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Title: SEDIMENT SOURCES AND CLAY MINERAL DISTRIBUTIONS OFF THE OREGON COAST: EVIDENCE FOR A POLEWARD SLOPE UNDERCURRENT

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Clay mineral analyses of surface sediments from the Oregon continental margin are combined with estimates of continental sediment influx to determine the relations between major source regions and dominant dispersal pathways of fine grained sediment in the offshore areas. Both the clay assemblages and sediment supply estimates indicate that the rivers of the northern California Coast Range, the Klamath Mountains and the Columbia Watershed are the principal sediment suppliers, providing over 90% of the silts and clays to the Oregon margin and Cascadia Basin. At the present time, the major sediment sources appear to be the Eel, Columbia, Klamath, Rogue and Umpqua Rivers, respectively.

Trends in the clay mineral distributions suggest that deposition of fine-grained sediments on the Oregon continental shelf is controlled by seasonal meteorological and oceanic factors such as periodic peak

river discharges, winter storms and summer coastal upwelling. A lobe of montmorillonite-rich clays on the northern Oregon shelf may be caused by a southward extension of the Columbia River Plume in May-June and/or discharge from local Coast Range streams and northward transport during the winter months.

On the continental slope, clays enriched in chlorite indicate that a portion of the massive influx from the northern California and southern Oregon coastal streams is carried northward, probably via the California Undercurrent. The imprint of this poleward flow can be traced to marginal areas off the Washington coast.

Montmorillonite-rich clays, typical of the Columbia River, appear to be transported through numerous submarine channels to abyssal fans off Washington and northern Oregon. Clays in the Cascadia Basin are a rather even mixture of Columbia River and southerly material, suggesting that northward flow may not be confined to the continental slope.

Sediment Sources and Clay Mineral Distributions Off the Oregon Coast: Evidence for a Poleward Slope Undercurrent

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SEDIMENT SOURCES AND CLAY MINERAL DISTRIBUTIONS OFF THE OREGON COAST: EVIDENCE FOR A POLEWARD SLOPE UNDERCURRENT

INTRODUCTION

The nature and distribution of the terrigenous fraction of modern hemipelagic sediments reflect complex interactions between sediment provenance, depositional processes and seasonal fluvial discharges and oceanic dynamics. The convergent margins of the Northeast Pacific Ocean offer an excellent setting in which to study how fine particles are carried from their source areas to depositional sites in the ocean. The offshore areas are strongly influenced by fluvial input with the rivers of northern California, Oregon and Washington together draining an area larger than all of the U. S. rivers emptying into the Atlantic Ocean (Curtis, 1973). Potential sources for fine sediments however, are well defined and possess distinctive mineralogies (Knebel et al., 1968; Griffin et al., 1968; Duncan et al., 1970; Scheidegger et al., 1971; Hayes, 1973). The fate of these river-borne sediments and the extent of their interaction with ambient oceanic conditions is, as yet, poorly understood.

This paper examines regional variations in the clay mineralogy of the less than 2 micron fraction of surface sediments off the coast of Oregon. Factors influencing the clay mineral distributional patterns are assessed and estimates of present day fine-grained sediment supply made from annual fluvial suspended sediment discharges and coastal erosion data. The study has three basic objectives: 1) to determine the provenance of fine-grained terrigenous sediments deposited on the continental margin off Oregon, 2) to evaluate the relative magnitudes and importance of various continental sources; and 3) to infer the dominant oceanic transport mechanisms responsible for the clay mineral distributions. The results suggest a strong imprint of seasonal oceanic processes on the long term sedimentary record off Oregon.

Because of their prevelance in the marine environment, clays and the variations in their mineralogies have been used extensively in recent years to study the association between continental influx and marine sedimentary processes occurring along continental margins (e.g., Biscaye, 1965; Porrenga, 1966; Jacobs and Ewing, 1969; O'Brien and Burrell, 1970; Hein, 1973; Rosato et al., 1974; Heath et al., 1974; Gibbs, 1977; Berry and Nacita, 1977; Chen, 1978). In the Northeast Pacific Ocean, previous clay mineral investigations either have been of very broad scope (Griffin et al., 1968; Lisitzin, 1972) or confined to specific physiographic environments such as the Cascadia Seachannel (Griggs, 1968), Astoria Fan (Russell, 1967), Cascadia Abyssal Plain (Duncan, 1968, 1970), Gorda Basin (Phipps, 1974) and the southern Oregon margin (Spigai, 1971). Regrettably, geographic overlap has been minimal and key areas of the central and northern Oregon margin have not been studied until now. Moreover, differing analytical techniques among the investigators introduce enough uncertainty in the composite data set to preclude confident interpretation of observed trends. The present study encompasses all depositional environments off Oregon and analytical methods are comparable to those employed in studies on the Washington margin (Baker, 1973, 1976) and in the Columbia River (Knebel et al., 1968).

MARINE GEOLOGY

Physiography

The geologic framework of the continental margins and abyssal areas of the Northeast Pacific Ocean has received considerable attention in the last decade, primarily from workers at Oregon State University and the University of Washington. The physiography, general sedimentology and previous work on clays are briefly summarized here, but more extensive discussion can be found in McManus (1964, 1972), Griggs and Kulm (1968), Carlson (1968), Nelson (1968), Silver (1969), Griggs et al. (1970), Duncan et al. (1970), and Kulm et al. (1975).

The offshore topography is relatively uncomplicated (Figure 1). The shelf is generally narrow and straight, except off central Oregon where prominent submarine reefs (the Hecata and Coquille Banks) promulgate seaward. The continental shelf width varies from about 16 km in the south to some 75 km near the Columbia River mouth (Komar et al., 1972; Kulm et al., 1975). The mid and upper continental slopes are gently dipping (2-3°) and in the south form elongated plateau-like features. The lower slope generally dips more steeply (5-6°) (Spigai, 1971; Silver, 1969). Off Washington and northern Oregon abyssal hills give complex topographic expression to the lower slope.

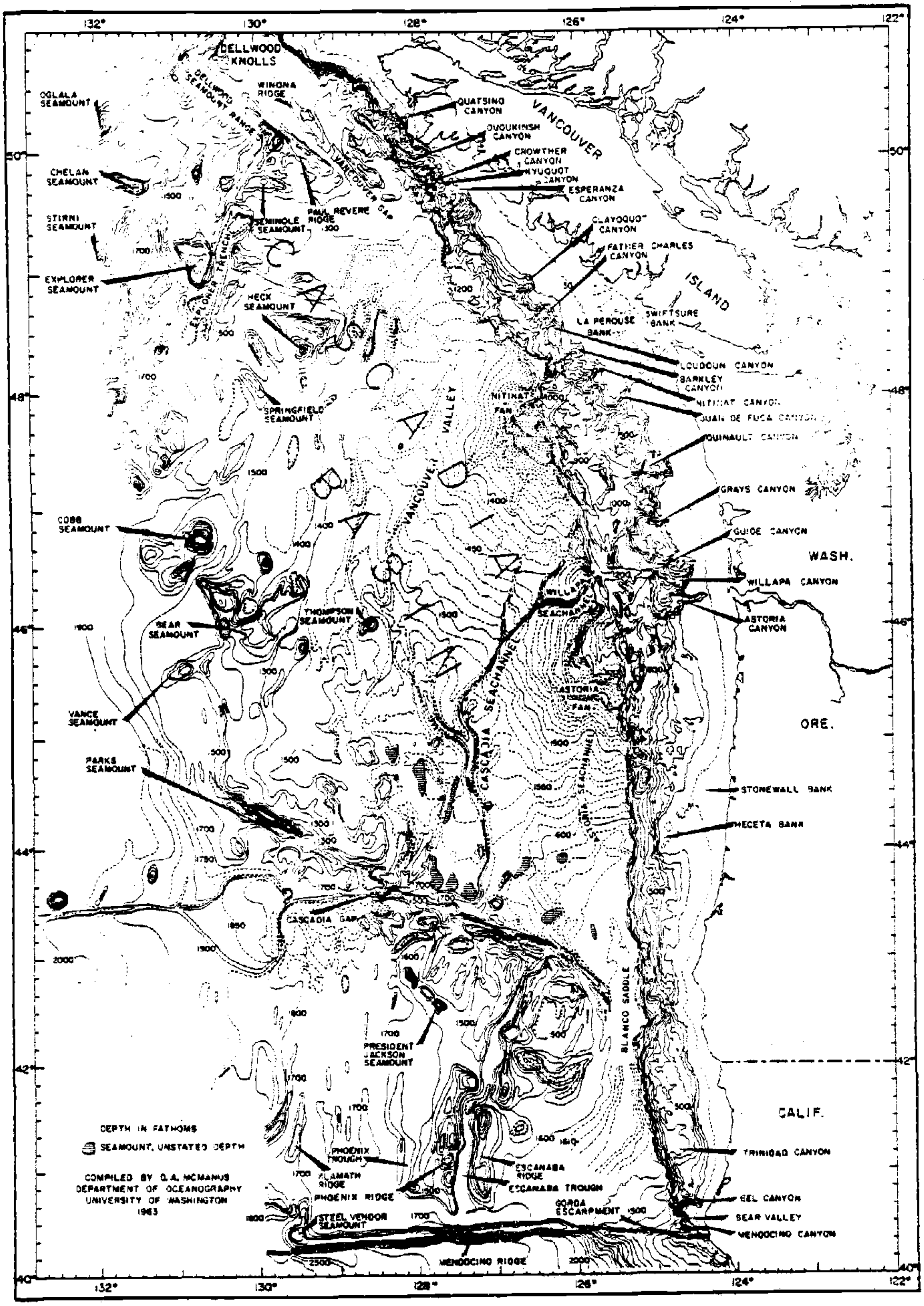

Figure 1. Bathymetry off the coast of the Northwestern United States. (after McManus, 1964)

Five major submarine canyons incise the continental margin. The Willapa and Astoria Channel systems, heading near the Columbia River, empty onto the lobate Astoria Fan and Cascadia Abyssal Plain (Carlson, 1968; Nelson and Kulm, 1973). Off California, the Eel and Mattole Canyons terminate on the Eel fan, a funnel shaped structure bounded on the east by the steeply inclined slope and to the south by the 1000 m high Mendicino escarpment. The Rogue Submarine Canyon, in contrast has no obvious adjacent abyssal fan.

Sediment Types

Continental margin sediments off Oregon display patterns similar to other exposed coasts (McCave, 1972). Well sorted sands occupy the inner portion of the shelf to about 50-120 m water depth (Runge, 1966; Roush, 1970; Kulm et al., 1975). A modern mid-shelf mud layer (MSML) occurs to seaward, the inner boundary probably being controlled by the surface wave regime (Komar et al., 1972). The outer shelf contains a mixture of muds and sands, the coarser components possibly being relict (Chambers, 1969; Spigai, 1971; McManus, 1972; Kulm et al., 1975). This pattern is common along most of the shelf, except behind the large outer shelf rock banks, where sediment distributions are more complex (Roush, 1970). Holocene shelf sedimentation rates are apparently quite variable. Spigai (1971) found rates of from 5 to 50 cm/10^3 yrs off Oregon based on C^{14} and Mazama ash (6600 yr bp) dates. In the vicinity of the mid- and outer shelf off the mouth of the Columbia River, Nittrouer (1977) reported Pb-210 accumulation rates of from 0.2 to 1.4 $gm/cm^2/yr$ (100 to 700 $cm/10^3$ yrs, if $\rho = 2.0\ gm/cm^3$). Rates decreased with distance from the river mouth and were greatest in the MSML.

Sediments on the open continental slope are predominantly monotonous, brownish to olive grey clays and muds, accumulation at high rates (30-60 $cm/10^3$ yrs) on the lower slope and at its base (Spigai, 1971; Cutshall, 1977; Dinkelman, unpublished data). The veneer of Holocene sediments on the upper slope tends to be thin, and off southern Oregon has sedimentation rates of about 10 $cm/10^3$ yrs (Carlson, 1968; Spigai, 1971). In scattered localities, patchy windows of Pleistocene foraminifera-rich, indurated, grey silty clays have been reported both off Oregon and Washington (Maloney, 1965; Spigai, 1971; Baker, 1973).

Cascadia Basin Holocene sediments are generally thick accumulations of olive grey to brown silty clays often with a gelatinous, brown, oxidized layer, 1-10 cm thick, at the surface (Duncan, 1968; Nelson, 1968; and others). Modern sedimentation rates are high (10-30 $cm/10^3$ yrs) throughout the abyssal region, but especially in the sea channel systems (Duncan, 1968; Griggs, 1969; Stokke et al., 1977) where rates greater than 50 $cm/10^3$ yrs are not uncommon. The lack of recorded turbidites in the last 6600 years suggest that hemipelagic deposition and/or low density turbid layer flows might be the dominant processes controlling lutite deposition in the abyssal basins (Nelson and Kulm, 1973; Stokke et al., 1977).

Clay Mineralogy

As mentioned earlier, previous clay mineral studies have been restricted to specific geographic and depositional environments, and have employed somewhat differing analytical techniques. In a comprehensive study of sediments on the northern Cascadia Abyssal Plain, Griggs (1969, 1970) and Duncan (1968, 1970) found that Holocene Columbia River-derived clays, characteristically high in montmorillonite, were carried via submarine channels to be deposited on the Astoria Fan and abyssal plain. Montmorillonite was found to decrease and chlorite to increase with distance southward from the Cascadia Sea Channel and Columbia River mouth. A southern chlorite-rich source was indicated but interpretations of transport mechanisms were inhibited because of a lack of samples on the continental margins. Spigai (1971), gave qualitative support to this hypothesis by finding chlorite and illite-rich clays on the shelf and slope in the vicinity of the Rogue River. A similar-chlorite-illite-rich clay assemblage has also been reported from surface sediments at DSDP Site 175 on the lower continental slope off north-central Oregon (Hayes, 1973).

On the Washington margin Olmstead (1972) found that montmorillonite-rich clays were ubiquitous, relecting the strong influence of Columbia River derived sediments. Using suspended sediment and bottom sampling, Baker (1973, 1976) showed that a thick bottom nepheloid layer (BNL) in submarine canyons on the Washington slope contained clays with a high Mo/Chl ratio, as did the underlying bottom deposits. He suggested that Columbia River material was carried via the BNL in channels down and across the continental slope to be deposited on the lower slope and abyssal plain.

Clays in the distal portions of the canyon and open slope areas showed a relative enrichment in chlorite. This was curious because no local source of chlorite has been reported from the nearby coastal mountains or in the lower reaches of the Columbia River. Baker attributed this enrichment to differential sedimentation. However, Gibbs (1977) has shown that montmorillonites being the smallest of the clay minerals, are transported farther than either illites or chlorites. Whether this is caused by size segregation or differential self floculation (Whitehouse et al., 1960; Ezwald and O'Melia, 1975) is still a matter of controversy. However, Baker's (1973) and Duncan et al. (1970) patterns of increasing chlorite away from a presumed continental source are opposite of predictions based on the relative size of the clay mineral. The present study proposes an alternative explanation.

PHYSICAL OCEANOGRAPHY

The surface circulation of the Northeast Pacific Ocean is controlled by a combination of the Westwind Drift and seasonally variable alongshore winds. The California Current, a broad sluggish southward flow has maximum velocities 200-500 km offshore or approximately over the Cascadia sea channel and westward (Wyatt et al., 1972; Nelson, 1976; Reid and Mantyla, 1976). The eastern limit varies seasonally. In the winter, the northward Davidson Current surfaces and extends offshore to 265 km, but seems to be concentrated within 160 km of the coast (Burt and Wyatt, 1964; Wyatt et al., 1972). Unfortunately, little is known of the circulation at depth in the deep ocean.

The continental shelf circulation is highly seasonal. From November to March, strong southwesterly winds induce northward and onshore geostrophic flow over the whole shelf (Huyer et al., 1975a,b). In the summer months, prevailing northerly winds cause coastal upwelling on the shelf (Figure 2a,b). During upwelling conditions narrow, nearshore currents flow northward over the inner shelf to about 15 km offshore. However, the general geostrophic flow is to the south and southwest (Huyer, 1974). A strong southward coastal jet with velocities between 20-40 cm/sec occurs over the mid- and outer shelf regions (Figure 2b) (Huyer, 1974; Huyer et al., 1975).

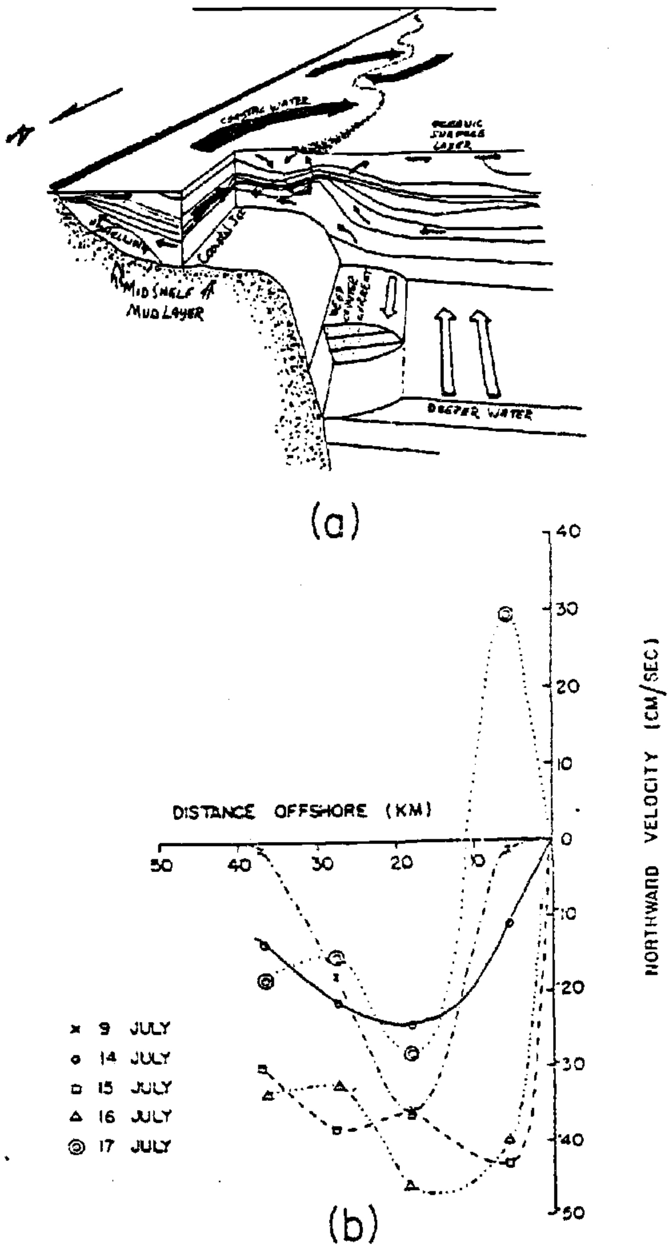

Figure 2. Summertime current structure during coastal upwelling on the continental shelf off Oregon. a) Schematic diagram (after Smith, 1975) showing nearshore upwelling, the southward coastal jet, and a deep water poleward undercurrent. b) Currents measured during CUE I in 1973. (after Huyer, 1974) Note the southward coastal jet centered from about 10 to 30 km. offshore.

The coastal jet is bounded by a subsurface poleward current with velocities between 10-20 cm/sec. The dimensions of the undercurrent and relation to the wintertime Davidson current are not well understood but the flow appears strongest on the upper slope and outermost shelf (Huyer et al., 1975) (see Figure 3, after Pak, 1970).

In contrast to the coastal rivers, which have flows highly skewed toward the winter months, the discharge of the Columbia River is maximal during the summer. This causes a large surface plume of low salinity, turbid water which radiates to the southwest, generally seaward of the upwelling zone (Figure 4). Using optical nephelometry, Pak et al. (1970) traced this water mass over 200 km southward along the Oregon coast. The flow is confined to the uppermost 40 meters water depth, based on temperature, salinity and optical properties. A secondary fluvial maximum from November to February is generally restricted to nearshore northward flow along the Washington coast (Barnes et al., 1972).

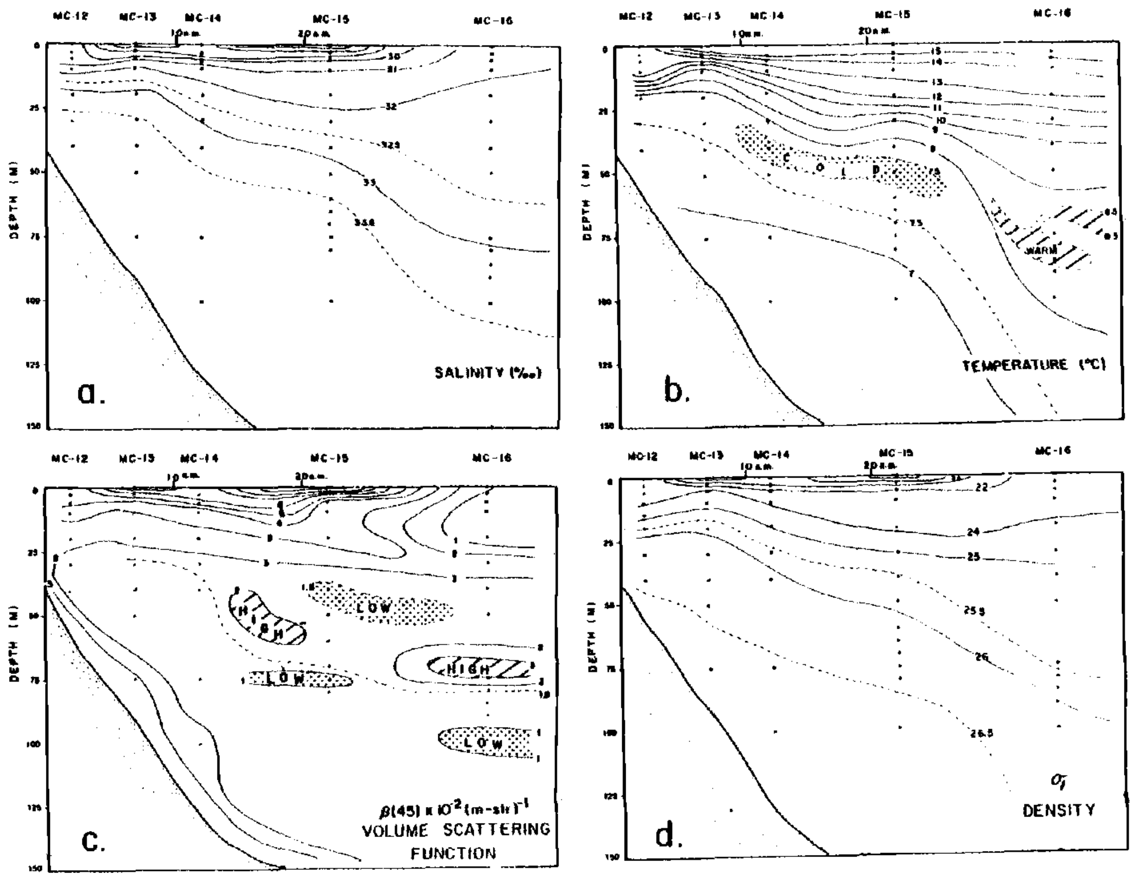

Figure 3. A profile of shelf upwelling during summer,1968 along 46°N. (after Pak, 1970) a) Salinity, b) temperature, c) volume scattering function (a measure of turbidity) and d) density. Zones of high turbidity are congruent with regions of warm (southerly ?) and cold (northerly ?) waters.

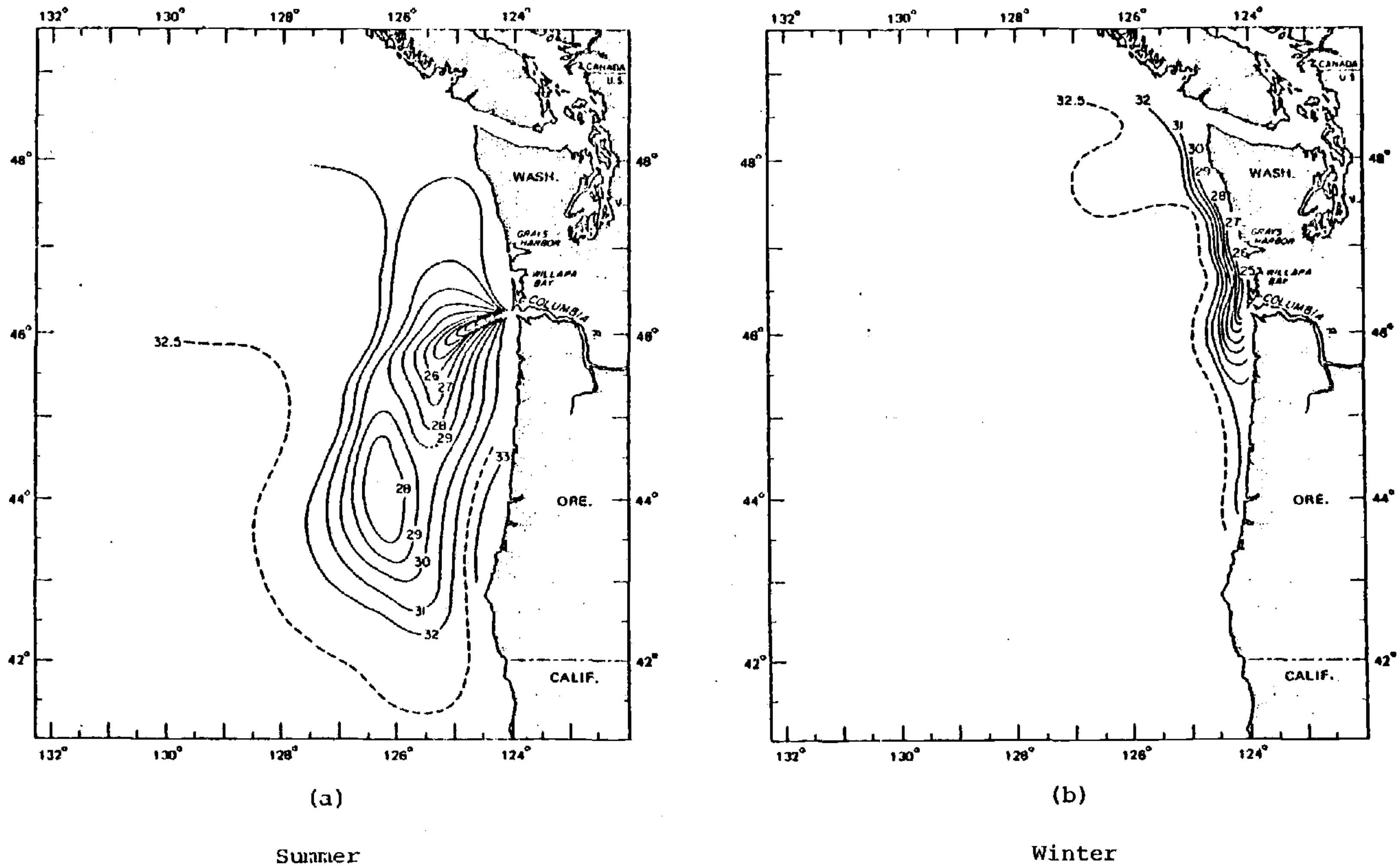

Figure 4. The Columbia River plume as evidenced by surface salinity in parts per thousand during a) summer and b) winter. (after Barnes, 1972)

SOURCE REGIONS

Hemipelagic sediments found on the continental slope and in the adjacent abyssal areas off Oregon are principally muds, the terrigenous fraction being primarily composed of clay and silt-sized particles. This material is potentially derived from four continental regions: 1) the vast basins drained by the Columbia River watershed, 2) the Washington-northern Oregon Coast Range, 3) the high Klamath Range of southern Oregon and northern California, and 4) the northern Californian Coastal Range province (Figure 5). The types of clay minerals present in the soils and rivers should be dependent on the parent rock, as well as the climate, topography and vegetation in each region. This section briefly describes the physiographic characteristics of the major source areas and the clay mineral assemblages to be expected in the rivers. The relative magnitudes of sediment discharges is deferred until later.

Columbia River Basin

With the second largest drainage basin (668,000 km^2) of any of the rivers in the conterminous United States (Curtis et al., 1973), the Columbia River drains diverse bedrock types and climatic regimes. Much of the watershed lies to the east of the Cascade Mountains where low rainfall, poor drainage and extensive flood basalts and volcanic

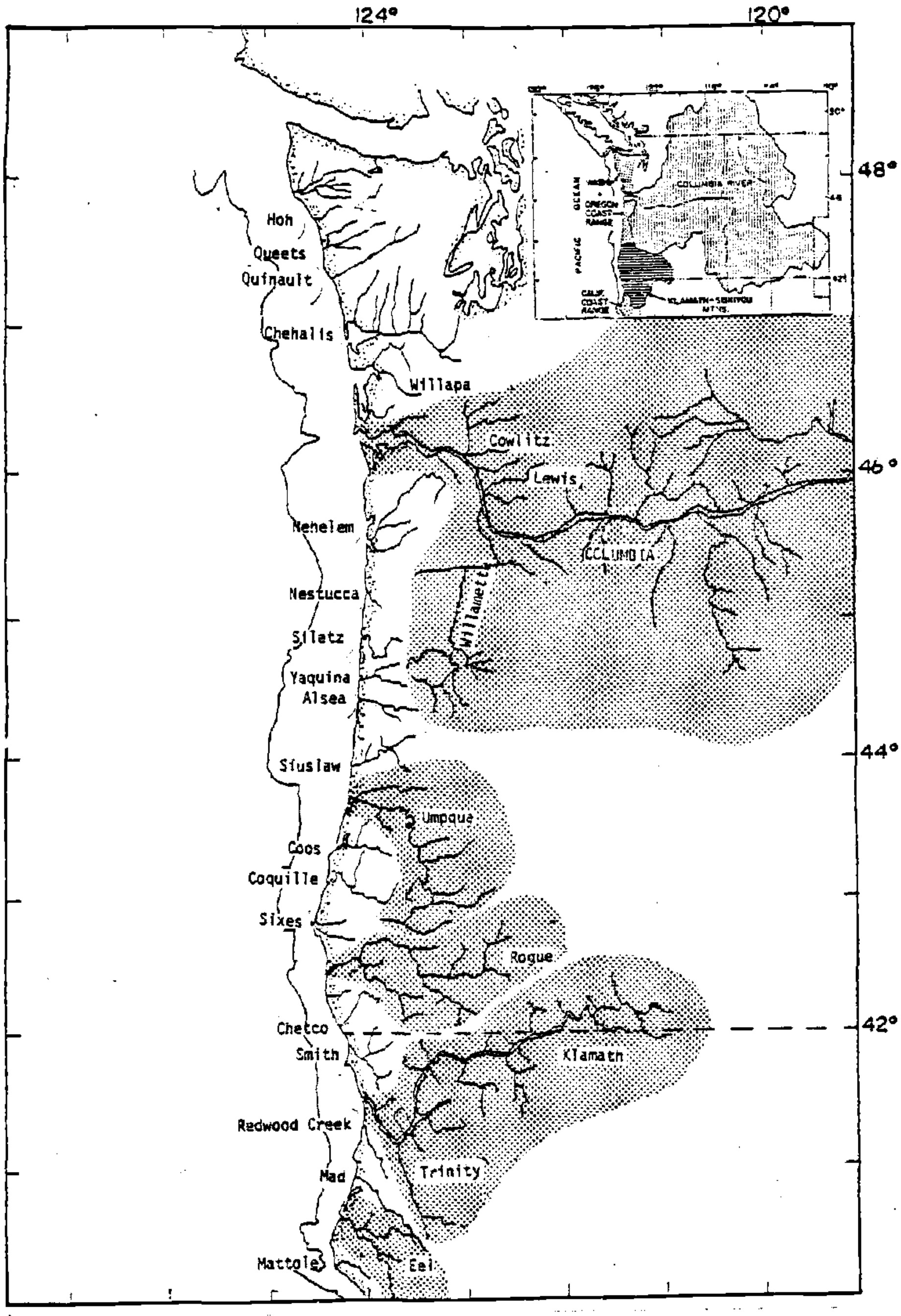

Figure 5. Streams and drainages of the American Pacific Northwest.

extrusives are conducive to the formation of montmorillonites*. Knebel (1968), in a thorough study of the clay mineralogy of Columbia Rivers sediments to the east of the Cascades, found that clays in the lower reaches of the river were highly montmorillonitic, reflecting the strong influx of sediments from the semi-arid Snake River sub-basin. The Upper Columbia River sub-basin, draining plutonic and metamorphic bedrock, presently contributes minor amount of illite and chlorite to the lower portions of the river. The volcanic extrusives in the Cascade Range and the volcano-sedimentary suites on the eastern flanks of the humid Coast Range presumably also add montmorillonites to the Columbia main stem via the Deschutes and Willamette Rivers (Snavely et al., 1964; Knebel et al., 1968; Baker, 1973; Youngberg et al., 1975). Consequently, by the time the Columbia reaches the Pacific Ocean, montmorillonites are the predominant minerals in the clay fraction of the riverine sediment.

Oregon-Washington Coast Range Province

The mountains of the Coast Range lie adjacent to the Pacific Ocean and extend from about the Coquille River in Oregon to the northern Washington border. Numerous streams drain the western

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* The term montmorillonite as used here is synonomous with smectite and refers to the generic grouping of clays which expand to 16.8-17 A on glycolation, or 17.4-17.8 A on treatment with glycerol.

flank of the range, the largest being the Umpqua in Oregon and the Chehalis in Washington. The terrain is composed of mixed volcanic and sedimentary suites of thick submarine basalt flows, breccias, arkosic and micaceous sandstones and tuffaceous greywackes (Baldwin, 1976; Snavely et al., 1964). Few clay analyses are available for rivers draining the area, but soil and rock analyses indicate that montmorillonites, illites and montmorillonites with chloritic intergrades are prevalent in the clay fraction (Jenne, 1961; Snavely et al., 1964; Niem et al., 1976). Thus the Coast Range probably has a clay mineralogy similar to that of the Columbia River.

Klamath Mountains Province

The Klamath Mountains are a rugged group of individual ranges spanning the Oregon-California border. The geology is complex with low grade regional metamorphism (greenschist facies), and extensive tectonic deformation effectively masking stratigraphic relationships (McKee, 1972; Baldwin, 1976). Uplifted metasedimentary and metavolcanic strata, and scattered ultramafic and granitic intrusions comprise the primary geologic units (Irwin, 1966; Davis, 1966; Dott, 1971; Baldwin, 1976). Detritus from these source rocks is carried mainly by the Rogue, Smith and Klamath Rivers. Published clay analyses from these rivers are scarce, but available information suggests clay low in montmorillonite and high in chlorite and illite is presently being supplied to the ocean (Duncan, 1968; Griffin et al., 1968; Hayes, 1973).

Northern California Coast Range Province

The complex melange known as the Franciscan Assemblage forms the core of the Northern California Coast Range. Greywackes with lesser amounts of shales, greenstones, cherts and intrusive serpentinites are the predominant rock types (Bailey et al., 1964; Page et al., 1965). The terrain is morphologically juvenile with prominent northwest trending ridges and deeply incised valleys. Because the strata is often schistose or phyllitic and structurally deformed the area is tectonically unstable and landslides and mass failures are common (Ficklin et al., 1975; Kelsey, 1977, 1978). North of Cape Mendicino, the principal streams include the Mattole, Eel and Mad Rivers and Redwood Creek. Chlorite and illite appear to be the major clay minerals present in the streams (Griffin et al., 1968; Hein, 1973; Ficklin et al., 1975).

METHODS OF CLAY ANALYSIS

To insure adequate regional coverage for clay analysis, surface samples from 72 box and gravity cores were selected from the study area (Figure 6). Cores were collected on numerous OSU research cruises from 1965 to 1976 and kept in refrigerated, moist condition in the OSU core library. One to two cubic centimeter samples were disaggregated and organics were removed in a 250 ml solution of 35% hydrogen peroxide, buffered to pH 7.0 with ammonium hydroxide. Clay size (≤ 2 μm) fractions were separated by settling and decantation. Carbonates were removed by treating the candle filtered clay concentrates with acetic acid, buffered to pH 4.8 with Na-acetate. After candle filtering to reconcentrate the suspension, each sample was saturated with 1 M $MgCl_2 \cdot 6H_2O$, centrifuged and the clear supernatant fluid was decanted. This process was repeated three times. In a similar manner, a cleanup procedure using hot, distilled water was performed twice to remove excess Mg^{++} ions.

Oriented X-ray mounts were prepared for each suspension by suctioning aliquots of uniform optical density onto porous silver plugs. Slides were dried in a dessicator overnight to remove excess water. This step proved important in improving precision in replicate analyses by allowing uniform expansion of the basal layers of the clays upon solvation. Four mounts were made per specimen. In

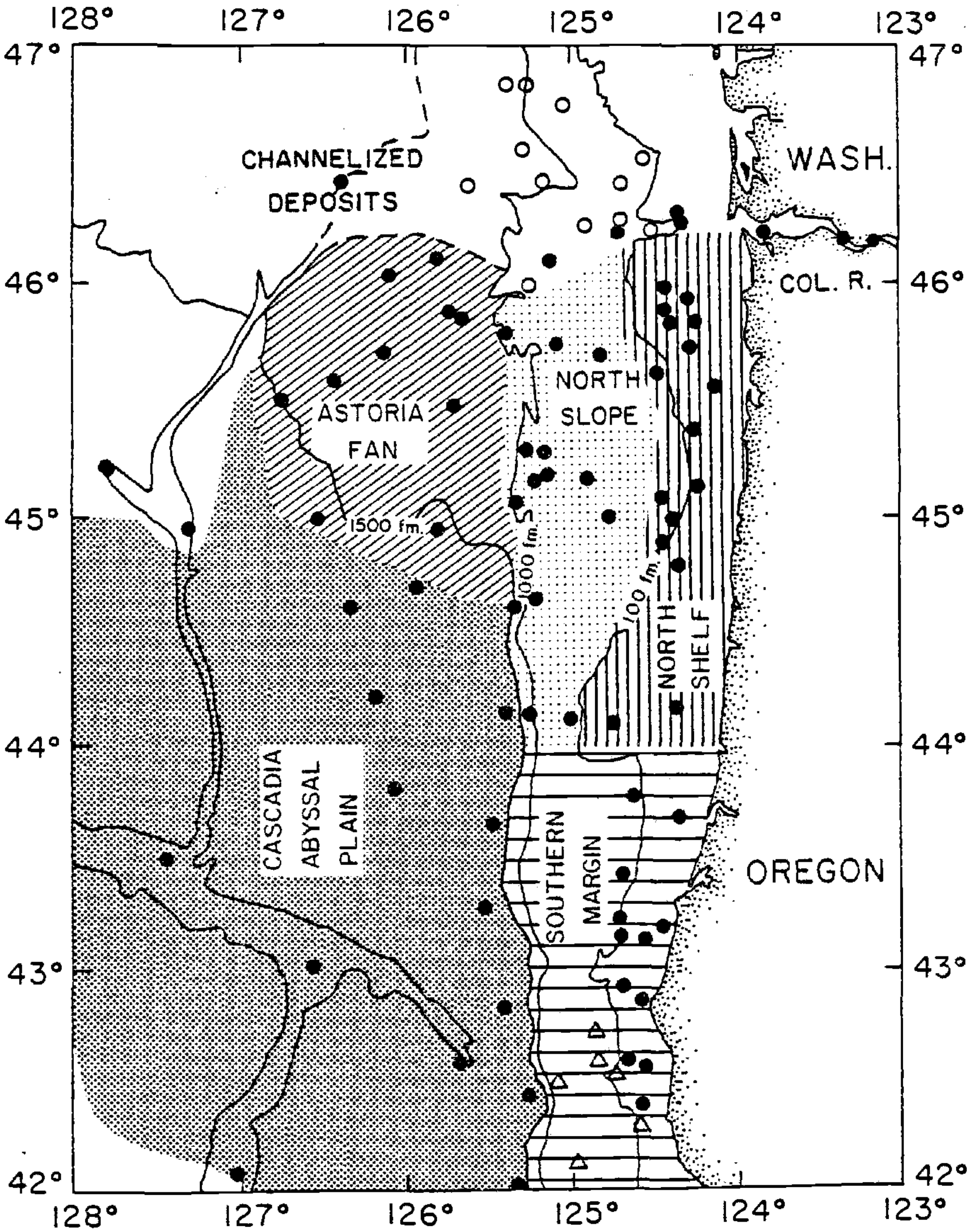


Figure 6. Location of cores and clay mineral province groupings. Open circles are samples analyzed by Baker (1973); open triangles are samples from Spigai (1971).

order to expand the 001 lattice of the montmorillonites, two of the slides were solvated in heated ethylene glycol vapor for two hours. The other two slides were treated with glycerol to check for consistency between the two treatments and to examine compatibility of these data with work by Spigai (1971) on the southern Oregon margin.

Slides were X-rayed on a Norelco diffractometer with a Geiger-Muller counting tube, using monochromatized Cu Kα radiation and a Ni filter. Forty of the samples were step-scanned from 3-30°2θ in increments of 0.02°2θ with 4 second counts; the remainder were scanned from 3-15°2θ under the same conditions. Smoothed diffractograms were generated from raw data recorded on magnetic tape by an 11 point smoothing algorithm on a CDC 3300 computer.

Stacked diffractograms showing north-south trends on the shelf and east-west trends along about 45°N are shown in Figures 7 and 8. All of the X-ray plots showed sharply defined peaks at 10 Å (illite) and 7 Å (chlorite and/or kaolinite). Based on Biscaye's (1965) criteria for distinguishing kaolinite from chlorite using the 3.58 kaolinite (002) and 3.54 Å chlorite (004) peaks, very little kaolinite was present. The 7 Å reflections were thus assumed to be solely from chlorite. Montmorillonites were also detected in all diffractograms. Peaks ranged from low shoulders and small humps to large, broad apices dominating the diffractograms. In some instances minor amounts of 14 Å vermiculite may have been present, but the stronger

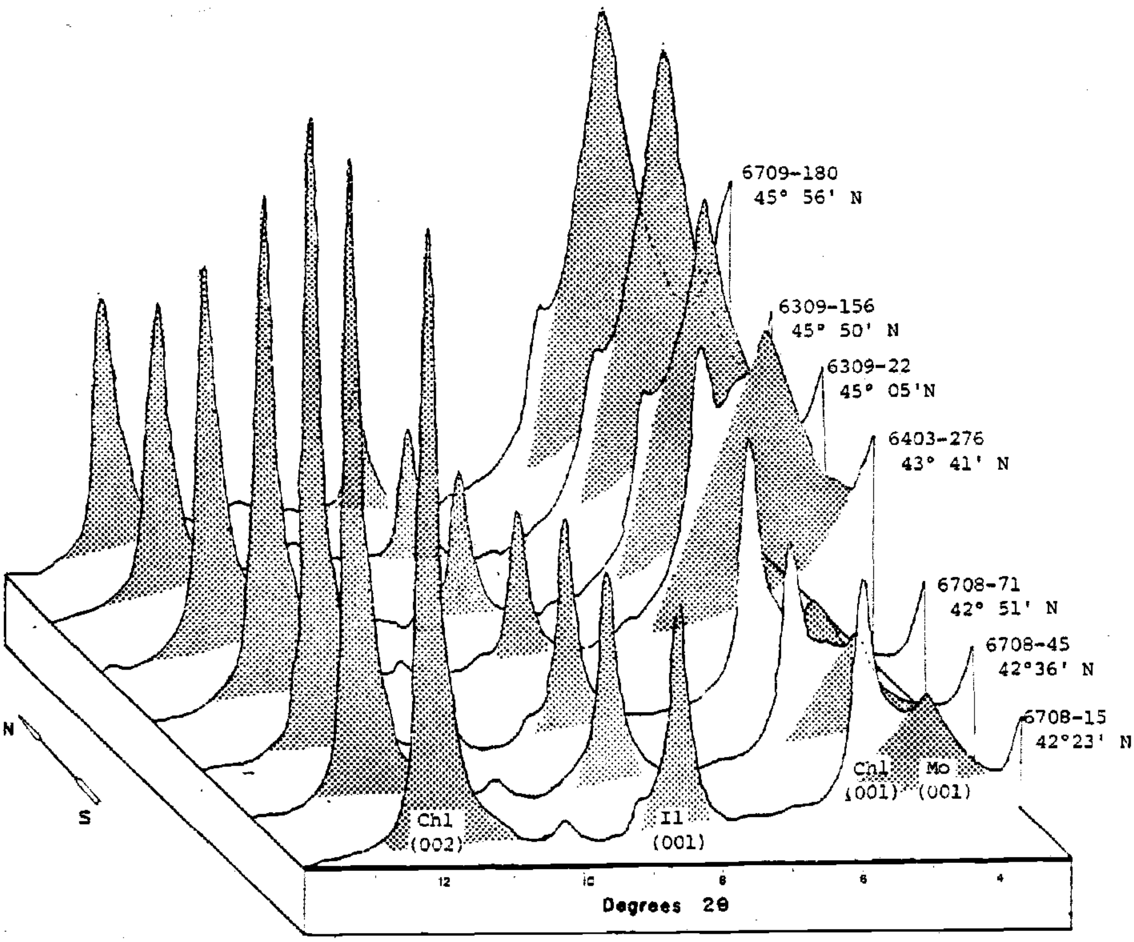


Figure 7. Stacked X-ray diffractograms arranged in a north-south transect along the shelf. Note the increase in montmorillonite (Mo) and decrease in chlorite (Chl) on the shelf, going from south to north. Illite (Il) remains fairly constant.

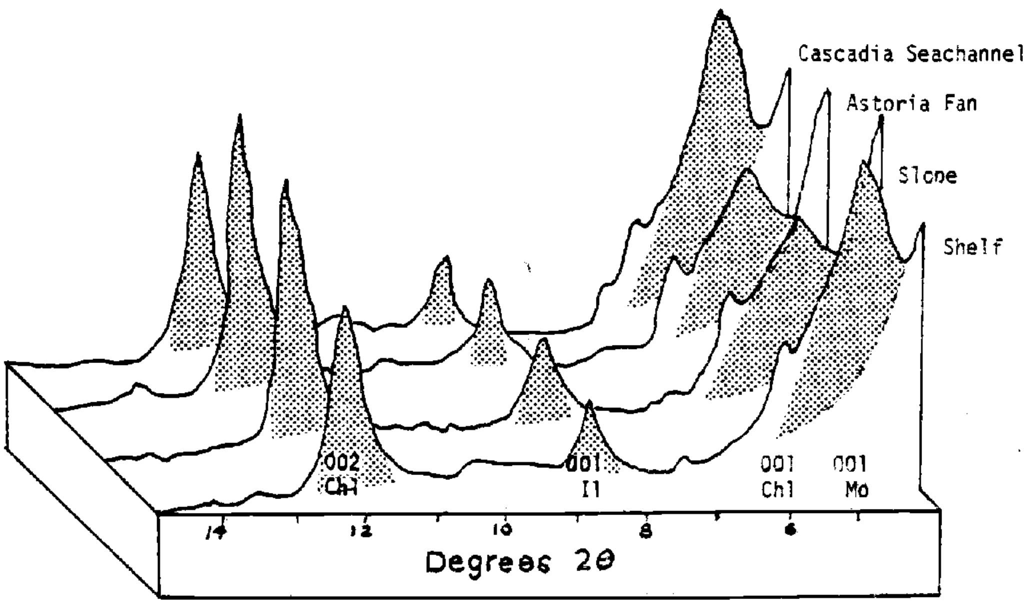


Figure 8. Stacked X-ray diffractograms along an east-west profile at about 45° N. Montmorillonite (Mo) is dominant on the shelf and in the Cascadia Seachannel while chlorite (Chl) shows stronger reflection peaks on the slope and Astoria Fan.

montmorillonite and chlorite reflections made positive identification difficult.

Mixed layered reflections were notably absent in all of the marine clays studied but did occur in clays from the Columbia River. This may suggest that halmyrosis of the poorly crystalline, intergraded clays found in soils occurs before final deposition in the ocean.

Other minerals were commonly identified in the diffractograms. These included minor peaks of 3.2 Å (feldspar), 4.26 Å (quartz), 9.2 - 9.4 Å (talc - pyrophyllite) and occasionally 3.0 Å (amphiboles). A low signal/noise ratios precluded further investigation.

With regard to solvation treatments, whether peak areas or percentages were used, the correlation between treatments was excellent ($r = 0.954$). However because of its higher dipole moment, hence better expansion capability, ethylene glycol gave proportionally larger montmorillonite peak areas than glycerol. This provided an expanded range of values with only a small increase in measurement error (variation between duplicates) due to uncertainties in determining the larger peak areas. For this reason and because studies on the Washington margin and Columbia River used ethylene glycol solvation, the glycolated samples were chosen for further study.

Semiquantitative clay "percentages" for 7 Å chlorite, 10 Å illite and 17 Å montmorillonite were calculated for all X-ray plots using the technique of Biscaye (1965). A smooth exponentially decreasing baseline curve was created by graphically fitting Gaussian curves to interpeak points on several diffractograms with a Dupont curve resolver. An averaged curve was then applied to all data. Areas were blocked out by extrapolating straight line segments from the half peak slopes. Areal determinations were made with a polar planimeter or a digital color image analyzer. Weighting factors of 1 x montmorillonite, 4 x illite, and 2 x chlorite peak areas then were applied and the "percentage" of each clay determined by dividing the weighted area of that clay by the sum of the weighted peak areas for all of the clays.

An estimate of precision for each clay type was made by calculating the square root of the variance (i.e. standard deviation) associated with the percent differences between duplicate slides. For the glycolated samples, values were: ± 3.3% for montmorillonite, ± 2.6% for chlorite, and ± 2.0% for illite.

CLAY MINERAL DISTRIBUTIONS

Graphical Analysis

A total of 72 glycolated samples were studied from various localities off Oregon (Figure 6). Over the entire area, the relative abundances of the three principal clay types (montmorillonite, illite, and chlorite) varied considerably (Table 1). Values range from 8-59%, 17-36%, and 22-60% for montmorillonite, illite, and chlorite, respectively.

When mapped areally, clay mineral percentages exhibit definite geographic trends (Figures 9, 10, 11). In general, montmorillonite abundances (Figure 9) are highest ($\geq$ 40%) in the vicinity of the Columbia River mouth, on the northern shelf and in channelized deposits of the Astoria and Willapa Canyons as well as the Cascadia and Astoria Fan Sea channels. Illite has a more cosmopolitan distribution, but is 10-15% higher on the southern margin (Figure 10). Chlorite is the predominant clay mineral in the southeast and south (Figure 11), especially on the southernmost margin.

Two major exceptions to this general pattern are found in the uniformly high montmorillonite (40-60%) on the northern shelf and the relatively high chlorite and low montmorillonite abundances (40-50% vs 20-30%) on the northern slope. The gradients of the montmorillonite percentage appear to emante from the Columbia River

TABLE 1. Summary of mean clay percentages, variances and ranges for each of the seven clay mineral province groupings.

		GROUP MEANS			GROUP VARIANCE			GROUP RANGE		
Group	N	Montmorillonite	Illite	Chlorite	MO	IL	CHL	MO	IL	CHL
1 Columbia River	3	52.2	22.5	25.3	10.6	8.5	1.6	49.8-55.9	19.2-24.8	24.3-26.7
2 Northern Shelf	16	44.5	22.7	32.8	39.3	8.5	28.4	36.3-58.8	17.4-28.2	21.8-41.9
3 Channelized Deposits	6	44.0	23.1	32.9	57.2	7.5	42.6	33.0-54.5	19.3-26.7	24.8-41.3
4 Astoria Fan	8	31.4	25.5	43.1	7.1	1.0	6.1	26.4-35.0	23.9-27.1	40.2-47.7
5 Northern Slope	14	27.8	29.4	42.8	25.1	6.0	26.6	22.4-42.0	25.3-35.1	27.8-51.6
6 Cascadia Abyssal Plain	15	24.9	27.6	46.5	9.5	6.6	6.3	20.5-30.6	23.8-33.7	43.5-51.9
7 Southern Margin	10	17.6	31.5	50.9	33.0	8.2	24.3	8.2-26.9	27.4-36.2	44.8-60.2
TOTAL	72	32.2	26.6	41.2				8.2-58.8	17.4-36.2	21.8-60.2

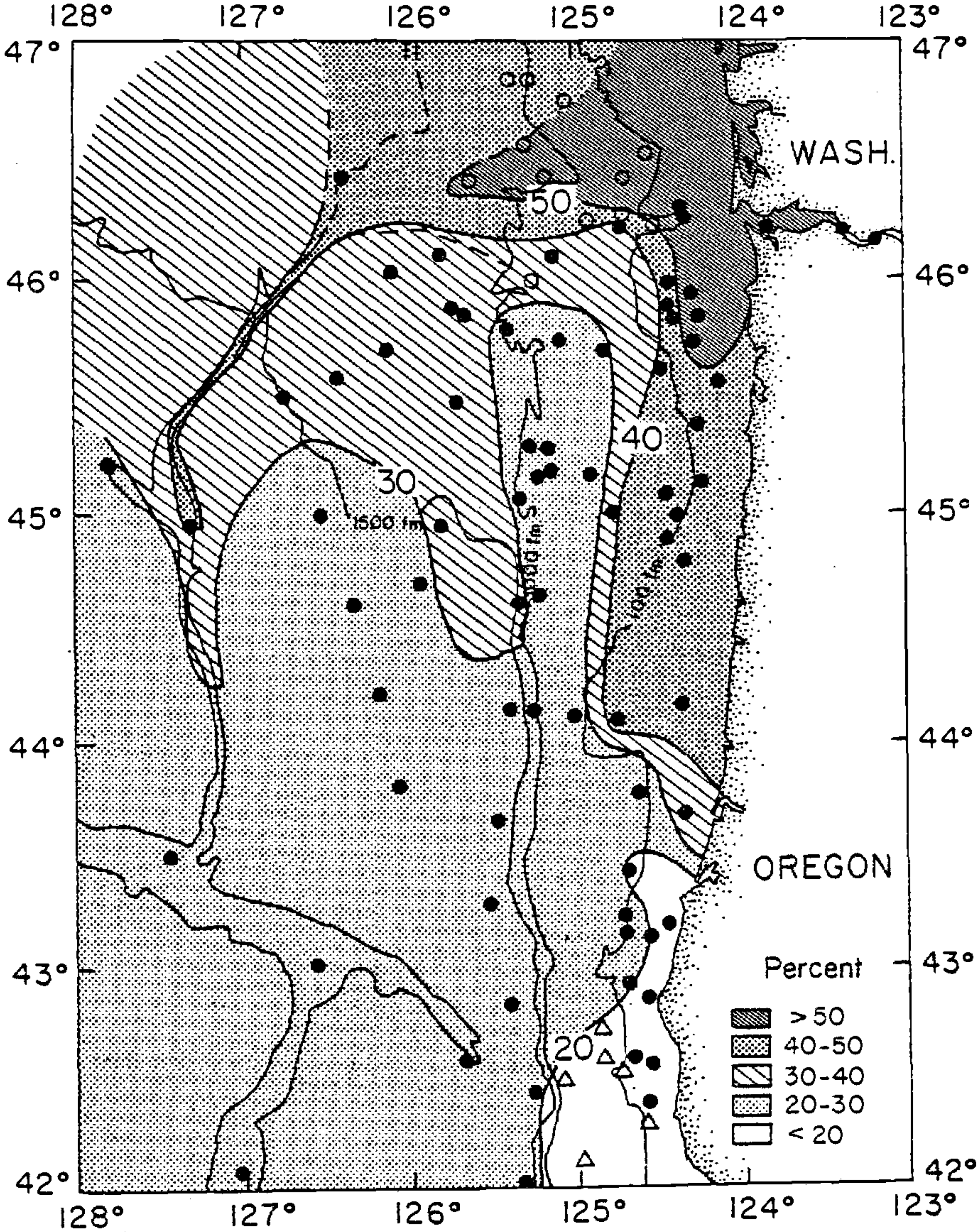


Figure 9. Montmorillonite distribution patterns (in percent)

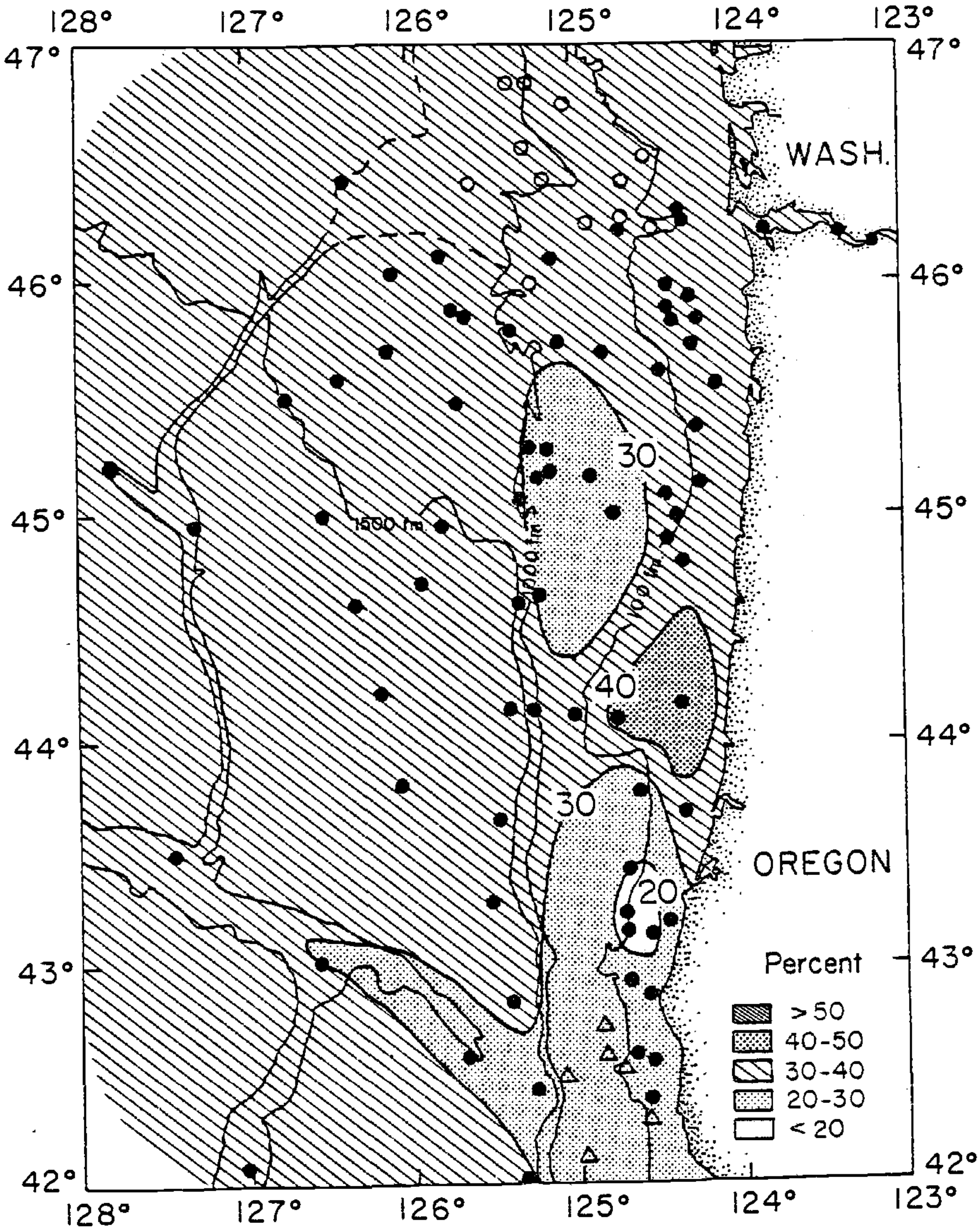


Figure 10. Illite distribution patterns. (in percent)

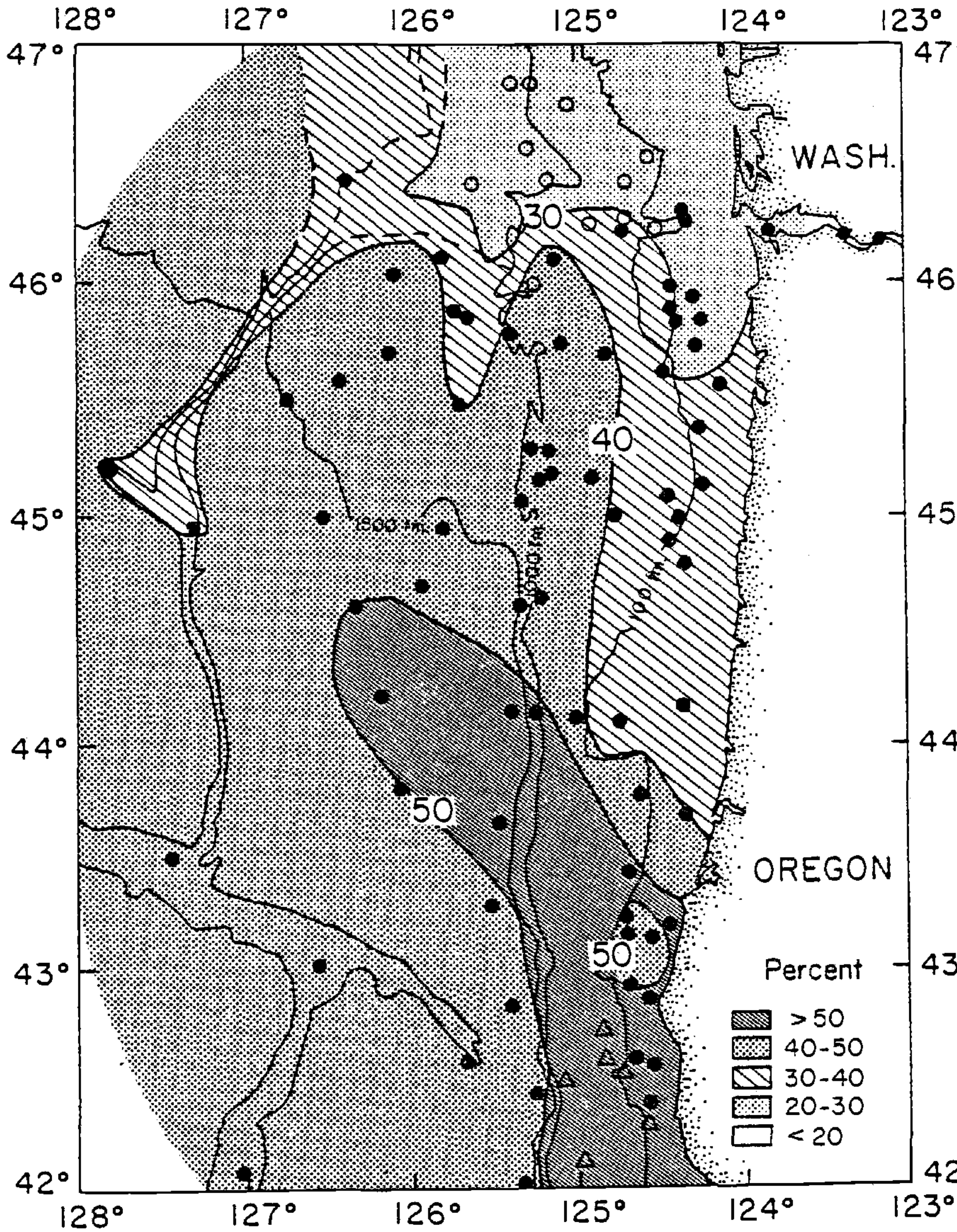


Figure 11. Chlorite distribution patterns (in percent).

and are largely confined by the topography. These patterns are in close agreement with bottom studies of manmade radionucleides by Osterberg et al. (1963) and Gross (1972). These workers found that radioactivity, characteristic of the effluent from the Hanford nuclear power plant on the Columbia River, was present in marine sediments in the Astoria Canyon and on the northern shelf but absent in slope sediments near the river mouth. The closely spaced montmorillonite contours and lack of radioactivity in the nearby slope sediments could imply that Columbia River derived clays are significantly admixed and diluted with non-radiogenic sediments from another source. Alternatively, deposition of the Columbia River type material could be limited to the shelf, upper slope and channels. These possibilities will be examined in the discussion.

When relative clay abundances are plotted on a ternary diagram, as a whole, the samples lie on a linear trend dominated by changes in montmorillonite and chlorite (Figure 12a). When the analyses of Spigai (1971) off southern Oregon and Baker (1973) from the Washington slope are added to the present data, the clay abundances off Oregon and Washington form a continuum (Figure 12b). The lack of scatter about a straight line drawn through the points is suggestive of mixing between two sources; one high in montmorillonite, the other high in chlorite and, to a lesser extent, illite.

To better study the relations between localities, the samples

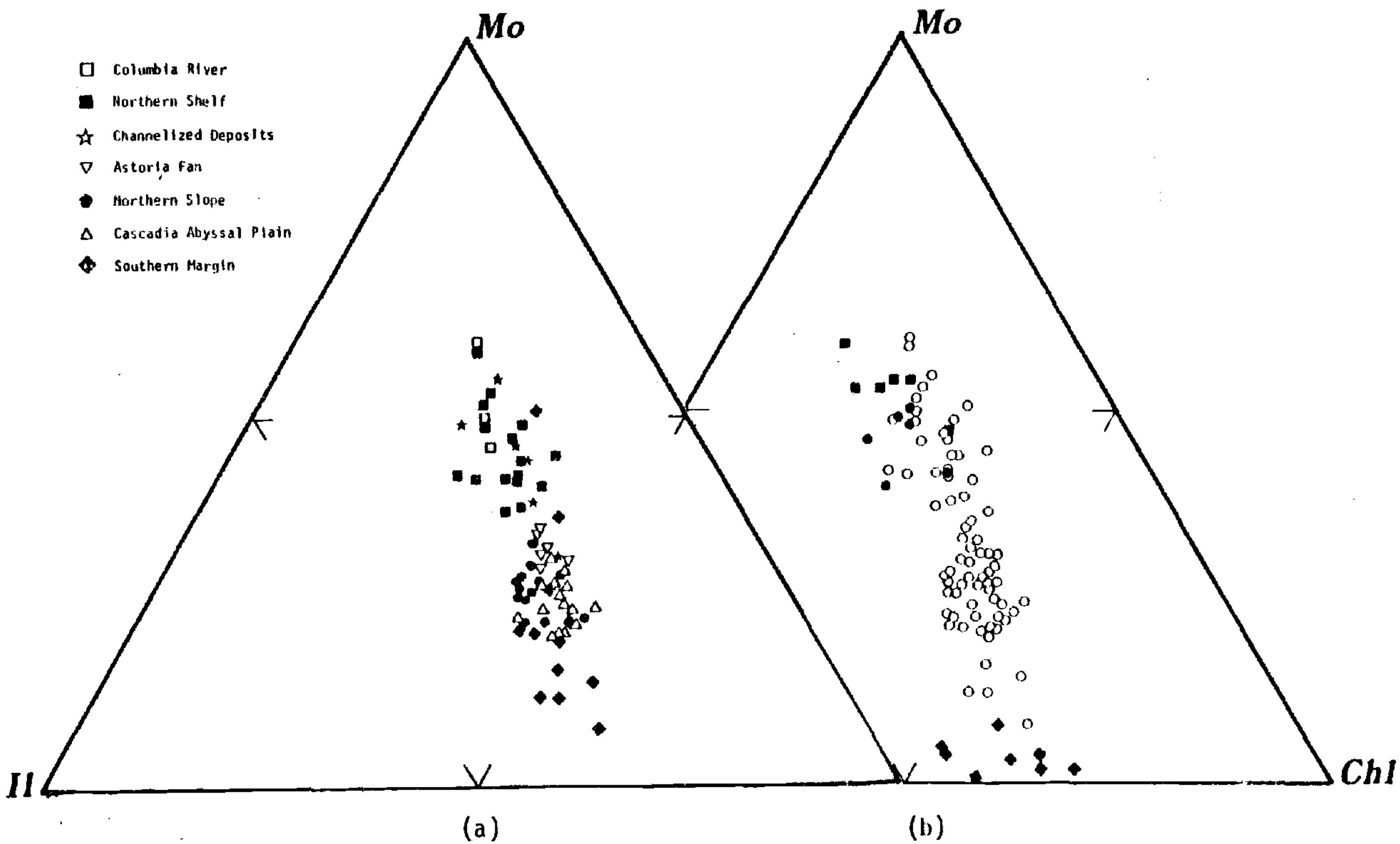


Figure 12. Clay mineral ternary diagrams with montmorillonite (Mo), illite (Il) and chlorite (Chl) as apeces. a) Samples from this study. b) Samples from this study (O), from Spigai (1971) on the southern Oregon margin (◆), and from Baker (1973) in channels (■) and open slope deposits (●) off the Washington coast.

were grouped into seven distinct clay mineral provinces (Table 1) (Figure 13a, b). In addition to clay mineralogy, classifications were delimited by geographic location and changes in offshore physiography. For instance, the north-south shelf division was chosen to coincide with the approximate Coast Range-Klamath Mountains boundary. The northern shelf-slope break was picked at about the 300-500 m contour where the slope steepens and clay mineral assemblages diverge. A lack of samples on the southern slope precluded subdivision of the southern margin; however, Spigai's (1971) analyses showed little variation in the clay mineralogy of shelf and slope samples in this area. The Astoria Fan-Cascadia Abyssal Plain boundary was chosen arbitrarily at the 2800 m contour.

When the samples are assigned to their respective groupings (Figure 13), several well defined clusters are observed. Groups 1-3 (Columbia River, northern shelf and channelized deposits) and Baker's (1973) Washington margin samples form the montmorillonite-rich terminus. The other extreme is occupied by the chlorite-rich southern margin samples from this study (Group 7) and Spigai (1971). Cascadia Basin (Groups 4, 6) and northern slope samples (Group 5) lie in an intermediate range, with the slope clays 10-15% lower in montmorillonite than expected from their locations relative to the postulated source areas.

On the Cascadia Abyssal Plain, the trend of increasing chlorite

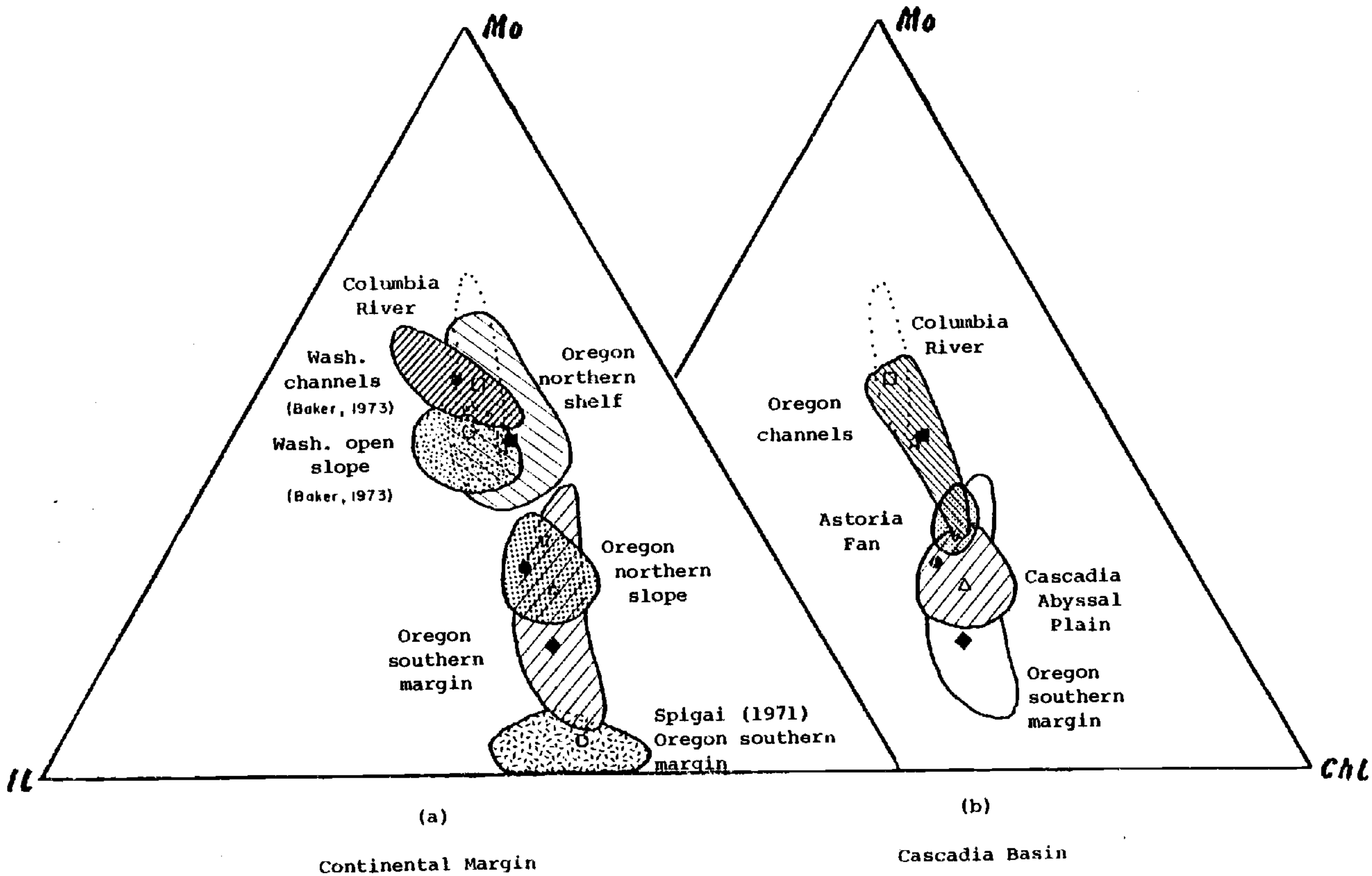


Figure 13. Samples grouped by clay mineral provinces on ternary diagrams; a) the continental margin, b) the Cascadia Basin. Symbols are the means of the clay province groupings. See Figure 10a for symbol identification.

and decreasing montmorillonite with distance from the Columbia River is identical to that noted by Duncan et al. (1970). However, Duncan's montmorillonite percentages are about 5-15% higher than observed in the present study, probably because of his use of smeared glass slides for X-ray diffraction. This method has been shown to selectively emphasize smaller particles such as montmorillonites, because of differential size sorting during slide preparation (Gibbs, 1965, 1968). Clay mineral percentages from samples taken in the same area as Spigai (1971) are in good agreement despite differences in solvation techniques.

Numerical Analysis

An analysis of variance (ANOVA) model (Neter and Wasserman, 1974) was used 1) to examine the differences between provinces, and 2) to determine the relative homogeneity of samples within each area. The ANOVA model involved three nested factor levels: slides, samples and groups (provinces). An estimate of the homogeneity of each group was made by comparing the total between sample variance within each group to the variance associated with duplicated measurements (cf. Table 2). Snedecor's F statistic was computed and compared with the critical value at $\alpha = 0.05$ level of significance. If between-sample variance was of about the same magnitude or less than within sample variation ($F_{obs} \leq F_{.95}$) the group was considered

TABLE 2. Between-sample versus within-sample analysis of variance. Within-sample variability is derived from differences between duplicates, i.e., $\frac{1}{n} \sum_{i=1}^{n} \sum_{j=1}^{2} (Y_{ij} - \bar{Y}_{i\cdot})^2$; between-sample variability, from the differences of the sample means from the group means, i.e., $\frac{1}{n-1} \sum_{i=1}^{n} (\bar{Y}_{i\cdot} - \bar{Y}_{\cdot\cdot})^2$. Groups are considered heterogenous when the F statistic (MSSB?MSSW) of at least two clay minerals is significantly larger than the critical table value of $F_{.95}$.

Group	N	Clay type	Between sample mean sum of squares (MSSB)	Within sample mean sum of squares (MSSW)	F statistic	Critical F $F_{.95(n-1,n)}$	Heterogenous	Homogenous
2 Northern Shelf	16	MO	39.32	9.71	4.05	2.36	*	
		IL	8.53	2.82	3.02	2.36	*	
		CHL	28.39	3.84	7.39	2.36	*	
3 Channelized Deposits	6	MO	57.15	15.02	3.80	4.39		*
		IL	7.51	2.16	3.48	4.39		*
		CHL	42.57	7.02	6.06	4.39	*	
4 Astoria Fan	5	MO	11.13	2.12	5.26	5.19		*
		IL	0.57	1.11	0.51	5.19		*
		CHL	10.13	0.72	14.17	5.19	*	
5 Northern Slope	14	MO	25.10	3.58	7.01	2.57	*	
		IL	6.02	1.89	3.19	2.57	*	
		CHL	26.70	1.70	15.04	2.57	*	
6 Cascadia Abyssal Plain	12	MO	9.50	2.69	3.54	2.72	*	
		IL	3.66	1.22	3.00	2.72		*
		CHL	5.96	2.54	2.34	2.72		*
7 Southern Margin	10	MO	33.38	4.57	14.61	3.02	*	
		IL	2.89	2.03	1.42	3.02		*
		CHL	26.36	5.33	4.94	3.02	*	

homogenous.

Based on at least two clay minerals, the abyssal groupings (i.e. the Astoria Fan, Cascadia Abyssal Plain and channelized deposits; Groups 3, 4, 6) were homogeneous. This may imply that the processes governing the clay mineral distributions are not localized phenomena. The minimal between-sample variation was observed regardless of whether the groups were considered separately or pooled into a larger unit. The margin groupings (Groups 2, 5, 7), in contrast, showed large between-sample variability. This heterogeneity may be due to inherent variability in a single source, mixing within a given depositional environment, or perhaps, differential sedimentation.

To determine whether the clay mineralogy of the *a priori* groupings were similar, differences between paried group means for each clay type were tested with a Student t-test. Based on at least two clay minerals at an $\alpha = .05$ significance level, no significant differences were found between the Columbia River, north shelf and channelized deposits. The similarity was largely due to the high between-sample variability in the latter two groups. While geographically separate, the northern slope, Cascadia Abyssal Plain, and southern margin provinces showed similar clay mineralogies, forming a cluster distinct from the other groups. Clays from the Astoria Fan had a similar mineralogy to those from the northern slope but differed from samples in other areas. Minor shifting of the areal boundaries of the provinces (i.e., placing individual samples in an adjacent grouping) had no significant affect on these findings.

The results of the analysis of variance support the more intuitive interpretations gained from Figures 9-13. Clays found on the mid- and lower continental slope and adjacent abyssal plain are more closely related to a southern source than to the nearby Columbia River or Oregon Coast Range sources. The continental shelf clay percentages are highly variable, but, in general, assemblages are proximal to their nearby source areas. Abyssal basin clays, in contrast, are relatively homogenous over a large area and appear to be a rather even mixture of two distinctive end member clay mineralogies. Specific source areas will be discussed in the next section.

SEDIMENT SUPPLY

Fluvial Influx

Mixing between sources of disparate mineralogy is the most obvious way of accounting for the observed systematic variations in the clay mineral distributions. Possible sediment sources include fluvial runoff, coastal erosion, and eolian input.

With regard to fluvial sources, the clay distributions off Oregon require a chlorite-rich southern source of comparable magnitude to the Columbia. Since clays reside almost solely in the suspended loads of rivers, it is worthwhile to consider the relative magnitudes of present clay suspended sediment discharge for rivers proximal to the study areas.

Previous regional estimates of sediment discharge by Hidaka (1966a, b), Judson and Ritter (1964), and Gross et al. (1967) concluded that the Columbia is the predominant sediment source in the area. However these studies did not have access to actual sediment discharge records. Values were estimated by multiplying average annual water discharges by a yearly mean particulate concentration. These concentrations, in parts per million, were adopted from measurements taken in 1910-1911 by Van Winkle (1914a, b). Since the coastal rivers discharge 80-95% of their water and sediment during brief winter storm periods (Percy et al., 1974), such averaged yearly concentrations give unrealistically low values for annual suspended sediment discharges. Major storm events were probably also missed in the Van Winkle data.

Table 3 is a compilation of currently available mean annual suspended sediment and water discharges for streams monitored daily by the USGS. Bedload, which may constitute 10-20% of the total load, is not considered here as it is mostly sand, and reliable information is sparse.

The gaging stations were located beyond tidal influences, generally a few miles upstream of the river mouth. The suspended loads thus assume dynamic equilibrium, that is, no net deposition downstream of the monitoring site. This assumption may not be unreasonable since hydraulic trapping of the silts and clay at least in the smaller estuaries is effective only on a seasonal basis because of scouring during peak winter discharges (Boggs, 1976). Moreover, suspended loads are typically 70-80% clay and silt, whereas most estuaries contain mainly sand (Kulm and Byrne, 1967; Brown, 1973; Percy et al., 1974).

Where rivers were not monitored, estimates of average yearly suspended sediment loads have been made from annual sediment yields (discharge/drainage area) for monitored streams in the same province. The yields chosen are consistant with sediment production maps (Hidaka, 1966a,b) which were derived from sediment ponding

TABLE 3. Mean annual water and suspended sediment discharges of coastal rivers from Cape Mendocino to the Straits of Juan de Fuca. Assumed annual sediment yields of 2600 tonnes/km^2-yr (7429 tons/mi^2-yr); 350 tonnes/km^2-yr (1000 tons/mi^2-yr) and 125 tonnes/km^2-yr (392.5 tons/mi^2-yr) are indicated by single (*), double (**), and triple (***) asterisks, respectively.

River	State	Gaged Drainage Area (km^2)	Years of Water Record	Average Annual Water Discharge (km^3/yr)	Period of suspended sediment discharge measurements (years)	Annual Sediment Yield tonnes/km^2-yr	Average suspended sediment discharge (10^3 tonnes/yr)	Ref.
California Coast Range								
Mattole at Petrolia	Ca	622	28	1.24		*	(1617)	1
Eel at Scotia	Ca	8063	66	6.59	1958-1976 (19)	2894.6	23339	1, 10, 11
+Van Duzen at Bridgeville		560	10	0.76	1958-1967 (10)	2522.3	1412.5	1, 7
Total		8623		7.35		2870.4	24751.5	
Mad at Arcata	Ca	1256	29	1.39	1958-1974 (17)	2004.5	2517.6	1, 11
Redwood Creek at Orick	Ca	720	25	0.98	1971-1976 (6)	2592.5	1866.6	8
TOTAL		11221		10.96			30753	
Klamath Mountains								
Klamath at Orleans	Ca	21970	49	7.38	1967-1976 (10)	179.7	3947.5	1, 2
+ Trinity at Hoopa		7392	49	4.83	1965-1976 (12)	937.4	6928.9	1, 9
Total		29362		12.21		370.4	10876.5	
Smith	Ca	1577	45	3.46		**	(552)	1
Chetco	Or	702	6	2.28		**	(246)	1
Pistol	Or	272	6	0.44		**	(96)	1
Rogue	Or	13394	15	10.10		**	(4688)	1

TABLE 3. continued

River	State	Gaged Drainage Area (km^2)	Years of Water Record	Average Annual Water Discharge (km^3/yr)	Period of suspended sediment discharge measurements (years)	Annual Sediment Yield tonnes/km^2-yr	Average suspended sediment discharge (10^3 tonnes/yr)	Ref.
Klamath Mountains, cont.								
Elk	Or	243	3	0.4		**	(85)	1
Sixes	Or	334	31	0.54	1968-1970 (3)	1071.3	357.8	1
TOTAL		45886		29.43			16901.	
Oregon Coast Range								
Coquille	Or	1960	47	2.21		***	245	1,4
Coos	Or	1567	17	2.71		***	196	1
Umpqua at Elkton	Or	9534	70	6.77	1956-1973 (18)	339.9	3243	1,6
Siuslaw at Mapleton	Or	1523	8	2.17	1969-1975 (7)	124.8	190	1
Alsea at Tidewater	Or	865	36	1.40	1973-1974 (2)	187.3	162	1,5
Yaquina	Or	655		0.96	1973-1974 (2)	128.8	84.4	1
Siletz	Or	523	56	1.42		***	65	1,4
Nestucca	Or	466	11	1.05		***	58	1
Wilson	Or	417	45	1.10		***	52	1,4
Trask	Or	376	29	0.86		***	47	1
Tillamook	Or	607	33	0.76		***	76	1
Nehalem	Or	1730	36	2.49		***	216	1
TOTAL	-	20228		23.90			4634	

TABLE 3. continued.

River	State	Gaged Drainage Area (km^2)	Years of Water Record	Average Annual Water Discharge (km^3/yr)	Period of suspended sediment discharge measurements (years)	Annual Sediment Yield $tonnes/km^2$-yr	Average suspended sediment discharge (10^3 tonnes/yr)	Ref.
Columbia River System								
Columbia at Vancouver	Or-Wa	624190	88	173.90	1964-1969 (6)	22.7	14170	1,2
+ Willamette	Or	28700		28.81		***	(3588)	1
+ Cowlitz	Wa	6104		8.77		***	(763)	1
+ Lewis (E & W Fork)	Wa	2217	33/39	4.93		***	(227)	1
TOTAL		661211		216.21			18748	
Washington Coast Range								
Willapa Bay								
Willapa at Willapa	Wa	337	21	0.60		***	(42)	1
Naselle at Naselle	Wa	142	47	0.39		***	(18)	1
North at Raymond	Wa	567	49	0.87		***	(71)	1
Greys Harbor								
Chehelis (3 rivers)	Wa	5439	20/47	6.89	1962-1965 (4)	114.5	(622.8)	1,3
Humptulips	Wa	337	35	1.21		***	(42)	1
Quinault at Quinault Lake	Wa	684	65	2.55		***	(86)	1
Queets at Clearwater	Wa	1153	21	3.75		***	(144)	1
Hoh at Forks	Wa	655	16	2.34		***	(82)	1
TOTAL		9314		18.60			1108	

TABLE 3. continued.

References:

1 USGS Water Data Reports, Water Resource Data for California, Oregon and Washington (1965-1976)

2 Curtis (1973)

3 Glancy (1971)

4 Roden (1967)

5 Brown and Ritter (1971)

6 Curtiss (1975)

7 Kelsey (1977)

8 Janda (1975, 1977)

9 Knott (1974)

10 Hawley and Jones (1969)

11 Brown (1971)

measurements behind reservoirs.

For comparison regionally, the discharge data are summarized by physiographic province in Table 4. In terms of water flow the Columbia River system is the major fluvial outlet to the ocean, supplying 216 km^3 of fresh water annually, or about 75% of the regional total. Individual coastal rivers contribute only a small fraction of this amount.

With regard to sediment load, however, the Eel River in northern California presently outranks the Columbia (24.8 versus 18.7 million tonnes annually), although the Eel is only 2% the size in drainage area. Other important sediment sources in 10^6 tonnes/year include the Klamath (10.8), Rogue (4.7 estimated), Umpqua (3.2), and Mad (2.5) rivers (Figure 14).

When combined, the rivers of the California Coast Range and Klamath Mountains provide about two-thirds of the yearly regional suspended sediment discharge (Figure 15). The Columbia system contributes only about a quarter of the total. Oregon Coast Range rivers together supply about 25% of the load of the Columbia but four times that of the Washington coastal rivers because of a larger drainage area.

The reasons for these anomalously large fluxes would appear to lie in the climates and geomorphologies of the various basins. The rivers of the northern California Coast Range, lying in the wet coastal belt, flow through landforms which are inherently unstable.

TABLE 4. Summary of mean annual fluvial water and suspended sediment discharges by region.

Region	Approximate Area (km^2)	Annual Water Discharge (km^3/yr)	%	Average Sediment yield (tonnes/km^3-yr)	Quality of Coverage	Annual Sediment Discharge (10^3 tonnes/yr)	%
Northern California Coast Range	11221	10.96	3.7	2000-3000	Good	30753	42.6
Klamath Mountains	45886	29.43	9.8	300-500	Fair	16901	23.4
Oregon Coast Range	20228	23.90	8.0	125-350	Fair	4634	6.4
Columbia River System	661211	216.21	72.3	20-120	Fair	18748	26.0
Washington Coast Range	9314	18.60	6.2	100-120	Poor	1108	1.6
TOTAL	747870	299.1	100.0			72144	100.0

FIGURE 14.

AVERAGE ANNUAL SUSPENDED SEDIMENT DISCHARGE OF MAJOR RIVERS OF THE PACIFIC NORTHWEST (10^6 TONNES/YEAR)

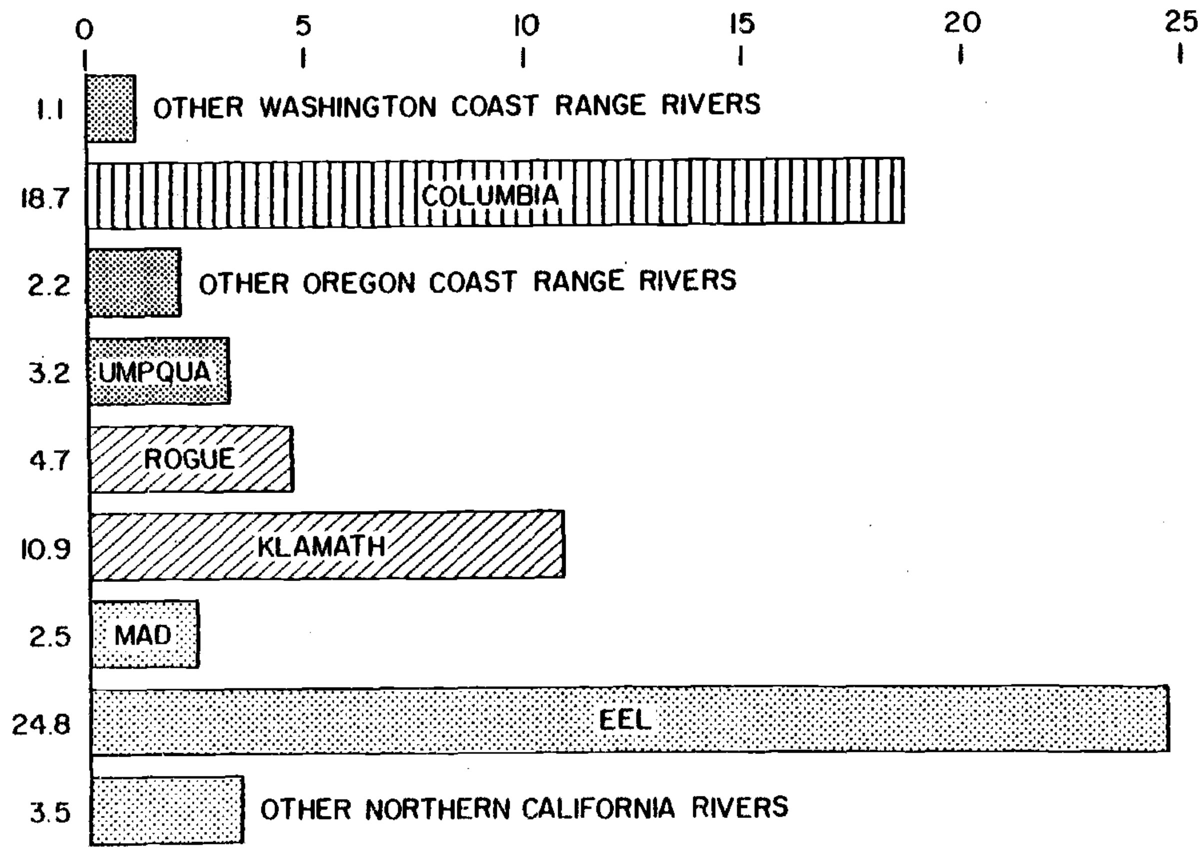
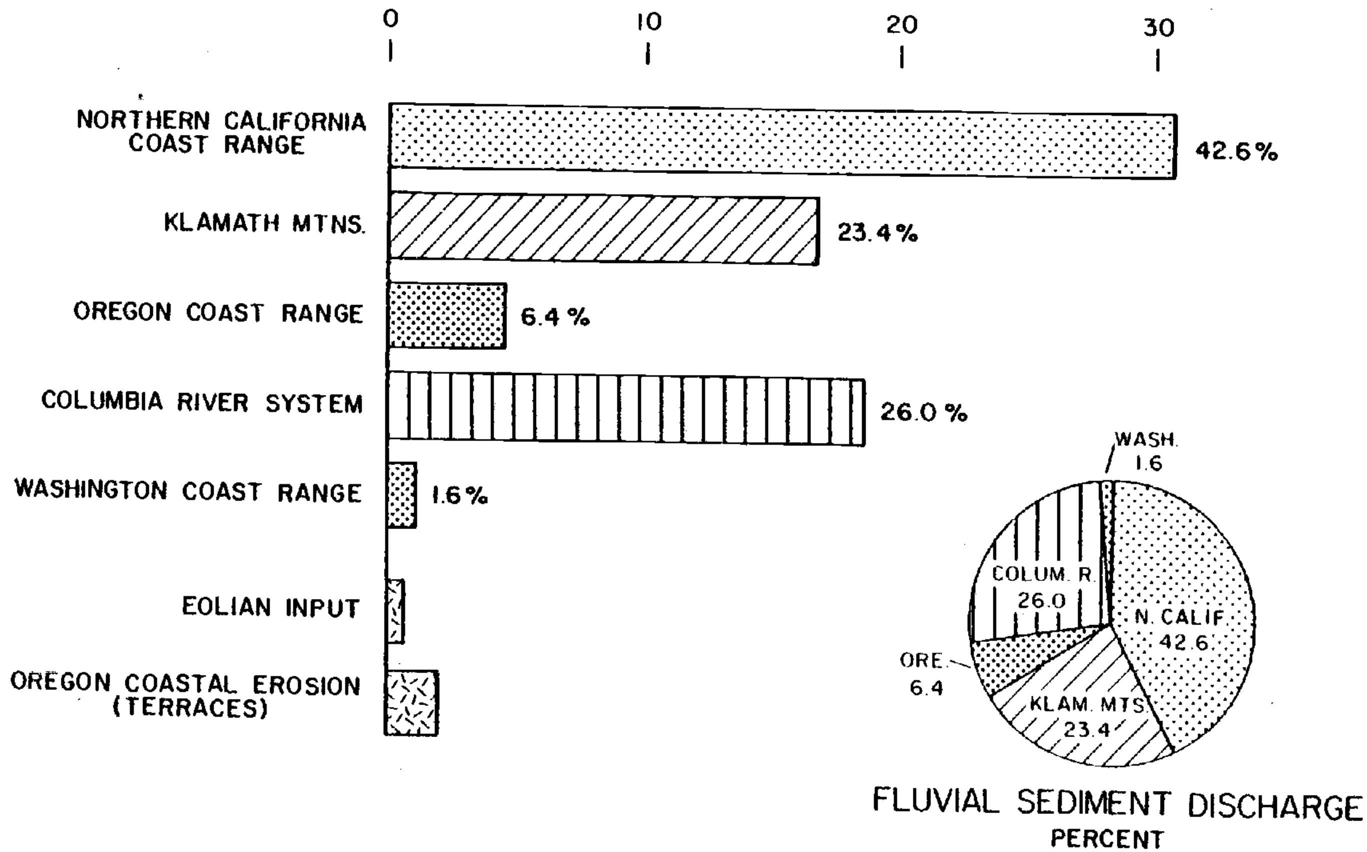


FIGURE 15.

SUSPENDED SEDIMENT DISCHARGE
BY REGION
(10^6 TONNES/YEAR)



Drainage patterns are tectonically controlled by numerous major faults in the area. River gradients are steep and the rock units are often schistose, thus mass slumping and stream sloughing are commonplace especially during the heavy winter runoff (Janda, 1975; Ficklin et al., 1975; Kelsey, 1977, 1978). This combination of circumstances gives the northern California region the highest sediment yield values in the United States and among the highest in the world (Judson and Ritter, 1964; Holeman, 1968; Curtis et al., 1973).

The Columbia River, in contrast, has a low sediment yield because much of its watershed lies to the east of the Cascade Range, where thin soil cover, poor drainage and semi-arid conditions are prevelent (Knebel, 1968; Baldwin, 1976). While the building of eleven dams in the last 60 years may have changed streambank configuration, considerably, Whetten (1969) found that the effects of damming of the Columbia seems to have been to interupt transport and concentrate the mass flux to times of high water, rather than to reduce the total annual suspended load. Thus manmade influences may have amplified the natural periodicity of sediment flux.

The Oregon-Washington Coast Range rivers have intermediate sediment yields consistant with other humid, forested mountainous basins of low relief (Langbein, 1958). The Klamath rivers have somewhat higher yields probably because of greater relief, morphologically juvenile terrain, and perhaps, more unstable geologic units (i.e., metasedimentary strata).

The coastal areas have been heavily logged in the last 100 years. Clear cut logging may have increased stream siltation through slope destablization and removal of protective vegetation. In studies of three small sub-basins of the Alsea River, Williams (1964), Brown and Krygier (1971), and Harris (1977) found that clearcutting increased stream suspended sediment discharges almost twofold over loads in the unlogged control areas. This condition persisted for about six years after actual logging stopped, whereupon sediment discharges returned to their prelogging levels. Thus while logging operations may temporarily increase particulate river loads, whether such practices could significantly affect the relative magnitudes of long-term stream sediment fluxes is uncertain.

Coastal Erosion

Coastal erosion is another potential source of fine-grained sediments. The 509 km long Oregon coastline can be divided into three broad morphologic categories: 1) unconsolidated sands in beaches and dunes (192 km), 2) Pleistocene terraces and older sedimentary deposits (246 km), and 3) volcanic headlands (71 km) (from the geognostic map of Dicken, 1961). Of these, the terraces and sedimentary units would be the only potential sources of silt and clay sized particles. Even so, most of this material is sand, since the majority of Pleistocene terraces are uplifted beach and nearshore deposits.

In an erosion study of about 100 km of central Oregon coastline, Smith (1978) found that in the past 34 years, annual erosion rates averaged 23.4 cm/yr (9.2 in/yr) for terraces, sedimentary deposits, and unconsolidated sands and 5.3 cm/yr (2.1 in/yr) for volcanic headlands. Assuming these rates to be representative of the entire Oregon coastline, if bluffs average about 15 m in height (Dicken, 1961), then about $862.3 \times 10^3 m^3$ or 2156 thousand tonnes (if $\rho = 2.5$ cm/cm^3) would be contributed annually to the ocean by Oregon coastal sedimentary deposits and terraces. This coastal erosion value is only about 3% of the total annual fluvial suspended sediment discharge. However, it amounts to about 20% of the yearly flux from the Coast Range and Klamath Mountain rivers in Oregon. Thus, even though coastal erosion may not be a major source of terrigenous sediment to the offshore areas, it may be locally important as a factor affecting compositional trends on the nearby continental shelf.

Eolian Input

The coincidence of the axis of the jet stream at about 30° N latitude with latitudinally zoned bands of high illite and quartz in marine sediments led Rex (1958) and Griffin (1968) to suggest that wind transported dusts may be significant sources of sediment, especially in the deep sea. Based on snowfield accumulations, Windom (1969, 1975) calculated that the eolian contribution to marine sediments may be on the order of .01 to .1 cm/10^3 yrs. In the area bounded by 40-48°N and 124-128°W, this would be equivalent to an annual influx of from 71 to 710 thousand tonnes per year, assuming a particle density of 2.5 gm/cm^3. The total fluvial suspended sediment discharge into the area is estimated at about 72 144 thousand tonnes per year (Table 4). Thus, eolian input is only about a tenth to one percent of the annual sediment load from rivers and would not be expected to have a major influence on compositional patterns of sediments in the study area.

SEDIMENT SUPPLY AND SEDIMENTATION RATES

If clays and other fine-grained sediments are supplied to the offshore Oregon areas mainly by the northern California rivers and the Columbia, sedimentation rates should then display a bimodal distribution analagous to the clay patterns. The compilation map of sedimentation rates, shown in Figure 16, illustrates that such is indeed the case. In general, rates vary from less than 5 to greater than 50 cm/10^3 years. Sedimentation rates are variable on the shelf, low to intermediate on the upper slope and very high on the lower slope. In the abyssal areas, rates are highest in the vicinity of the Astoria and Willapa Fans in the north and near the Blanco Fracture Zone to the south. To the west of the Cascadia Sea Channel, rates are very low, suggesting that most of the terrigenous sediment is deposited adjacent to the continent. Barnard (1973) and Stokke et al. (1977) found high sedimentation rates on the Nitinat Fan. This might imply that other rivers, such as the Fraser which empties into the Straits of Juan de Fuca, are perhaps also important as sediment sources off the Washington coast.

To determine if the amounts of sediment presently being contributed by rivers is comparable to the amount of Holocene material deposited in the adjacent oceanic areas, we can compute a rough sediment budget, assuming that all of the continentally derived

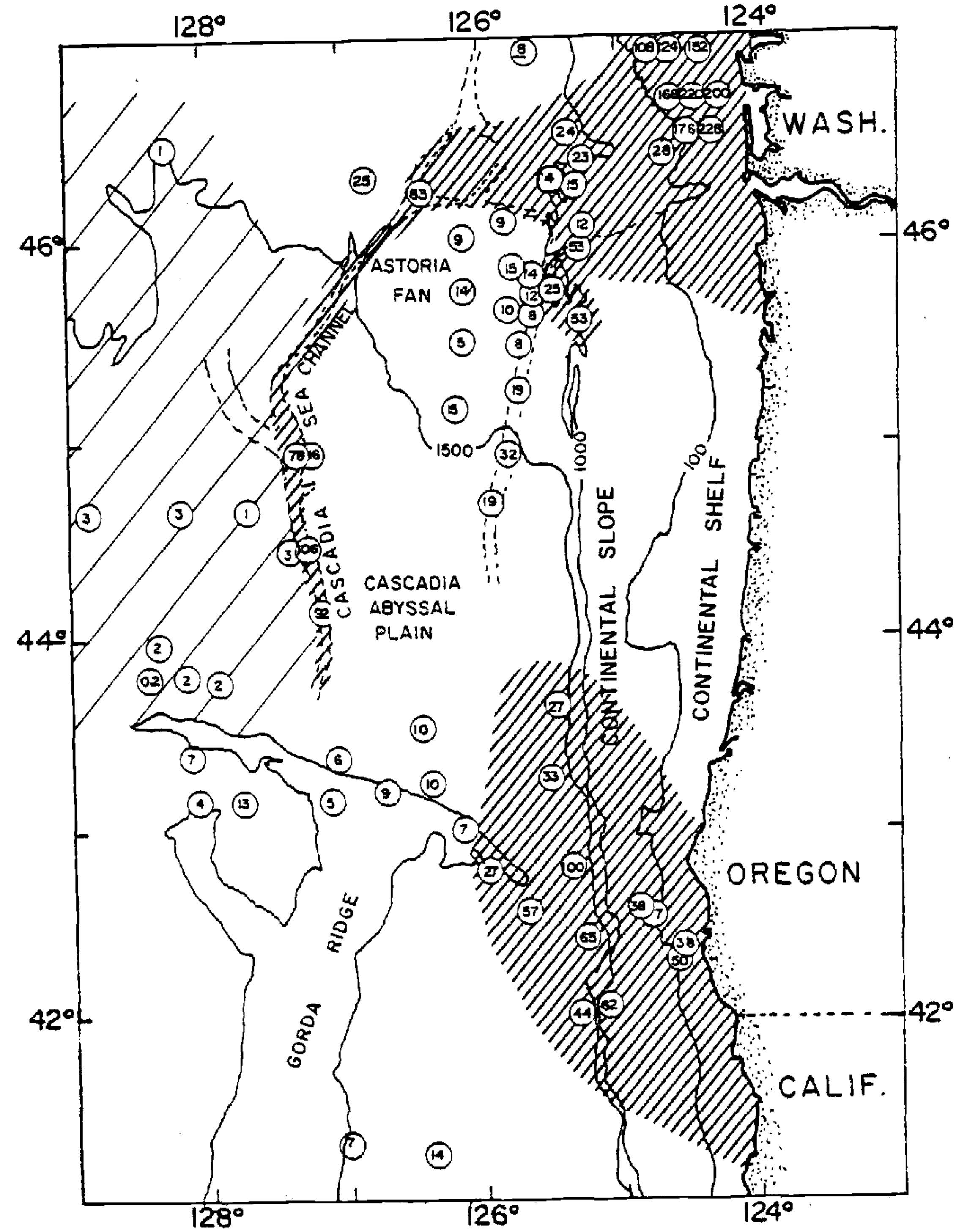


Figure 16. Sedimentation rates off the Oregon coast, based on Mazama ash (6600 years B.P.), C-14 and Pb-210 dating. Rates are in cm/10^3 years. (From Duncan (1968), Griggs (1968), Spigai (1971), Phipps (1974) and Nittrouer (1977))

material is confined to the area bounded by 40-48°N and 124-128°W in Figure 12. Using the relatively low sedimentation rate of 10 cm/10^3 yrs (12.5 gm/cm^2/10^3 yrs, if ρ = 2.5 gm/cm^3, porosity = 50%), the mass of sediment accumulated in the past 1000 years is about 3.0 x 10^{10} tonnes. Input from the rivers of northern California, Oregon and Washington is about 7.2 x 10^{10} tonnes for the same time span. Some of this riverine sediment is undoubtedly trapped as estuary infill. Even so, as these values are of the same order of magnitude, present day fluvial supply rate estimates would appear to be reasonably representative of long term continental sediment supply.

OTHER FACTORS AFFECTING CLAY MINERALOGY

Other factors which can affect the composition of hemipelagic sediments include the mixing of relict with modern sediments and differential sedimentation. The importance of these processes is difficult to evaluate. Pleistocene and older sediments can become mixed with modern material either through erosion by waves and currents, resuspension and redeposition of exposed relict material or by bioturbation in areas where sedimentation rates are low. Duncan (1968), Silver (1969), Barnard (1972), Barnard and McManus (1973), Downing (manuscript), and others have reported ponds of exposed Pleistocene sediment, of unknown areal extent, on the upper continental slope and at the heads of canyons. These sediments are well-compacted, contain abundant foraminifera, very few radiolarians and typically have clay mineralogies high in illite ($>50\%$).

In the present study, 14 cores from the shelf, northern slope and eastern abyssal plain were examined for their foraminifera/radiolaria contents. With a single exception (which was also high in illite), the coarse fraction of all of the surface samples contained only radiolaria, thus indicating little in situ reworking of ancient (i.e., pre-10,000 yrs BP) with modern sediments. Thus, the combined lack of scatter about the mixing line in Figure 12, and the relatively low illite percentages throughout the area/suggests that reworking, if present, is a localized phenomenon, perhaps confined to the high energy, regimes of the outer shelf and uppermost slope.

The relations between source area, dispersal pathways and compositional trends in bottom sediments can also become obscured if the identities of clay mineral assemblages are altered during transport. According to Stokes' Law, particles or flocs can become vertically differentiated if size or density differences exist. In the presence of unidirectional flow, this selective differentiation might cause areal changes in relative clay mineral abundances. Patterns of increasing montmorillonite and decreasing illite and kaolinite abundances with distance from source have been reported in studies of marine clays off the mouths of major rivers such as the Niger (Porrenga, 1966) and Amazon (Gibbs, 1977).

Whitehouse et al. (1960) and Edzwald and O'Melia (1975), using pure clay minerals standards, found that montmorillonites form floccules and settle more slowly than either illite or kaolinite flocs; hence, montmorillonites might be expected to be carried further from their source. Gibbs (1977) found no evidence of such differential flocculation in natural aggregates from the Amazon River. He argued, instead, that physical size sorting of individual particles would cause the observed mineralogical trends; that is, the montmorillonites, being the smallest of the clays, would stay in the water column the longest, and be transported the furthest.

This study and others in the North Pacific do not show obvious patterns which might be readily explained by such mechanisms. The nature of the sources might be partially responsible for this apparent disparity. Whereas the Klamaths and northern California rivers generally contain very little montmorillonite, the Columbia and, probably, the Coast Range rivers are predominantly montmorillonitic. Thus, even if differential sedimentation were prevelent in the marine environment, in the NE Pacific, its effects would be minor and probably overshadowed by mixing between various sources.

CLAYS AND OCEANIC TRANSPORT

Shelf Circulation

The clay abundance patterns and sediment supply calculations raise some interesting questions as to the relations between provenance and oceanic dispersal mechanisms. Since clays reside mostly in the rivers' suspended load and concentrations are highest during periods of maximum discharge, the direction that these fine-grained sediments take may be determined by the oceanic current regime present at times of peak discharge. On the shelf, distribution patterns may also be modified by such seasonal influences as increased wave action, coupled with intensified wind-induced currents due to storms.

Numerous studies have indicated that much of the Columbia River load is deposited on the Washington margin or is channelized to abyssal fans in the northern Cascadia Basin (Duncan, 1968, 1970; Carlson, 1968; Griggs, 1969; McManus, 1972; Baker, 1973, 1976; Nittrouer, 1977; Stokke et al., 1977). However, on the northern Oregon shelf, the shape and intensity of the montmorillonite-rich lobe (Figure 9) may suggest that Columbia River-derived clays are transported southward for long distances. The southerly limit could be controlled by the narrowing of the shelf to the south of the Umpqua River and complex eddy-type currents in the vicinity of Hecata Bank.

Because of snowmelt in the high mountains, the Columbia River reaches maximum discharge in May-June, when over one-half of the annual flow is released to the ocean (Seaman, 1978) (Figure 17). The summertime fluvial discharge and resultant plume (Figure 2) coincide with the upwelling related coastal jet which flows southward over the mid- and outer shelf with velocities over 20 cm/sec (Huyer et al., 1975). The coastal jet appears to carry large amounts of suspended matter as evidenced by the high values of light scattering in the nephelometry profiles of Pak (1970) (Figure 3). This southerly current is roughly congruent with the region of maximum mud accumulation on the shelf, and indeed, the Mid Shelf Mud Layer (MSML) is thickest in the vicinity of the Columbia River (Runge, 1966; Kulm et al., 1975). Also, most of the clay-sized material occurs at water depths greater than 120 m, where bottom conditions are more quiescent and less affected by resuspension due to wave action. Thus while the bulk of Columbia River-derived material appears to be transported northward to accumulate on the Washington margin, the imprint of summertime transport via the equatorward coastal jet may remain in the mid- and outer shelf muds.

Alternatively, the montmorillonite-rich lobe may arise from sediment carried by the rivers of the Oregon Coast Range. These streams discharge from 80-95% of their water (Percy et al., 1974, Figure 18) and presumably sediment from November to February, when flow over the whole shelf is strongly to the north. During this

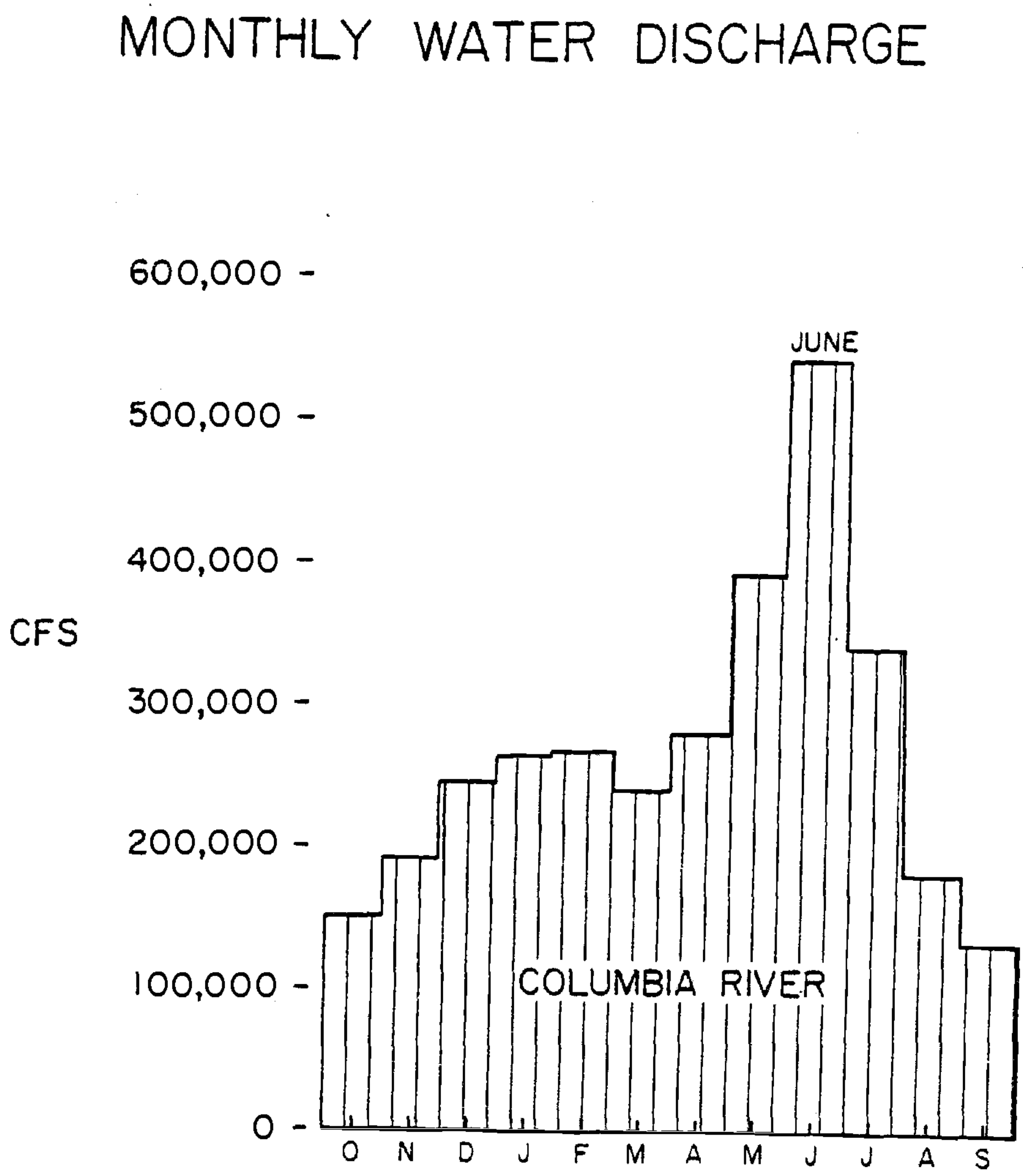


Figure 17. Average monthly water discharge of the Columbia River. (after Percy, et.al., 1974)

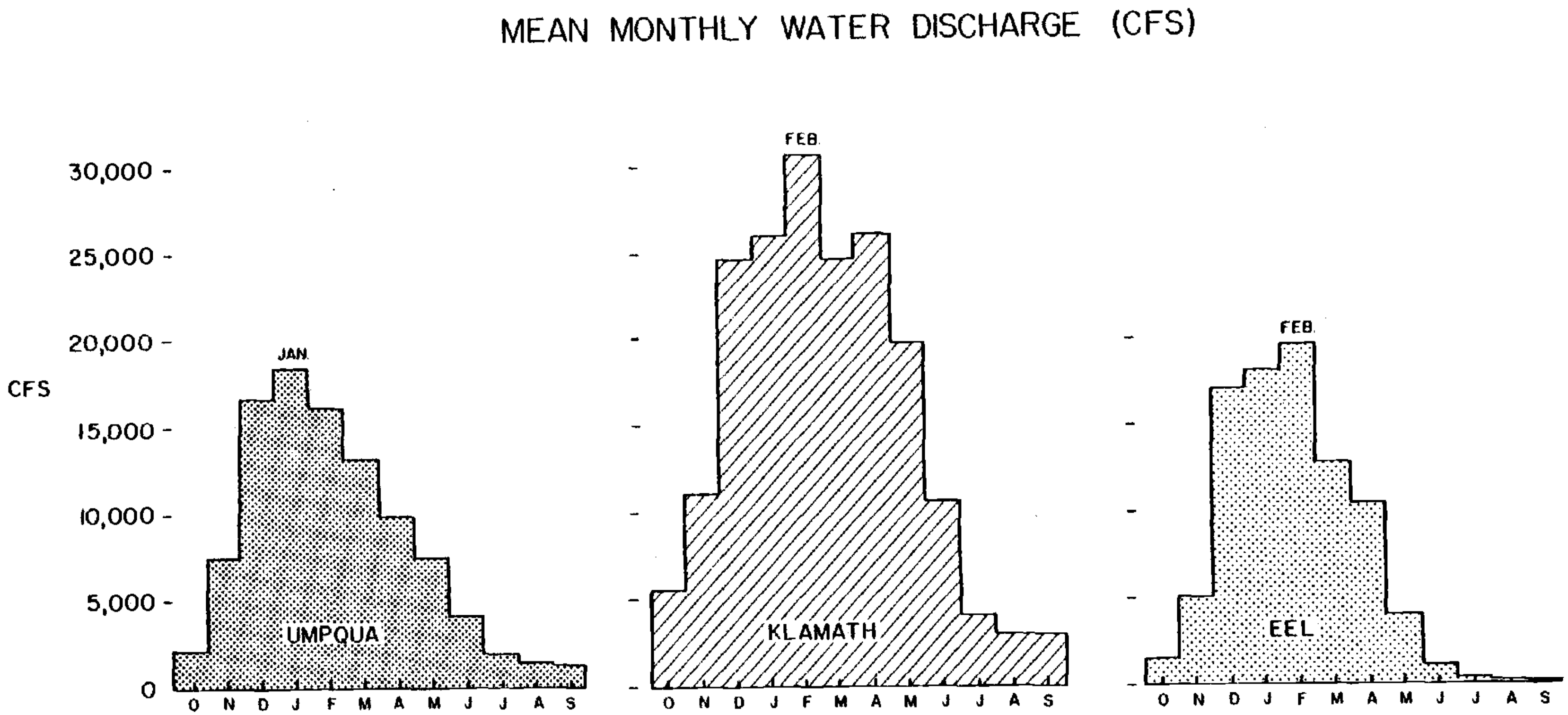


Figure 18. Average monthly water discharges of some major coastal rivers in the Pacific Northwest. (after Percy, et. al., 1974)

period, the Columbia River Plume is confined to a relatively narrow band along the Washington coast (Barnes et al., 1972) (Figure 4).

Because of severe storm activity, bottom sediment transport on the shelf is most likely in the winter months (Sternberg and Larsen, 1972; Smith and Hopkins, 1972). Oscillatory ripple marks have been found in sands at depths exceeding 125 km (Komar et al., 1972) and heavy mineral studies by Scheidegger et al. (1971) showed that the sand fraction derived from local Coast Range rivers trends predominantly northward. Thus accumulation of muds to the north of their source should not be unexpected.

To see whether the collective sediment flux from Coast Range rivers is enough to account for observed Holocene mud deposits on the shelf, we can estimate the length of time required for these streams to fill up the MSML, given present suspended sediment discharge rates. The MSML, from Coos Bay to the Columbia River and from 50-100 fathoms occupies an area of about 8200 km^2 and has a thickness of up to 40 cm (Kulm et al., 1975). Assuming a porosity of 50% and a sediment density of 2.5 gm/cm^3, the MSML then contains about 4.1×10^9 tonnes of sediment. The present Coast Range suspended sediment discharge rate is about 4.6×10^6 tonnes/year (Table 4). With these values, the combined input of the Coast Range rivers alone, could create the MSML in only about 890 years. (This time would be considerably less if input from coastal erosion and the

Columbia were included.) Since sea level has remained within 20 m of its present stand for the past 6000 years (Curray, 1960, 1965; Dillon and Oldale, 1978) the Coast Range rivers must then constitute a significant source of sediments to adjacent offshore areas. Furthermore, accumulation of fine-grained sediments from these rivers must not be confined to the mid- and outer shelf.

It is unclear, then, as to whether the observed clay patterns on the shelf arise from southward summertime transport of Columbia River-derived material, northward movement of sediments from local coastal stream or a combination of both factors. The resolution to this problem will probably have to await measurements of suspended sediment flux in the water column coupled with bottom sediment accumulation budgets using adequate dating control.

Poleward Slope Undercurrent

Another intriguing question raised by the abundance patterns is what happens to sediment once it leaves the high energy shelf regime. Much attention has focused on submarine canyons as the major conduits of sediment to the deep sea, but other dispersal agents have been largely neglected. This is due, in part, to a lack of detailed sedimentological studies on the slope and a paucity of direct current and suspended sediment observations in the deep ocean.

The concept of channelized transport of Columbia River-derived material is supported by the montmorillonite-rich clays found in the deposits of the Astoria and Willapa Canyons and in the Cascadia Sea channel. However, the bulk of these clays are confined to the northern sector of the study area.

The clays on the northern Oregon slope are indistinguishable from clays on the southern margin. The patterns are suggestive of northward advection of clays from sources in northern California and southern Oregon. If this hypothesis is viable, then the low Mo/Chl ratios noted by Baker (1973, 1976) in open slope and distal canyon deposits off Washington could be readily explained by mixing of bottom transported Columbia River-derived clays with chlorite-illite-rich clays advected from the south. Moreover, the anomalously low man-induced radioactivity found in the slope sediments near the Columbia River mouth by Gross (1972) could be due to strong dilution of the radiogenic Columbia River effluent by southerly material.

If the bulk of fine sediment is moved in bottom boundary layer flow, such transport would be constrained by the topography. Off northern California, the presence of the 1000 m high Mendecino escarpment would preclude possible southward bottom sediment transport. Further, the axis of the Eel Abyssal Fan trends northwesterly and topographic contours on the margin and abyssal plain would not tend to inhibit northward movement. Hence, a sediment reservoir is potentially available to the south of the study area.

Any hypothesis of northward advection along the continental slope must, of course, be consistent with the physical oceanography. Over the continental slope, a major poleward undercurrent has been detected by recent current measurements (Huyer, 1974; Reid and Halperin, 1976; Halperin et al., 1978). Variously called the California Undercurrent or Countercurrent, this northward flow appears to be a permanent manifestation of the general circulation (Hickey, 1978). The lateral and vertical extent of the flow are unknown, but the core, with velocities greater than 15 cm/sec appears to be deeper than 800 m in spring, shoaling and moving shoreward during the summer (Huyer, 1974). Its seasonal movement may be related to the winter Davidson Current and to a summer subsurface undercurrent on the upper slope and outer shelf (Huyer et al., 1975; Huyer and Smith, 1976).

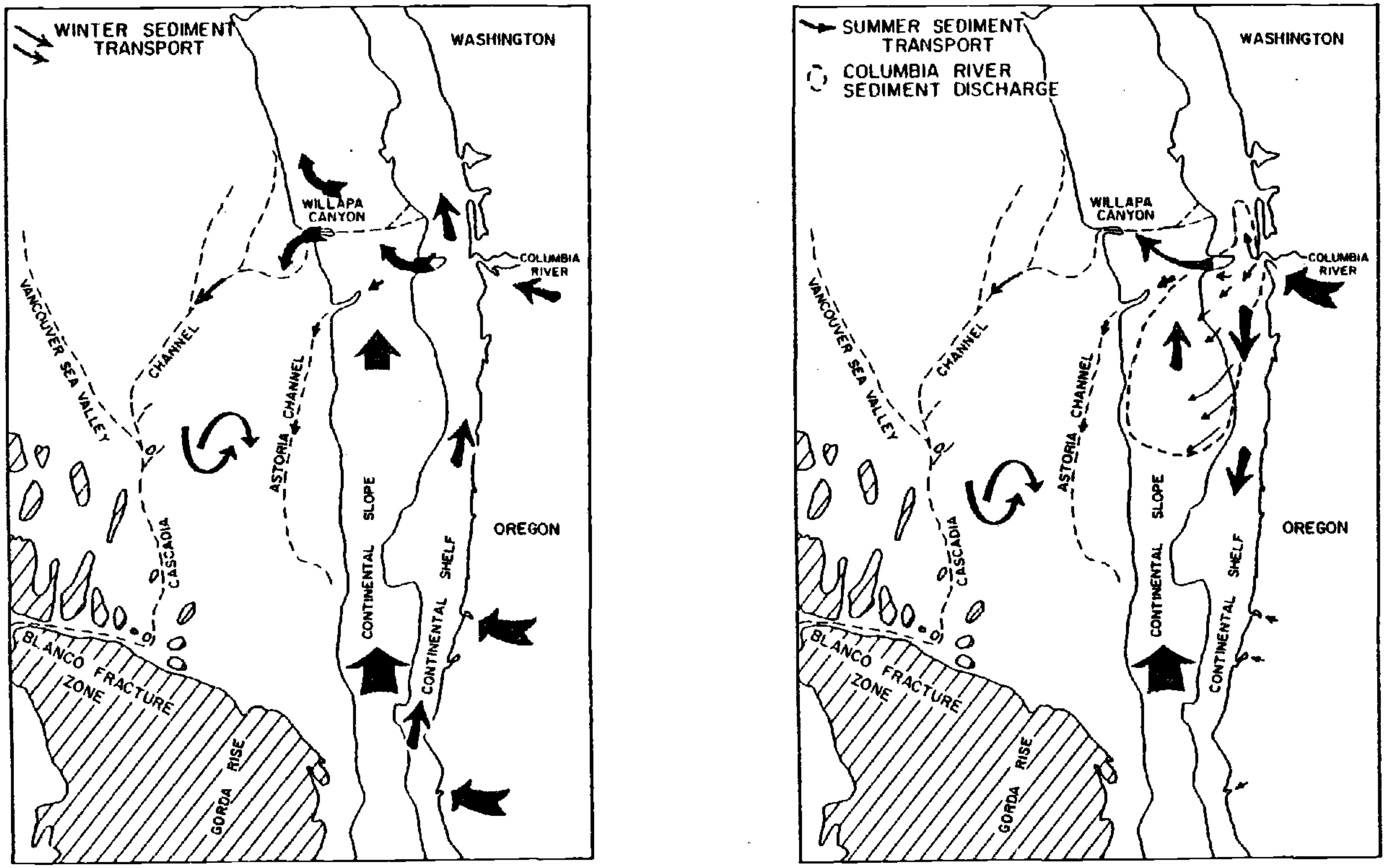
Thus the available information on the ocean circulation is also compatable with northward slope advection via a poleward undercurrent. The validity of this hypothesis could be tested by detailed textural and compositional studies of the slope sediments coupled with direct current and suspended sediment measurements in the water column.

CONCLUSIONS

The mapping of variations in proportions of clay minerals in surface sediments is a valuable tool for inferring dispersal pathways for the terrigenous components of hemipelagic deposits on the continental margins of the northeast Pacific Ocean. The mineralogical trends and sediment supply estimates reveal coherent regional patterns (illustrated in Figure 19) from which the following can be inferred.

(1) The streams of the northern California Coast Range and Klamath Mountains and the Columbia River are the principal sources of marine clays. In order of importance, the major suppliers of sediment presently are the Eel, Columbia, Klamath, Rogue and Umpqua Rivers, respectively. Coastal erosion and input from streams in the Oregon-Washington Coast Range is relatively minor, but may be significant in proximal areas on the continental shelf.

(2) Because of seasonality of river discharge and the ambient oceanic conditions, clays from the Columbia River are more important off the Washington coast, while southern sources are more dominant off Oregon. Cascadia Basin muds appear to be a rather even mixture of clays from both source regions, except in channelized deposits where Columbia River type clays are



(a)
Winter

(b)
Summer

Figure 19. Transport pathways inferred from the clay mineral distribution patterns in a) winter and b) summer.

prevalent.

(3) A lobe of montmorillonite-rich clays occurs on the northern Oregon shelf and upper slope. This material may result from either summertime peak discharge of the Columbia River coupled with southward currents associated with coastal upwelling and/or winter discharge of the Coast Range rivers with concommittant northward shelf flow.

(4) The bulk of Columbia River-type clays appears to be carried northward along the Washington coast, then funnelled into submarine canyons and deep sea channels for transport to abyssal areas to the north of the study area. Northerly current patterns on the shelf during the winter months are most conducive to this form of transport.

(5) Clays on the slope off both Oregon and Washington show chlorite-illite-rich components characteristic of a southern origin. Along slope advection via the poleward California Undercurrent is the most reasonable explanation for these distributions. This hypothesis is also supported by physical oceanographic observations and bottom sediment radionucleide studies.

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APPENDICES

APPENDIX I

Sample Locations and Clay Mineral Percentages

No.	OSU Core	North Latitude	West Longitude	Montmorillonite	Illite	Chlorite
Southern Margin						
1	6404 383	42°56.0'	124°41.4'	21.22	33.96	44.82
2	6708 15	42°23.2'	124°33.5'	12.52	36.24	51.23
3	6708 45	42°35.6'	124°39.1'	16.21	32.35	51.44
4	6708 48	42°33.4'	124°33.3'	14.34	28.99	56.67
5	6708 71	42°51.7'	124°35.1'	12.38	33.97	53.65
6	6708 87	43°11.9'	124°26.9'	8.22	31.56	60.22
7	6401 331			22.50	27.42	50.08
8	6403 260			21.03	32.31	46.66
9	6403 309			20.28	29.99	49.73
10	6708 75	43°09.7'	124°41.8'	26.94	27.98	45.08
Northern Slope						
11	7610 9	45°49.1'	125°26.4'	26.54	29.67	43.80
12	7610 9A	45°44.5'	125°05.2'	27.95	28.16	43.89
13	7610 10	45°41.7'	124°48.7'	29.88	28.18	41.94
14	7610 3	44°07.1'	125°00.4'	28.43	25.37	46.20
15	7610 4	44°08.7'	125°15.3'	23.16	25.29	51.55
16	6809 9	45°10.7'	125°08.0'	25.37	31.09	43.54
17	6809 10	45°09.3'	125°13.3'	26.49	31.41	42.10
18	6809 11	45°16.9'	125°09.5'	27.24	31.15	41.60
19	6809 12	45°17.6'	125°15.3'	28.32	29.99	41.70
20	6809 13	45°04.0'	125°19.5'	22.50	30.39	47.11
21	6809 15	44°36.5'	125°20.0'	22.40	33.06	44.54
22	6809 16	44°39.0'	125°12.8'	32.90	26.21	40.89
23	6809 19	45°00.3'	124°39.6'	42.00	30.24	27.76
24	6809 8	45°07.6'	124°54.4	25.40	31.93	42.67
Northern Shelf						
25	7610 1	44°10.0'	124°22.0'	44.65	17.39	37.96
26	7610 2	44°06.0'	124°44.7'	48.82	19.19	31.99
27	7610 11	45°36.5'	124°28.0'	48.25	23.95	27.79
28	7610 12	45°34.1'	124°08.5'	47.16	21.33	31.51
29	7610 14	45°08.0'	124°13.9'	43.86	22.05	34.09
30	7610 15	44°59.8'	124°21.7'	40.34	21.37	38.29
31	7610 16	44°47.5'	124°20.1'	41.91	23.25	34.84
32	6309 1 22	45°05.0'	124°26.2'	40.89	23.77	35.34
33	6309 67	45°23.0'	124°16.0'	37.47	25.09	37.44
34	6309 1 133	45°44.0'	124°16.8'	58.78	19.41	21.81
35	6309 1 154	45°50.0'	124°24.0'	41.31	25.07	33.62
36	6309 1 156	45°50.0'	124°15.4'	52.68	21.01	26.31

APPENDIX I. continued.

No.	OSU Core	North Latitude	West Longitude	Montmorillonite	Illite	Chlorite
Northern Shelf, continued						
37	6309 1 167	45°53.0'	124°25.6'	36.98	27.65	35.37
38	6309 1 180	45°56.0'	124°17.2'	51.64	22.46	25.89
39	6309 1 191	45°59.0'	124°25.8'	41.79	28.17	30.04
40	6403 1 276	43°41.0'	124°20.3'	36.31	21.82	41.87
Channelized Deposits						
41	PC 2	46°05.0'	125°08.0'	33.03	25.63	41.34
42	PC 7	46°16.0'	124°20.0'	54.51	19.28	26.21
43	PC 12	46°12.8'	124°42.8'	38.44	23.33	38.23
44	6403 1 239	46°17.0'	124°20.6'	48.53	26.66	24.80
45	6509 15A	44°57.0'	127°16.4'	45.85	21.78	32.37
46	6705 6	46°25.0'	126°24.0'	43.84	21.66	34.50
47	A 3 2	46°02.0'	126°06.0'	32.36	25.27	42.37
48	C 3	45°42.0'	126°07.0'	29.90	27.14	42.96
49	C 4 2	45°30.0'	126°45.0'	31.41	26.24	42.35
50	E 3	45°29.0'	125°42.0'	34.30	25.15	40.55
51	G 1	46°06.0'	125°48.0'	34.99	24.81	40.20
52	KA 2	45°35.0'	126°26.0'	30.76	23.87	45.36
53	6509 4	44°57.0'	125°47.2'	30.94	25.36	43.70
54	6509 7	44°59.2'	126°31.2'	26.42	25.91	47.67
55	6908 1A	44°53.8'	127°26.9'	30.63	24.69	44.70
56	6509 3	44°42.0'	125°55.4'	29.22	24.73	46.05
57	6511 5	43°39.5'	125°28.6'	26.68	25.83	47.49
58	6511 69	42°00.5'	125°19.5'	27.20	28.02	44.78
59	6601 1	43°01.1'	126°34.0'	24.16	29.85	45.99
60	6604 11	43°17.0'	125°31.0'	26.39	26.88	46.73
61	6604 12	42°50.0'	125°24.0'	24.30	26.21	49.49
62	6609 1	42°26.0'	125°15.0	20.50	30.47	49.03
63	6609 2	42°35.0'	125°40.0'	22.88	33.66	43.46
46	7407 2	43°30.0'	127°25.0'	25.01	27.06	47.93
65	7610 5	44°09.1'	125°23.9'	21.34	29.27	49.39
66	7610 6	43°48.2'	126°04.0'	20.95	28.97	50.08
67	7610 7	44°12.8'	126°10.6'	24.29	23.83	51.88
68	7610 8	44°36.3'	126°19.5'	22.05	27.19	50.76
69	7211 3	42°05.0'	127°01.0'	27.93	26.85	45.22
70	COL R	46°12.0'	123°50.0'	55.91	19.23	24.86
71	COLX 1 10	46°11.0'	123°10.0'	50.90	24.80	24.30
72	COLY 6 10	45°59.0'	122°50.0'	49.80	23.50	26.70

APPENDIX II

Comparison of Solvation and Mounting Techniques

Effects of Analytical Technique

A major obstacle to the synthesis of results from various investigations into a regional perspective lay in differences in the preparation of clay samples before X-ray analysis. Principal sources of uncertainty are due to differences in X-ray mounting media and the use of varying polar organic liquids to expand clay lattices.

Mounting Media - Two methods for preparing oriented X-ray mounts have been commonly employed in the study of clays from the Northeast Pacific. The suctioning of clay suspensions through porous silver membranes or plugs was used in work on the Washington continental margin (Baker, 1973; and others), Columbia River (Knebel, 1968) and in the present study. Glass slides smeared with clay paste were used on samples from the Cascadia Abyssal Plain and Astoria Canyon and Fan (Duncan, 1968, 1970; Griggs, 1968; Russell, 1967).

Comparing various techniques, Gibbs (1965) found that suctioning methods gave the least biased results. Smear-on-glass mountings produced artificially enriched smectites because of preferential settling of the smaller sized particles. For this latter method, the importance of smectite-rich sources may be overemphasized in localities where variations in relative clay mineral abundances are large.

To evaluate the effects of mounting media, seventeen of the samples from the Cascadia Basin were compared with clay analyses of Duncan (1968) on cores taken at the same location (11 cases) or within 15 km(6 cases). Montmorillonite percentages for smear-on-glass mountings varied from 5 to 15% higher than for similar suctioned samples, depending on relative abundance (Figure 20). However, the general trend of a southward decrease in montmorillonite and increase in chlorite observed by Duncan was confirmed by the present study.

Solvation Effects - Whereas most clay mineralogy studies of Northeast Pacific sediment used ethylene glycol, studies on the southern Oregon margin (Spigai, 1971; Phipps, 1974) employed another common solvating agent, glycerol, to enlarge the 001 basal layer spacings of the expandable clays (i.e. smectites). To examine the effects of these different solvation treatments, four mounts were prepared for each of the 79 samples; two of the slides were saturated with glycerol; the other two heated in ethylene glycol vapor for two hours.

To assess the effects of treatment, on each clay type the peak

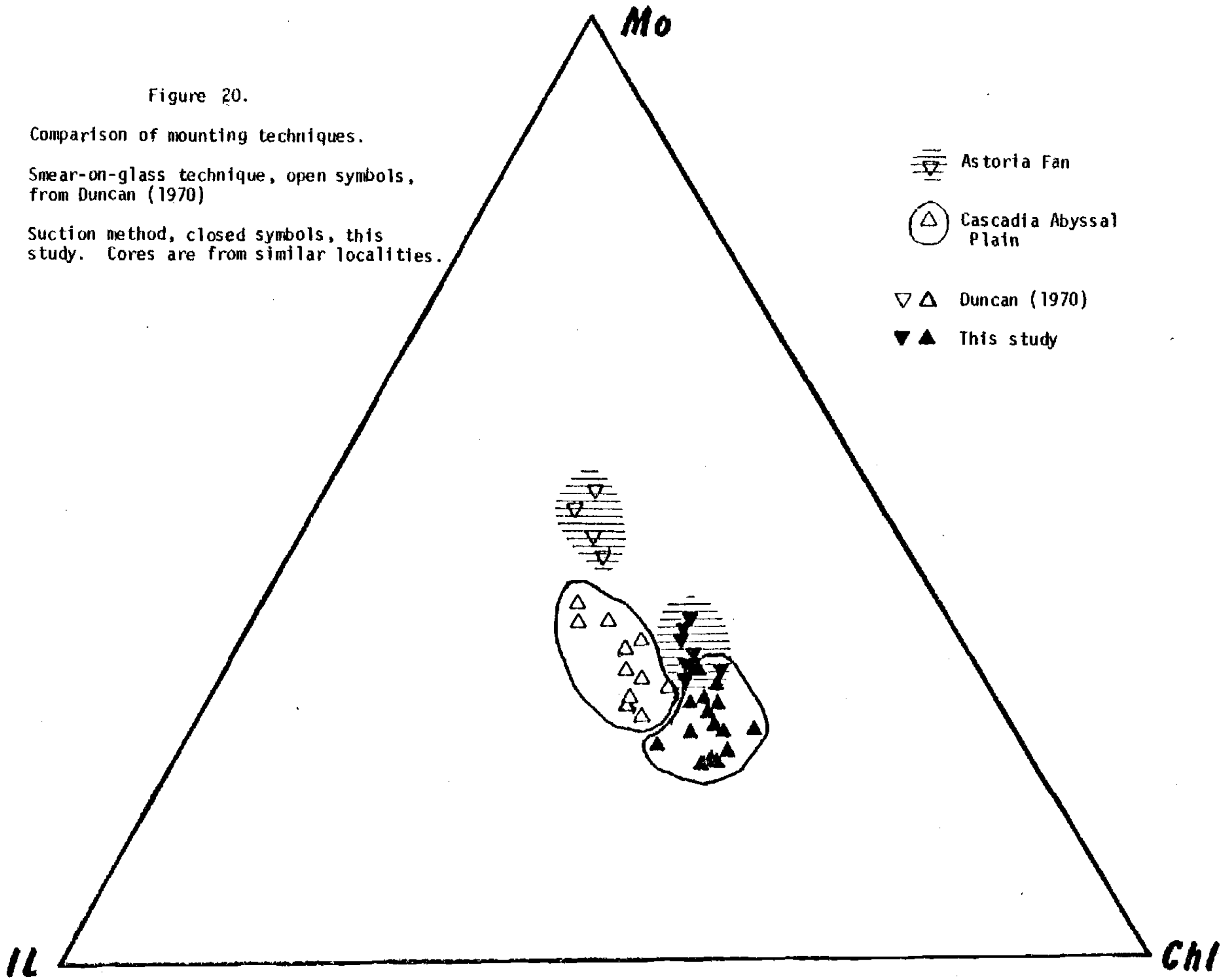

Figure 20.

Comparison of mounting techniques.

Smear-on-glass technique, open symbols, from Duncan (1970)

Suction method, closed symbols, this study. Cores are from similar localities.

areas of forty glycolated and glycerol-solvated samples (2 slides per specimen per treatment) were compared. As expected, illite and chlorite were little affected by solvation. However, in montmorillonites, variance due to treatment effects was much greater than the variance associated with peak area differences between duplicated slides. A regression fit of montmorillonite percentages (Figure 21) gave excellent correlation between solvation treatments ($r = .954$) and suggested a strong linear relation.

Glycerol gave lower smectite percentages and areas than ethylene glycol. This was probably due to the combined effects of glycerols lower dipole moment, hence reduce expansion capability and diffractogram smoothing when the signal is higher in the exponential baseline region. For low montmorillonite abundances solvation effects on a given sample were of the same magnitude as variations between the duplicates. Thus, samples from the southern margin, regardless of treatment, were in good agreement with results of Spigai (1971) and Phipps (1974) because montmorillonite abundances were low. However, as these relative abundances increase, ethylene glycol gave an expanded range of values with only a small increase in measurement error (variation between duplicates) due to uncertainties in determining the larger peak areas. Thus, although either solvation technique was suitable, the glycolated samples were chosen for further study.

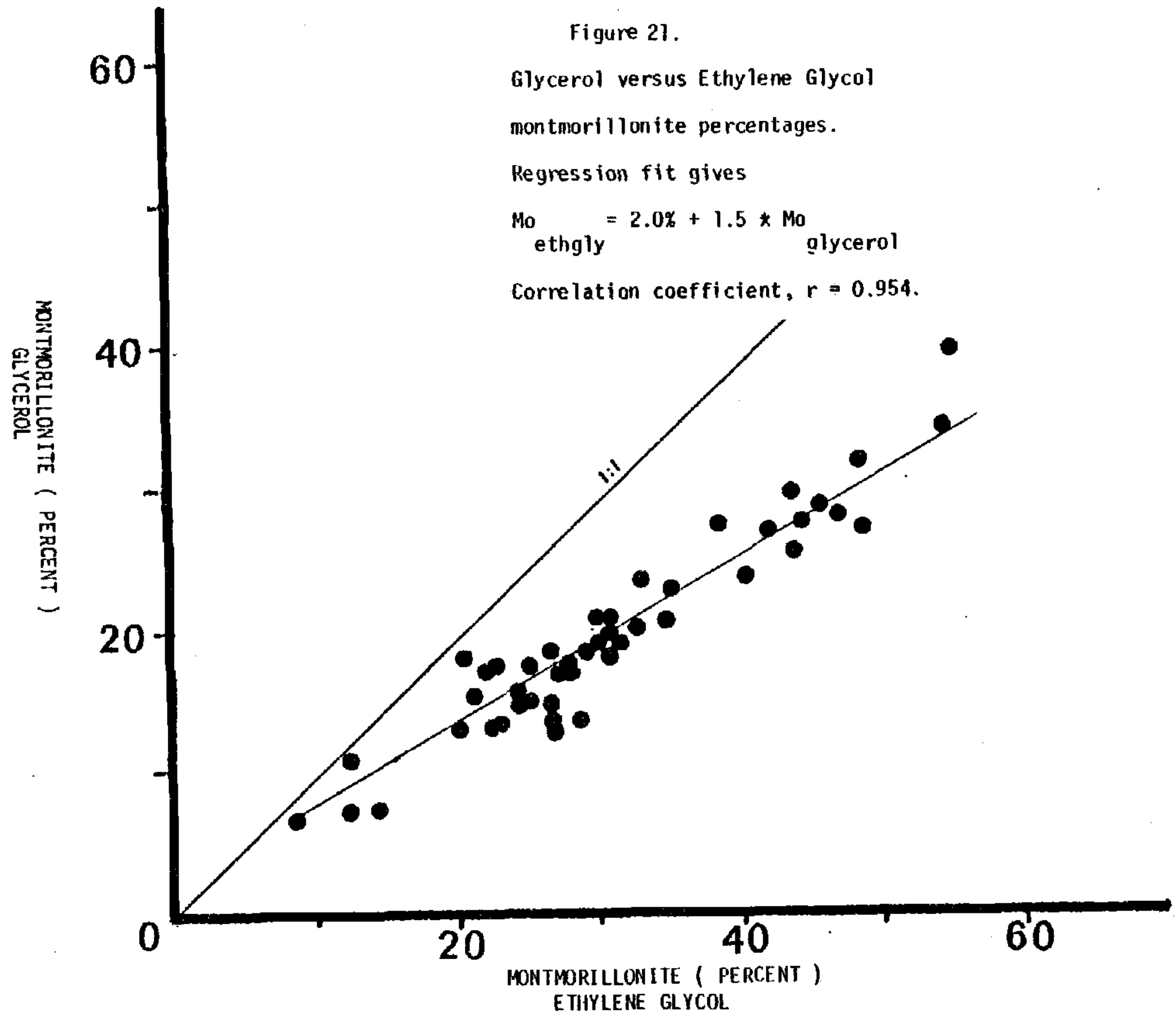

Figure 21.

Glycerol versus Ethylene Glycol montmorillonite percentages.

Regression fit gives

$$Mo_{ethgly} = 2.0\% + 1.5 * Mo_{glycerol}$$

Correlation coefficient, r = 0.954.