbonate solution and the procedure repeated until everything settled out of suspension in three minutes. Usually at least ten centrifugations were necessary to remove all of the clay. The silt and sand remaining in the sediment were discarded.

Most researchers in clay mineralogy (for example, Griffin, 1962, and Biscaye, 1965) emphasize the importance of controlling the cation saturation of the clays for accurate X-ray identification. Sodium chloride was added to the clay suspensions. This flocculated the clay minerals and also insured sodium ion saturation. Samples which were to be run in potassium or magnesium saturated forms were converted from the sodium form by four washings with a 1 M solution of the chloride salt of the desired cation. They were then washed twice with distilled water to remove excess salt.

All of the slides were prepared according to the spatula smear technique developed by Theisen and Harward (1962) and discussed by Gibbs (1965). Eight samples were processed in duplicate and duplicate slides were prepared. Comparisons between the duplicates showed that the X-ray traces for any sample pair were identical. The results were clear and easy to interpret. It is concluded, in agreement with Griffin (1962), that workers who complain of poorly crystalline Recent clays probably did not prepare their samples correctly.

Sample Treatment and X-ray Techniques

Several samples were X-rayed while saturated with cations from normal sea water. It was hoped that these data would characterize the clay minerals as they actually exist in their oceanic environment. However, these data proved to be too difficult to interpret and this technique was abandoned. Some X-ray traces were run on sodium ion-saturated clays. These data were equally difficult to interpret and this technique was also abandoned.

Identification criteria utilizing potassium ion saturation, heat treatments, and several scans of the same slide are discussed by Brown (1961) and were used by McAllister (1964) and Griffin (1962). These techniques were used initially in this research. However, it was discovered that, although they could be easily interpreted, they added no information which could not be obtained from analysis of a magnesium ion-saturated sample.

Because of the above findings all further samples were X-rayed only in the magnesium form. The magnesium ion-saturated slides were treated with ethylene glycol vapors for one hour at 65°C. They were cooled in the ethylene glycol vapor for 24 hours and then analyzed. One scan of samples treated in this manner was adequate to identify all of the clay minerals in any sample and all of the interpretation was based upon the magnesium ion-saturated, glycolated slides.

The X-ray work was done on a Norelco diffractometer with Geiger-Müller counting tube. Data were recorded on a linear scale, strip chart recorder at one degree per inch per minute. No pulse height analyzer was used. Other machine settings were as follows: time constant at four seconds, rate meter at 1000 counts per second as full scale, current at 35 ma, voltage at 50 KV, 1° scatter and receiving slits, 0.006 inch divergence slit. Nickel-filtered copper radiation (lambda = 1.541Å) was used for all samples.

All of the samples were scanned from 3° to 14° 2θ. Within this range are the 001 peaks of montmorillonite, chlorite, vermiculite, illite, and kaolinite, and the 002 peaks of montmorillonite and chlorite. These peaks were adequate to identify all of the clay minerals except for distinguishing chlorite from kaolinite. In order to differentiate between these two a scan was run over the 24° to 26° 2θ range (Biscaye, 1964a) with the rate meter turned down to 500 counts per second as full scale.

The necessary X-ray time was 15 minutes per sample. Each sample takes two days to prepare but one can prepare samples in batches of eight and finish one batch every day. This procedure gives a total time of only one and one quarter hours per sample for the total preparation and analysis. It is believed that this technique is nearly optimal for the clay mineral analysis of marine sediments.

III. CLAY MINERALS: DEFINITION AND IDENTIFICATION

The montmorillonite group of clay minerals is characterized by a basal spacing which expands upon treatment with ethylene glycol. The montmorillonite minerals are of the 2:1 type (Grim, 1962) with the 2:1 units held together loosely by interlayer cations. The several members of the family (here called only montmorillonite) were identified by a basal spacing of 16.8Å after ethylene glycol treatment. No attempt was made to separate the various members of this group, as discussed by Brown (1961).

Vermiculite is a 2:1 type of clay mineral with an 001 peak which is not affected by glycolation. Potassium ion saturation plus heat will cause the 001 peak of vermiculite to collapse to near 10Å (Brown, 1961). This test confirmed that vermiculite was absent in any of these samples. It is not known how the presence of vermiculite might have affected the analysis technique as it has been developed.

Illite is a 2:1 type clay with the 2:1 layers held together firmly by potassium ions. The 001 peak is very sharp at 9.95Å and is unaffected by ethylene glycol.

Chlorite is the only 2:2 clay mineral. It has a basal spacing of 14Å which does not change upon treatment with ethylene glycol or potassium saturation plus heat. The 002 peak at 7.05Å is commonly much stronger than the 001. For a confirming test several samples were heated in hydrochloric acid for two hours. This treatment in many cases removes hydroxide layers and destroys the 14Å peak (Brown, 1961). X-ray analysis confirmed that the 14Å and 7Å peaks were not present after the acid treatment.

Kaolinite is a 1:1 clay with a basal peak at 7.0Å and a sharp 002 peak at 3.5Å. This mineral is especially difficult to identify in the presence of large amounts of chlorite, which has a basal sequence of 14.0Å, 7.0Å, 4.7Å, 3.5Å. The criterion which was finally adopted for distinguishing kaolinite was that of Biscaye (1964a) who differentiated between kaolinite and chlorite in Recent Atlantic Ocean sediments. He noted a measurable difference between the 004 peak of chlorite at 3.54Å and the 002 peak of kaolinite at 3.58Å. Biscaye found that these two peaks could be resolved in a slow speed scan over the 3.5Å region. However, the present study shows that they were easily resolved in a scan at normal speed. The only change made in the machine setting was to lower the full scale setting by a factor of two, so that the peaks were enlarged.

Mixed layer clays, which are interstratifications of illite-chlorite, illite-montmorillonite, or chlorite-montmorillonite (Weaver, 1958), also occur in nature. These interstratifications may be regular or irregular. Such clays are characterized by smeared basal spacings at 10Å to 14Å as well as some regular spacings at 20Å to 24Å. Higher order peaks are possible for regularly interstratified systems. All X-ray traces were begun at 29Å ($3^{o}2\theta$), but no peaks were visible at a higher angle than the montmorillonite at 16.8Å. Both the 10Å and the 14Å peaks were reasonably symmetrical and fell off rapidly to a low background in the region between them. It is therefore concluded that no detectable amount of interstratified material was present in these samples.

IV. RESULTS

X-ray traces (Figure 2) of two typical hemipelagic sediments from Astoria Fan show a short broad 16.8Å montmorillonite peak, an indistinct 001 chlorite peak at 14.2Å but a sharp 002 chlorite peak at 7.05Å, and a short, sharp illite peak at 9.95Å. Biscaye (1964b) developed criteria which he modified from those of Weaver (1958) for quantitatively analyzing the clay minerals in Recent marine sediments by X-ray diffraction. Biscaye measured the areas of certain peaks, then multiplied the areas by a scale factor to allow for differences in the expected diffraction intensities. His factors and areas used for the quantitative analysis are one times the 17Å montmorillonite peak, four times the 10Å illite peak, and twice the 7Å peak divided between kaolinite and chlorite. It is believed that no kaolinite is present, so the 7Å peak represents only chlorite.

Taking the total of the clay minerals to be 100 percent, we can calculate the percentage of each from the weighted peak areas. Such a calculation for the typical hemipelagic sediment gives 40 percent montmorillonite, 30 percent illite, and 30 percent chlorite. These calculations are inexact, with a probable accuracy of only ±10 percent.

A second clay mineral assemblage (Figure 3) shows typical Pleistocene clays. The areas under the peaks are all greater, but the ratios among the areas are similar to those of the Recent clays.

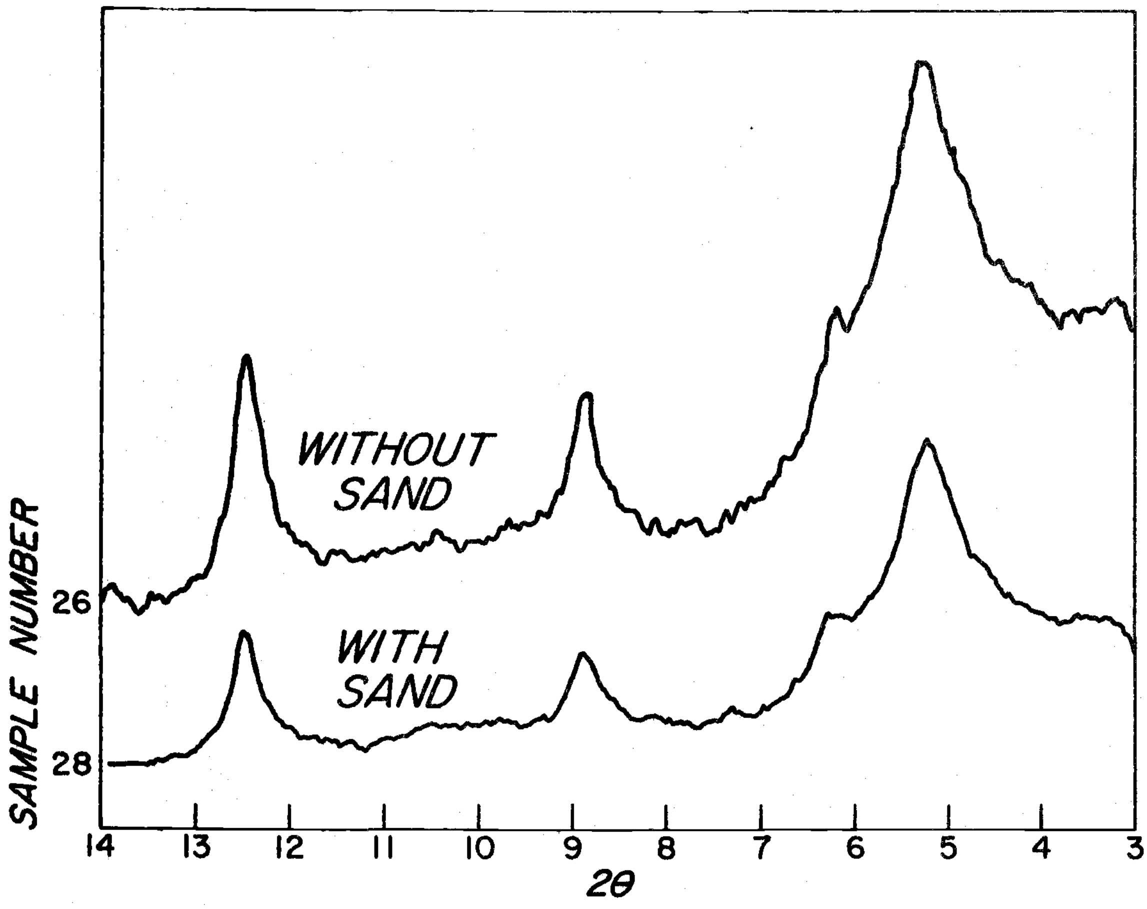

Figure 2. X-ray traces of clay minerals from Recent sediments.

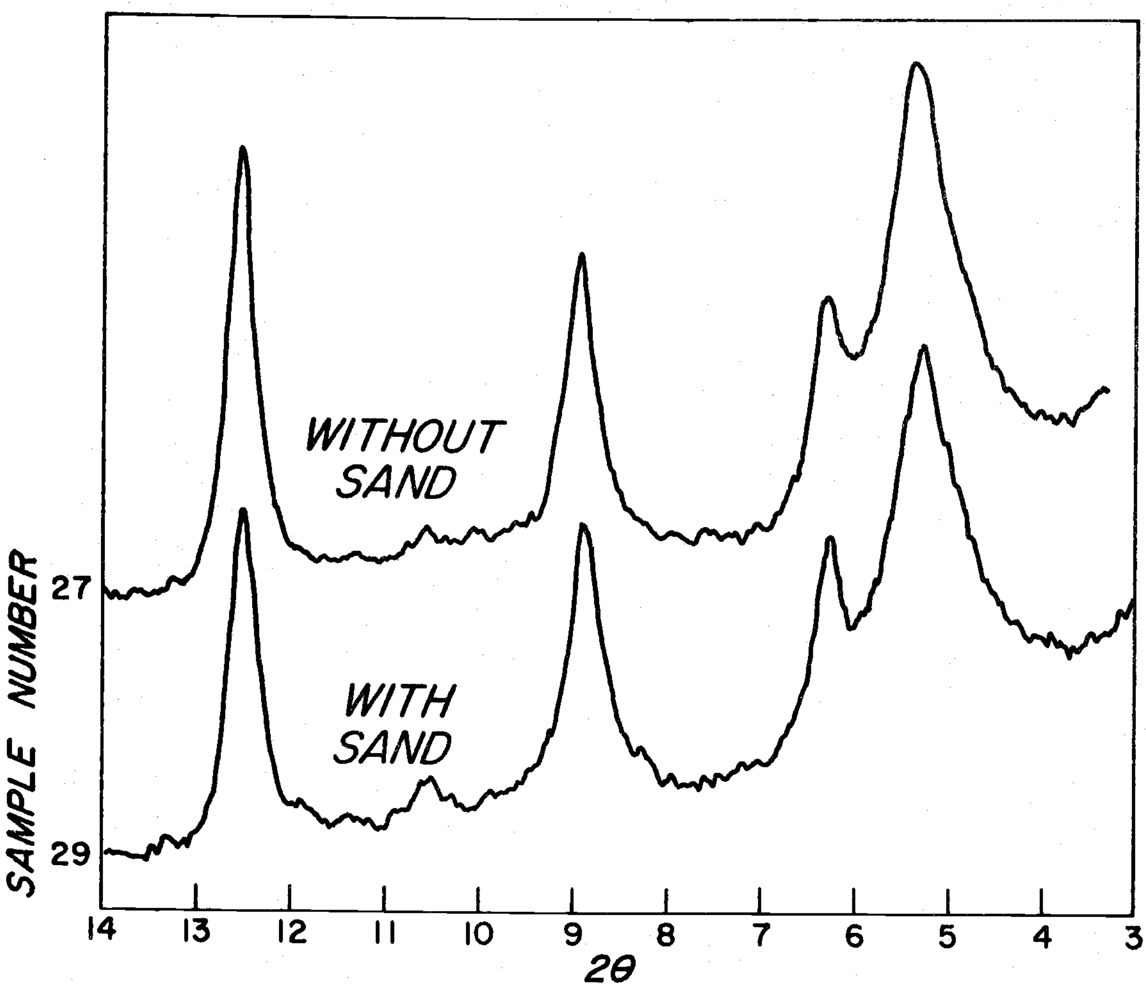

Figure 3. X-ray traces of clay minerals from Pleistocene sediments.

This indicates that although the X-ray traces are visibly different, the quantitative differences between the assemblages are insignificant. All of the peaks for the Pleistocene clays (Figure 3) are higher and sharper. The 001 peak of chlorite is clearly visible and the 001 of illite is much more distinct. All of the samples studied had X-ray traces identical with those of Figure 2 or Figure 3.

Chlorite versus Kaolinite

A preliminary report by Gross, McManus, and Creager (1963) on sediments off the mouth of the Columbia River stated that chlorite, illite, and montmorillonite are the most abundant clay-size minerals present and that kaolinite, if present, is not a major constituent. This statement is surprising in view of the occurrence of kaolinite in many Oregon soils (Harward, personal communication). Consequently, special efforts were made to check for the presence of kaolinite.

In two recent publications Biscaye (1964a, 1965) discussed a method for identifying kaolinite in Recent sediments. He said that the top of the peak near 3.5Å (24° to 26° 2θ) should be a double peak which could be resolved at a slow scanning speed. He said that the 002 of kaolinite would be at 3.54Å and the 004 of chlorite at 3.58Å. Most of the present samples had single peaks at 3.53Å although some showed peaks at 3.52Å or 3.54Å.

The 3.5Å region is shown (Figure 4) for those clays which were used as examples in Figures 2 and 3. The 3.5Å region (24° to 26° 2θ) was scanned for all samples without finding any definite evidence of kaolinite. As a confirming test, some API standard kaolinite was added to a few of the samples. The X-ray trace then showed a double peak with chlorite at 3.54Å and kaolinite at 3.58Å. As a second confirming test samples were treated with warm hydrochloric acid for two hours. This treatment should destroy all of the chlorite but not kaolinite. After this treatment the 3.54Å peak was no longer present. It has now been confirmed by John Whetten (personal communication) that there is no kaolinite in the Columbia River sediment load. What happens to the kaolinite in Oregon soil after it enters the stream load remains an unsolved problem.

Lateral Distribution

The lateral distribution of clay minerals on Astoria Fan is remarkably uniform. The surface hemipelagic materials are indistinguishable by clay mineralogy at any point on the fan (Figure 5). Sample 17 was taken within Astoria Canyon and illustrates the similarity of the canyon sediments to those of the fan. This is further evidence for the contention of Carlson (unpublished research) that Astoria Canyon is currently filling rather than eroding.

It was hoped that a study of clay minerals would furnish data on

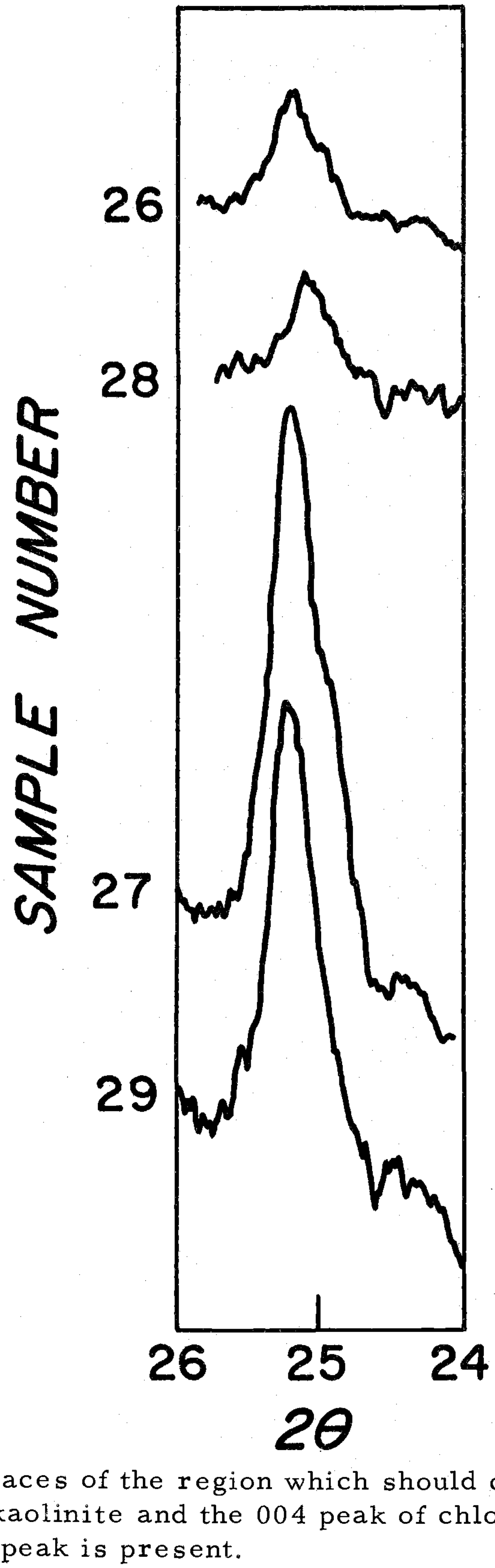

Figure 4. X-ray traces of the region which should contain the 002 peak of kaolinite and the 004 peak of chlorite. Only the chlorite peak is present.

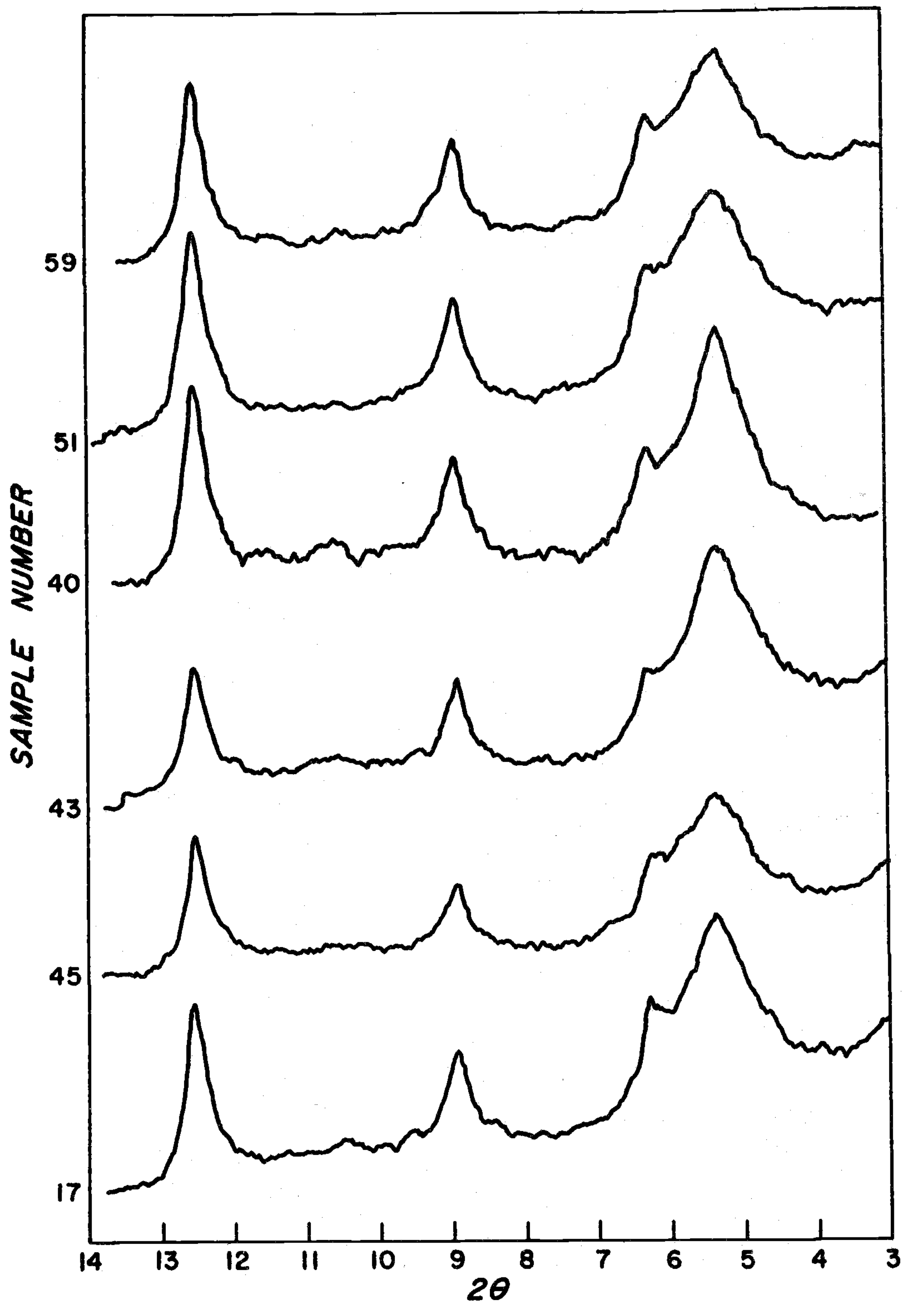

Figure 5. X-ray traces of surface samples showing uniformity in clay mineralogy over the fan and into the canyon.

the transporting media. Samples were intentionally chosen for their wide textural variations. Thick sand layers in sediment cores commonly show graded bedding and contain terrestrial plant fragments and displaced fauna. These sand layers are normally interpreted as turbidity current deposits. Sand-free layers with normal marine faunas are generally interpreted as hemipelagic sedimentation. In both Figures 2 and 3 one sample was chosen from a turbidity current-deposited layer and one from a hemipelagic layer. The similarities in clay minerals within each group show that the clays are not useful for identifying the method of transportation.

Vertical Distribution

Samples were taken from five cores to study vertical distributions of clay mineral assemblages. One of these cores was discarded as useless for sampling purposes because foraminiferal and textural evidence indicated that it contained slumped material. Two of the cores, C-3 and 6509-1-2, are from the central fan. These are very similar and only 6509-1-2 is shown (Figure 6). Five samples were taken from this core at approximately 50 cm intervals.

The similarities among the five samples are striking. There are no trends within the five samples, nor is there any one sample which is different from the others. The samples are typical of the Recent hemipelagic material (Figure 2) which everywhere covers

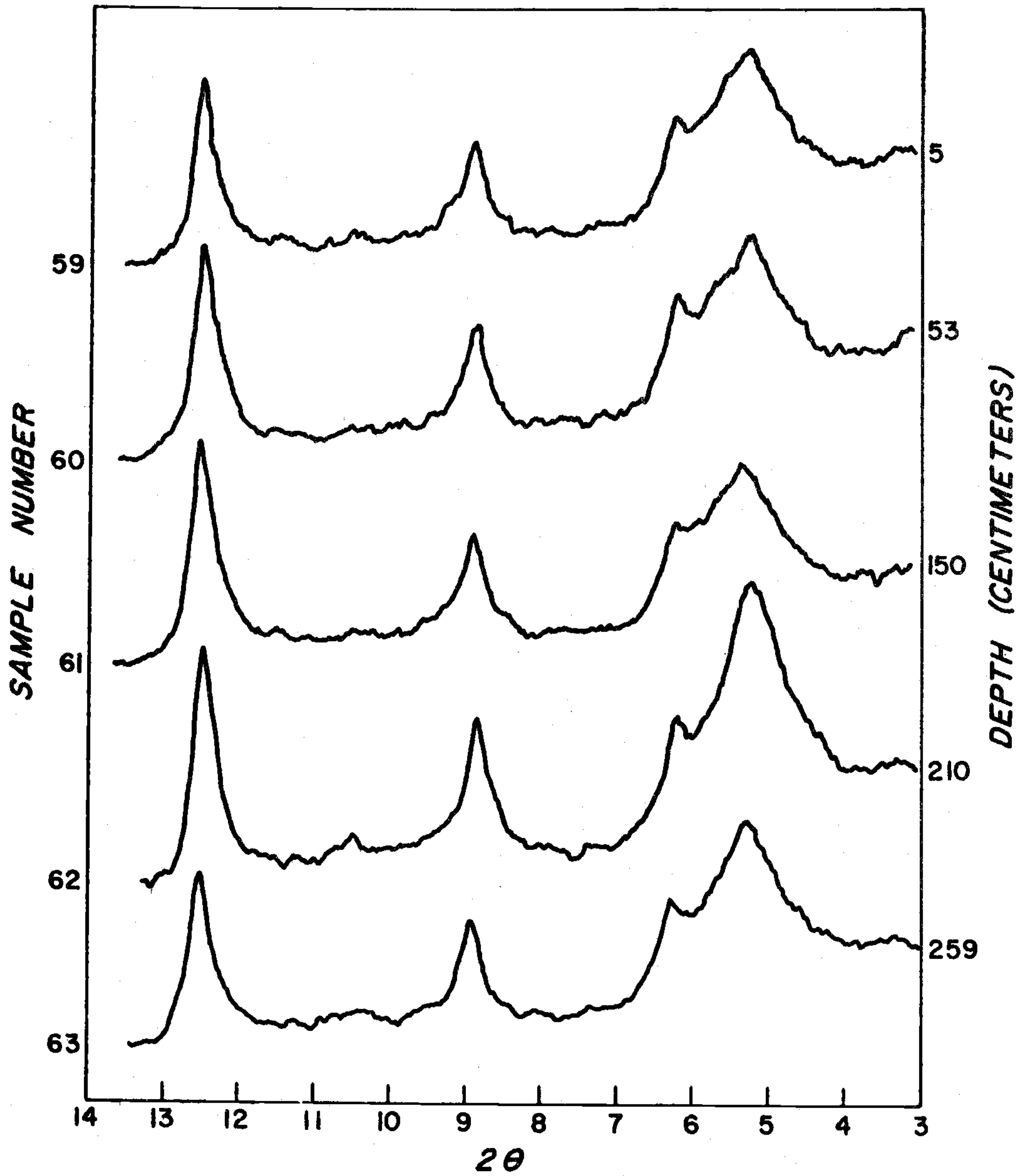

Figure 6. X-ray traces of samples at selected intervals in core 6509-1-2.

the surface of Astoria Fan. Any diagenesis in the clay minerals after burial should be visible as changes in the appearance of the X-ray traces with depth, and consequently, with time. These samples show no evidence of marine diagenesis after burial. Samples from the other short core, C-3, show exactly the same results.

Two cores KA1 (Figure 7) and 6509-1-7 (Figure 8) penetrated the Recent-Pleistocene boundary described in this area by Fowler and Duncan (1967). These cores do not show the vertical homogeneity of clay mineralogy which was so clear in Figure 6. In Figure 7 a distinct change in the appearance of the X-ray traces occurs between samples 5 and 6. The change is from the type of clays shown as Recent (Figure 2) to those identified as Pleistocene (Figure 3). This same break occurs in Figure 8 between samples 53 and 54. These stratigraphic breaks are the same ones picked by Fowler and Duncan on paleontological evidence as the Recent-Pleistocene boundary.

Within both cores the Recent clay minerals are all alike. They are identical with the surface hemipelagic material (Figure 5). There is no visible effect of transporting media on the clay mineralogy. The Pleistocene clays appear to be somewhat different from those of Recent age. However, the Pleistocene clays as a group are all identical (Figures 3, 7, 8) and do not show evidence of marine diagenesis or of the type of transporting media. The fact

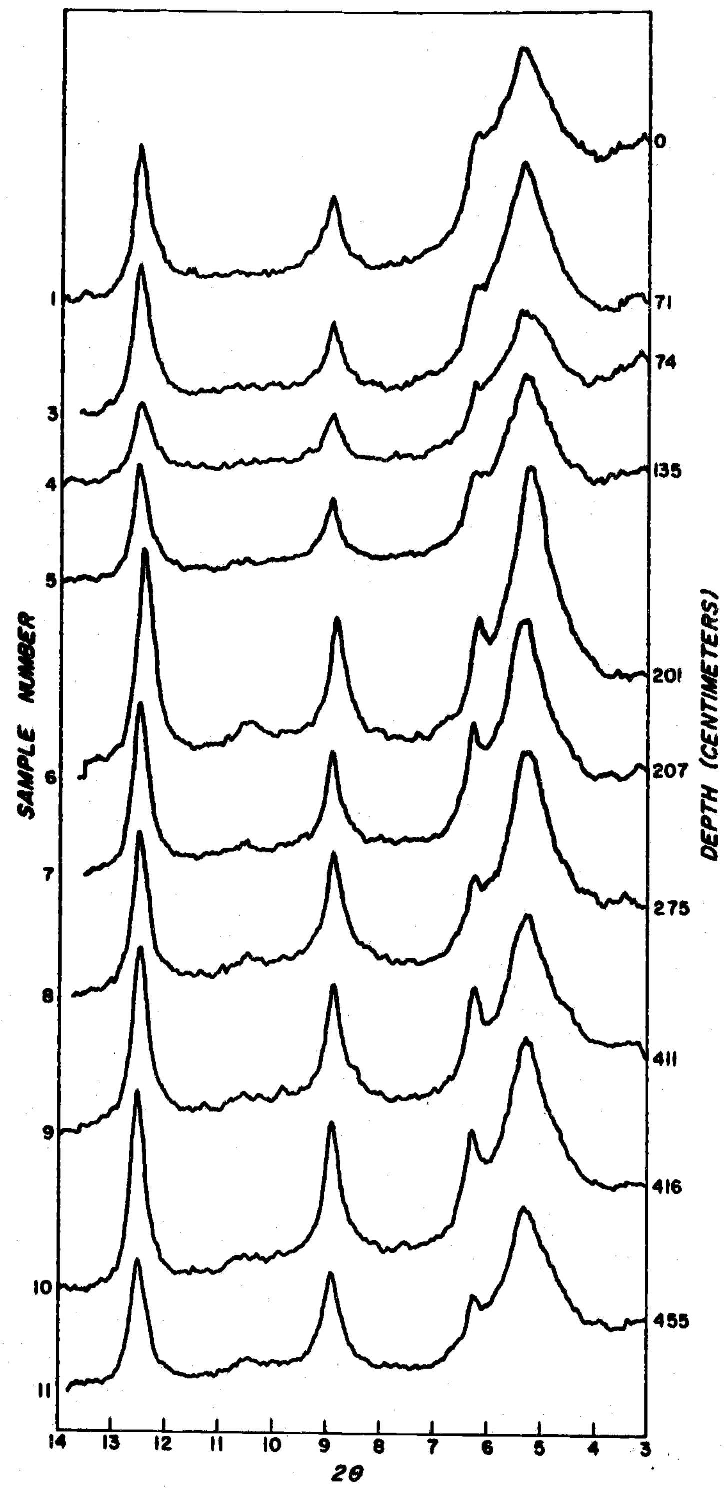

Figure 7. X-ray traces of samples from core KA1. The Recent-Pleistocene boundary lies between samples 5 and 6.

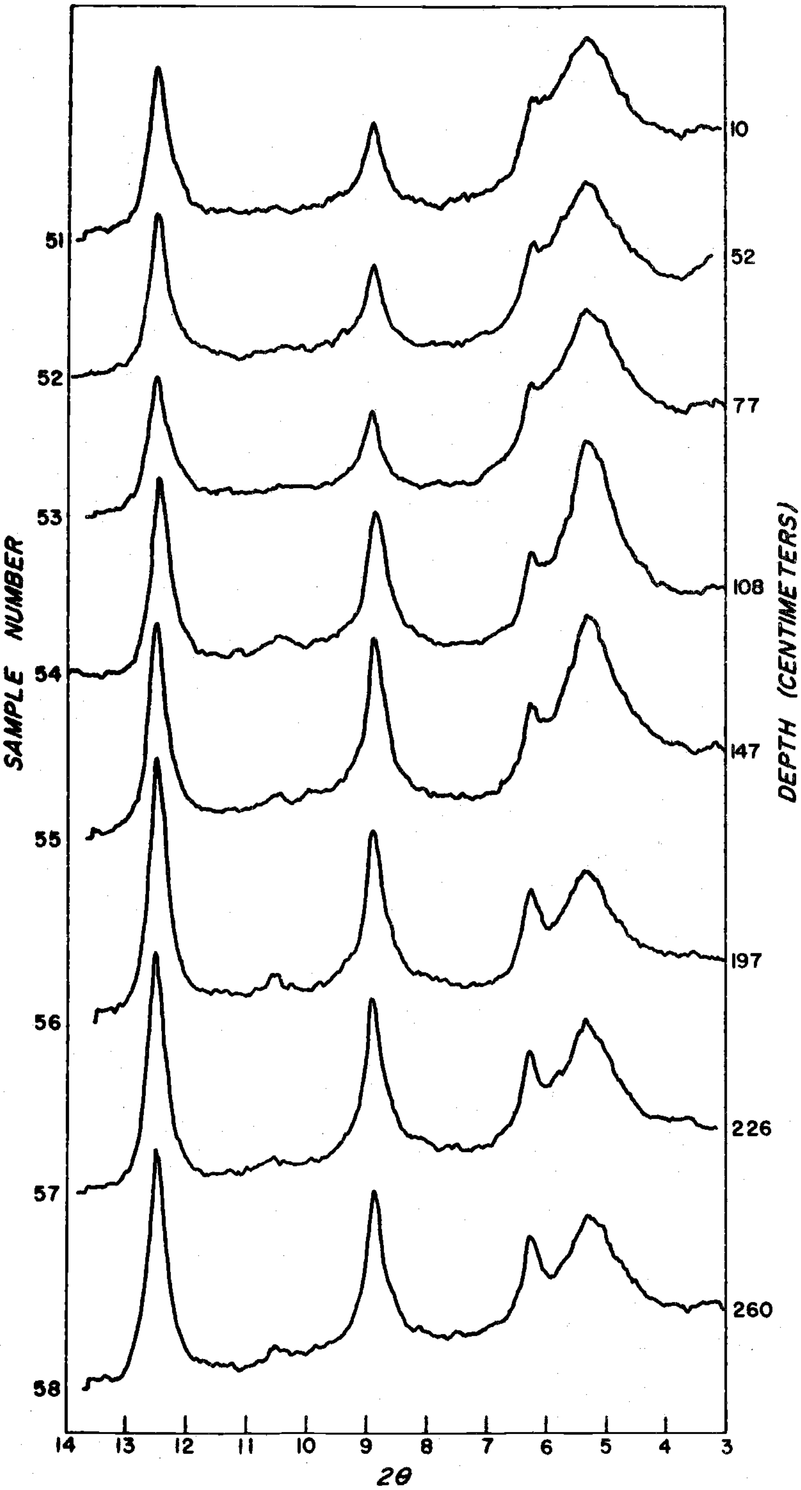

Figure 8. X-ray traces of samples from core 6509-1-7. The Recent-Pleistocene boundary is between samples 53 and 54.

that the clay minerals do not vary within any group emphasizes the importance of the source in determining the mineralogy of clay mineral assemblages.

V. ORIGIN OF CLAY MINERALS

The Columbia River is the dominant source of sediment for Astoria Fan. This fact can be demonstrated both logically and quantitatively. The uniformity of the clay mineralogy within the Recent sediment suggests that this sediment all comes from a single source. This source must have been present at least for all of Recent time. The uniformity of the surface sediment extends over the fan and to the head of Astoria Canyon. The Columbia River delivers a large amount of sediment to the continental shelf near the head of Astoria Canyon. The proximity of Astoria Fan to the mouth of the canyon suggests that the sediment was transported down the canyon and onto the fan.

Any potential sediment source for Astoria Fan must be capable of constructing the fan within a reasonable period of time. It must also be able to furnish sediment at the rates measured for the Recent sedimentation. All sediment sources except the Columbia River can be eliminated as important by one or both of these criteria. Menard (1960) used a similar technique off the California coast.

The volume of Astoria Fan is calculated by taking slices along contour lines (Figure 1) and summing the volume of each slice. This method includes the assumption that Astoria Fan is not in isostatic equilibrium, that is, that the sea floor is flat at 1600 fathoms.

A minimum volume for the fan is adequate for the purpose of finding sediment sources which could build this minimum volume. The calculated volume is 6120 cubic kilometers. The average rate of Recent sedimentation measured by Nelson (unpublished research) is 15 cm/ 1000 years. These two criteria are the basis upon which the importance of sediment sources can be judged.

Possible sediment contributors to Astoria Fan include the erosion of Astoria Canyon, coastal erosion, coastal streams, shelf and slope sediments, eolian transport, and the Columbia River. The sediment which was removed to form Astoria Canyon would appear from the bathymetric evidence to have been deposited on Astoria Fan. The void of Astoria Canyon has (Byrne, 1963) a length of 102 kilometers, an average depth of 0.52 kilometers, and an average width of 6.5 kilometers. This gives a volume of only 345 cubic kilometers of material which must have been removed. This material forms at the most six percent of Astoria Fan.

Runge (1966) points out that material eroded from the coast is mainly contributed to the inner continental shelf. He estimates that 8.4×10^{-4} cubic kilometers of material is eroded from the coast each year between the Columbia River and Heceta Head. This material is not found in the outer shelf or upper slope sediments.

Runge noted that coastal streams supply almost no sand to the shelf region. The sand load of the streams is mostly trapped within the estuaries (Kulm, 1965). Runge comments that coastal streams do appear to contribute some silt and clay to the shelf. If their contribution to the shelf is very small, it can be assumed that any contribution to the volume of the fan must be insignificant.

The fan extends for many miles along the base of the continental slope. Thus, one possible sediment source is slumps of material from the shelf and slope. Such slumps undoubtedly do occur. However, Byrne, Fowler, and Maloney (1966) pointed out that material is accreting on the continental terrace off Oregon. Therefore, the net amount of material being removed from these areas by slumps must be small.

Rex and Goldberg (1963) and Bonatti and Arrhenius (1965) have emphasized eolian transport in furnishing sediment to the Pacific Ocean. There are no reliable measurements of the flux of dust but we can make a calculation based upon some reasonable approximations. Boubel (personal communication) has measured a dust concentration in the air over Corvallis of 0.05 to 0.10 mg/m^3. We will make the calculations using his maximum concentration, 0.10 mg/m^3, in an air column 10^3m high moving at 1 m/sec.

$$0.1\ mg/m^3 \cdot 10^3 m \cdot 1\ m/sec \cdot 10^7 sec/yr = 10^9 mg/m \cdot yr$$

Therefore 10^9 mg of dust pass over each meter of coast per year.

This dust will fall out over a meter wide strip of ocean 10^6m long and will form a blanket of sediment of density 1 gm/cm^3.

$$\frac{10^9 \text{ mg/m} \cdot \text{yr}}{10^6 \text{m}} = \frac{10^3 \text{ mg}}{\text{m}^2 \cdot \text{yr}} = \frac{10^3 \text{ gm}}{\text{m}^2 \cdot 1000 \text{ yr}}$$

$$\frac{10^3 \text{ gm}}{\text{m}^2 \cdot 1000 \text{ yr}} \cdot \frac{1 \text{ m}^2}{10^4 \text{ cm}^2} = \frac{0.1 \text{ gm}}{\text{cm}^2 \cdot 1000 \text{ yr}}$$

$$\frac{0.1 \text{ gm/cm}^2 \cdot 1000 \text{ yr}}{1 \text{ gm/cm}^3} = \frac{0.1 \text{ cm}}{1000 \text{ yr}}$$

Deposition of dust at a maximum rate of 0.1 cm/1000 yr, compared with the average rate of sedimentation on the fan of 15 cm/1000 yr, would be undetectable by X-ray methods unless the air transported sediment were of completely unique composition.

Hickson (1960) estimated that the Columbia River discharged (before the upstream dams were constructed) 1.48×10^{-2} cubic kilometers of sediment per year. This discharge onto the shelf at the mouth of the river is 18 times greater than the total amount of coastal erosion, the next greatest contributor. We can test this discharge against the dual criteria of total minimum volume and of rate.

$$\frac{6120 \text{ cubic kilometers}}{1.48 \cdot 10^{-2} \text{ cubic kilometers/yr}} = 4.14 \cdot 10^5 \text{ years}$$

This calculation demonstrates that the Columbia River could provide the visible volume of sediments on Astoria Fan within 414,000 years, easily within Pleistocene time. Even if a more correct picture showed that Astoria Fan were isostatically compensated and had a volume six times that of our minimum calculation (Emilia, unpublished research) then the time limit would only be pushed back into Late Pliocene, and the argument is still equally valid.

The rate of sedimentation criterion can also be easily evaluated. The area of the fan (Figure 1) is about 24,700 square kilometers.

$$\frac{1.48 \cdot 10^{-2} \text{ cubic kilometers/yr}}{2.47 \cdot 10^{4} \text{ square kilometers}} = 6.0 \cdot 10^{-7} \text{ kilometers/yr} = 60 \text{ cm/1000 yr}$$

This potential rate is four times the actual 15 cm/1000 yr rate measured by Nelson. The Columbia River overpowers any other potential sediment source in the studied area. It furnishes adequate sediment to leave some sand on the shelf, build Astoria Fan, and contribute sediment to other parts of the northeast Pacific.

The clay minerals in the Columbia River load are largely unstudied at the present time. Because of the large number of upstream dams, at least 50 percent (Hickson, 1960) of the Columbia River sediment never gets to the ocean. The present sediment output is largely dependent upon the Willamette and Cowlitz Rivers plus a contribution depending upon the amount of water passing the upstream dams. In fact, the strong possibility arises that one can best investigate the past Columbia River contribution by studying the offshore sediments.

Two samples (Figure 9) were taken in a location behind McNary Dam where radioactivity studies show that deposition and erosion occur in yearly cycles. The similarity between these sediments and the surface hemipelagic material offshore is obvious and striking. The Oceanography Department, University of Washington (John Whetten, personal communication) is working on a major study of the Columbia River suspended load. They confirm that illite, chlorite, and montmorillonite all make large contributions to the suspended load and that kaolinite is absent.

The correct explanation of the difference between the Recent and the Pleistocene clay minerals cannot be given at the present time. The X-ray peaks for the clays in the older sediment are higher and sharper, yet the apparent compositional difference is small. This may be due to better crystallinity in older samples or to less X-ray-amorphous material (allophane) mixed with them. Another possibility is a different size distribution within the clay-sized fraction. The clay minerals within the older sediments reflect conditions during glacial times. It is probable that they encountered more mechanical weathering and less chemical weathering.

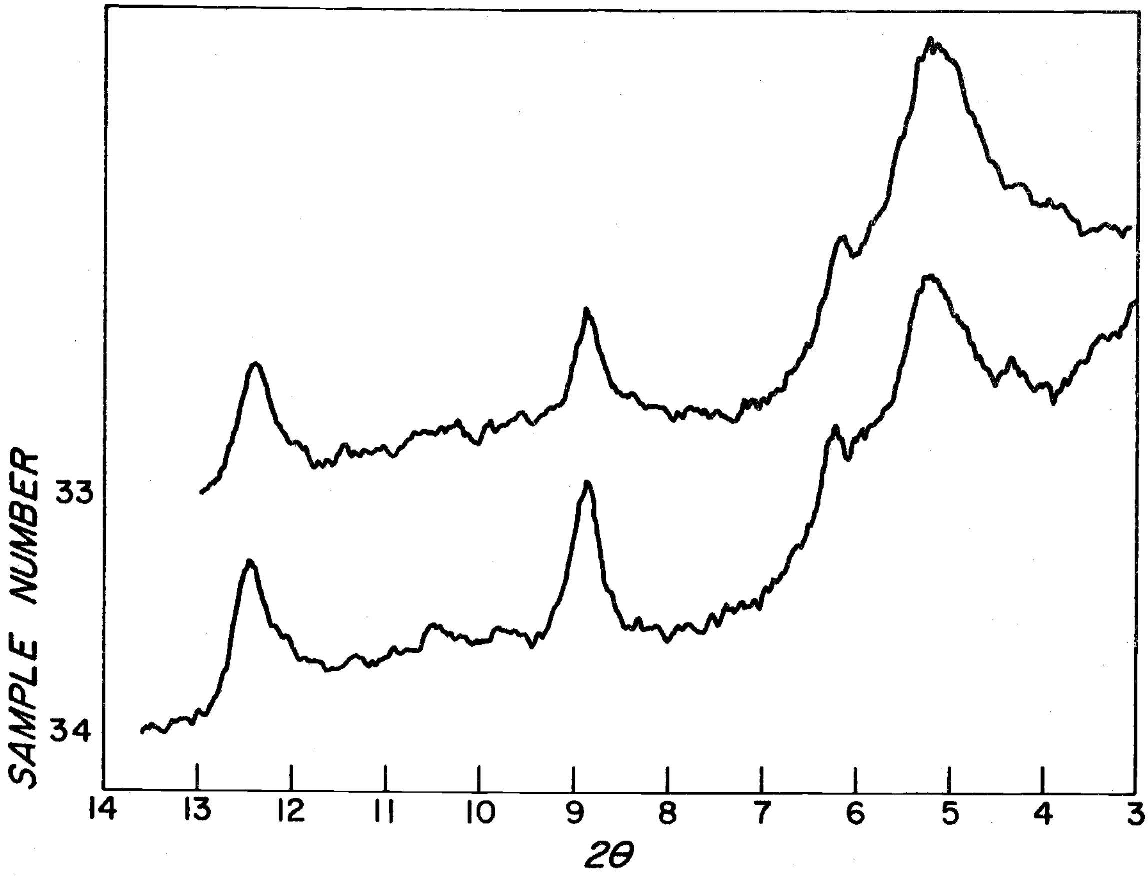

Figure 9. X-ray traces of clay minerals from samples taken behind McNary Dam, 416 kilometers upstream in the Columbia River.

VI. CONCLUSIONS

A modified technique was developed for the X-ray analysis of marine clay minerals. This technique is nearly optimal for both laboratory time and X-ray time. The technique allows one to differentiate montmorillonite, chlorite, illite, and kaolinite. It is not known how this technique would be affected if vermiculite were present in the samples.

The clay mineral assemblage on Astoria Fan contains only montmorillonite, chlorite, and illite. This assemblage has the same composition over the entire fan and in the bottom of Astoria Canyon. The composition is approximately 40 percent montmorillonite, 30 percent illite, and 30 percent chlorite.

The Columbia River is quantitatively demonstrated to be the most important sediment source in this area. The Columbia River could furnish all of the sediment now being deposited on Astoria Fan and still furnish considerable sediment to regions farther offshore.

The clay mineral assemblages are identical everywhere over the fan down to the Recent-Pleistocene boundary. The Pleistocene clays are a similar assemblage yet the X-ray traces are distinctly different. A detailed study of the vertical distributions of clay minerals would allow one to isopach the Recent sediments on Astoria Fan.

All of the Recent clays studied were exactly alike. Similarly, all of the Pleistocene clays were exactly alike. The difference between the two groups is presumably due to different weathering conditions during the Pleistocene. The transporting media had no effect on the clay mineralogy. The homogeneity in clay minerals within each group emphasizes the importance of source in determining clay mineral ratios. This lateral and vertical homogeneity denies any visible marine diagenesis.

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APPENDIX

APPENDIX - Sample Locations

Sample No.	Lat.	Long.	Official OSU No.	Depth within sample - in cm.
1	45°08.0'	126°10.0'	KA1	0
2	"	"	"	60
3	"	"	"	71
4	"	"	"	74
5	"	"	"	135
6	"	"	"	201
7	"	"	"	207
8	"	"	"	275
9	"	"	"	411
10	"	"	"	416
11	"	"	"	455
12	lost in processing			
13	45°49.0'	125°45.5'	C2	0
14	45°53.1'	126°34.0'	B4	0
15	46°13.0'	124°30.0'	PD4	0
16	46°06.4'	125°09.5'	PD5	0
17	46°03.5'	125°08.0'	PD6	0
18	46°15.2'	124°31.8'	PD8	0
19	46°18.5'	124°32.0'	R3	0
20	46°03.2'	124°48.5'	R4	0
21	46°13.9'	124°50.1'	R5	0
22	46°06.3'	125°11.4'	R7	0
23	46°06.9'	125°19.3'	R8	0
24	45°53.9'	125°18.9'	R9	0
25	46°02.2'	125°22.0'	R10	0

APPENDIX - Sample Locations
(cont.)

Sample No.	Lat.	Long.	Official OSU No.	Depth within sample - in cm.
26	46°02.1'	126°06.4'	A3$_2$	0
27	"	"	"	95
28	46°14.3'	124°25.0'	PC6	181
29	"	"	"	245
30	"	"	"	322
31	"	"	"	403
32	46°12.8'	124°42.8'	PC12	0
33	416 kilometers upstream in the Columbia River in the center of the river			
34	" " " " " " " " " " " " "			
35	46°01.9'	125°14.2'	PC17	0
36	46°08.5'	124°51.4'	PC16	0
37	45°29.0'	125°42.2'	E3	0
38	45°49.8'	125°35.0'	D2	0
39	45°21.0'	126°10.0'	D4	0
40	45°30.0'	126°45.0'	C4	0
41	45°52.5'	125°53.5'	B3	0
42	46°03.2'	124°45.7'	C14	155
43	45°51.8'	126°07.0'	C3	78
44	"	"	"	87
45	45°08.0'	126°10.0'	KA1	0
46	45°41.8'	126°07.0'	C3	417
47	46°13.7'	124°27.3'	AH15	0
48	45°41.8'	126°07.0'	C3	10
49	44°41.3'	127°35.2'	Th9	0
50	46°19.9'	126°49.6'	A5	0

APPENDIX - Sample Locations
(cont.)

Sample No.	Lat.	Long.	Official OSU No.	Depth within sample - in cm.
51	44°59.2'	126°31.2'	6509-1-7	10
52	"	"	"	52
53	"	"	"	77
54	"	"	"	108
55	"	"	"	147
56	"	"	"	197
57	"	"	"	226
58	"	"	"	260
59	44°40.5'	125°40.0'	6509-1-2	5
60	"	"	"	53
61	"	"	"	150
62	"	"	"	210
63	"	"	"	259
64	44°40.0'	126°54.5'	6509-1-16	36
65	"	"	"	138
66	44°38.4'	126°54.5'	6504-23-1	0
67	30 kilometers upstream in the Columbia River near shore			
68	" " " " " " " " "			
69	46°03.2'	124°45.7'	C14	146
70	"	"	"	160