set. From the standard deviation of the time-of-arrival estimates (0.0006 second), that of the magnetic field measurement is found to be $\pm 0.62 \times 10^{-3}$ gauss.

The time-of-arrival measurements have also allowed us to determine the repetition period of the pulses to surprising accuracy. A very small difference of timing between the pulses and the signal-sampling equipment produces a cumulative drift of the time-frequency trajectory of the pulses. Our measurements, corrected for Earth's orbital velocity and rotation, are given in Table 1. For CP 1919, the period matches very closely that published in (*5*), in distinction to that in (*1*).

Using the best-fit relation (Eq. 2), we displaced each spectrum of a set to a common frequency origin and then averaged the spectra. Figure 3 (top and bottom) shows the spectral characteristics of the average pulse.

The frequency structure of these two sources is quite similar to the time structure already reported (*6*). They both have a basic triangular shape and sudden onset and termination. There was no evidence of any power outside of the main pulse.

The peak power density, average power, and average bandwidth of these pulsar signals are given in Table 2.

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22 May 1968

Morphology and Origins of Sedimentary Structures on Submarine Slopes

Abstract. *Submarine slopes in deep water, such as continental slopes, are often indented by valleys or channels and made uneven by ridges or levees. The origins of many of these features are unknown or disputed. Morphologically, however, there is often great similarity between forms on deep slopes and forms on shallow slopes or on land. Structurally the slopes in deep water are less well explored, but several observations reveal features, such as lamination and cross-bedding, that are known from shallow water also. Measurements of current indicate that periodically the movement of water near the bottom is fast enough to move particles of sediment from time to time. Morphology, fine structure, and currents suggest that internal waves and associated currents, as well as gravity, may control the shape of deep submarine slopes analogously to the shaping by surface waves of slopes in shallow water.*

In shallow water, the morphology and fine structure of sea-floor slopes are very strongly influenced by waves and associated currents. Observations of intermittent currents in the deep ocean seem to justify an attempt to relate topographic and structural forms of the sediment on the slopes to internal waves and currents associated with them. The making known of the unknown often depends on formulation of the right question; thus the purpose of this report is to ask whether the descriptions and explanations of the morphology of deep-sea slopes are furthered by suggestion of the existence of physical processes analogous to those in shallow water.

The many observations in shallow water (*1*) have led to some satisfactory hydrodynamic models relating water movement and particle transport. In shallow water (characterized in this discussion by the depth at which wind waves interact with the sea floor—generally shallower than 150 m), slopes are commonly inclined between 2 and 7 deg. Bars, troughs, terraces, and channels are some forms that can make slopes uneven; on a smaller scale, sand waves, ripples, or individual constituents of sediments may impose a surface roughness. Most topographic features are associated with distinct structures and textures of the sediment. One finds layers, laminae, and even preferred orientations of individual grains that indicate the movement of the water from which the sediment settled. Forms and structures are often very complex: for instance, a bar may be superimposed on a gentle slope, and superimposed on both may be ripples of more than one set. Thus a cross section shows different orientation of sets of laminae or of the constituent sand grains.

Waves, mostly generated by winds, and currents induced by them play the dominant role in modification of shallow-water slopes. Wave height and period are characteristic parameters, although they describe the waves only partially. Depth of water and type of bottom exert further control of what waves do as they travel up a slope. In a first approximation, analogies with ray optics can be made; thus water waves are known to be reflected, refracted, and diffracted somewhat analogously with light waves; interference patterns, resonance, and composite oscillations are some of the more complex but not uncommon resultant forms. Direct measurements are difficult. Fluctuations in temperature, as well as water motion, are often recorded at fixed points. Spectrum analysis is applied for production of information about the characteristic wave parameters.

As well as directly modifying shallow-water slopes, wind waves can establish longshore drifts of sediment when their fronts are not normal to the coast; such a drift is perhaps the largest single mechanism for sand transport nearshore. A peculiar short-periodic flow of water induced by waves is known as rip current; rip currents provide the return flow of water that has been "piled up" higher on the slope, and thus they carve channels sometimes more than 1 to 2 m in depth. Despite many attempts to describe the process, a detailed picture only now appears to evolve (*2*).

In deep water, major slopes such as continental slopes have similar inclinations, 2 to 7 deg, as have beaches and their shallow-water extensions; they have been studied much less intensively. The ever-increasing number and quality of echo soundings, direct observations by divers, and photography reveal ever more detail. As they become better known, the slopes appear less and less smooth. Not many years ago only the major submarine canyons were known or partly known; modern maps show submarine canyons on the slopes of all continents (*3*).

The frequency of smaller valleys and channels on a map often appears to be proportional to the intensity of bathymetric survey of the area. Probably the

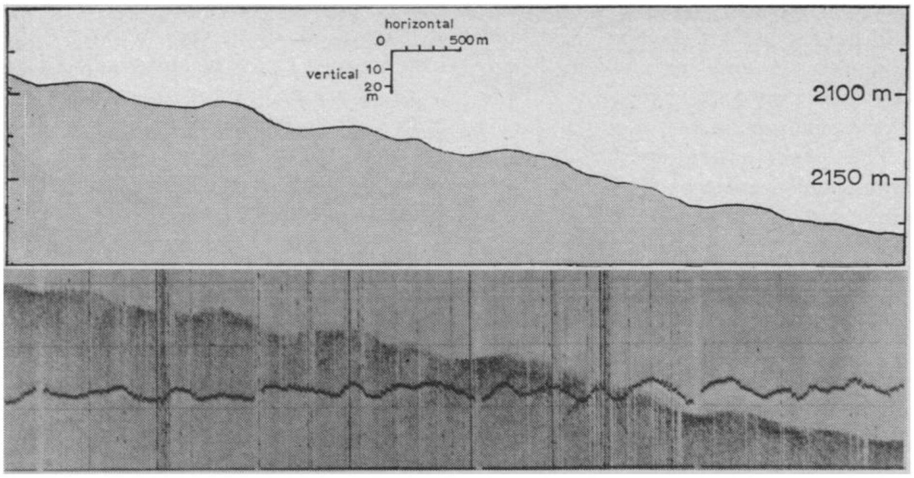

Fig. 1. Echo sounding normal to continental slope south of Nantucket, Mass. The form of the sea floor at water depths of 2100 to 2200 m resembles bottom profiles of many shallow-water slopes. Depths (m) of water are shown (right). This section of profile is from the vicinity of a moored current-meter station that recorded velocities greater than 20 cm/sec at a water depth of 2000 m. The sediment is a greenish-gray clay containing Foraminifera tests. [From record of R.V. *Chain*, cruise 47, Woods Hole Oceanographic Institution]

slopes off North America and in the Mediterranean are best known in general; however, many details of individual echo-sounding profiles cannot be contoured accurately on large-scale maps because the spacing of the profiles is wide (of the order of kilometers) and the accuracy of their geographic positions is limited (fractions of 1 km in the best surveys).

Nevertheless, existing maps and profiles let us recognize on deep slopes not only many submarine canyons and channels but also other features reminiscent of features on shallow-water slopes (Fig. 1). For instance, there are ridges and troughs subparallel to the trend of the shelf break or at an acute angle to the dip of the slope; relatively smooth sections of slope alternate with more-undulated or truncated areas; ripple marks also are known (*4*).

Structural analyses of deep-slope sediments are just beginning. Oriented cores, although few, provide the most direct evidence; several show lamination and cross-bedding (*5*) that are characteristic of shallow-water slopes also. Most seismic profiles lack sufficient resolution for identification of the fine structure of the sediment, but they do reveal areas of slumping of the little-consolidated or unconsolidated surface layer.

In the past, geologists have concerned themselves more with the origin of continental slopes or of midocean ridges than with modifications of the surfaces of the slopes. Canyons—and to a lesser extent terraces, scarps, and slumps—also have attracted considerable attention; processes recognized as the chief contributors to their existence are subaerial erosion and shallow-water working at times of lower sea level, turbidity currents, faulting, and static adjustments of gravity.

The theories of drowned river valleys, slumps, and turbidity currents (*6*) explain better than any other theory the origin and preservation of many of the large canyons; they do not explain all slope valleys, channels, and ridges, nor are they meant to do so (*7*). One may conjecture that while slumping a block of sediment disintegrates and forms ridges and troughs that cross the slope obliquely, or that by rotational movement the back of a slump forms a trough with the surface across which it has slid. Although such an origin for slope modulation seems plausible, the question of whether all oblique troughs and ridges on deep slopes are related to slumps—and whether internal structures confirm the explanation—remains to be tested.

Measurements of currents over deep slopes are extremely rare; systematic surveys are just beginning. However, some records over periods of from several hours to a few weeks, taken near the sea floor close to the top of the continental rise of the Atlantic coast of the United States, near the tops of the continental slopes on both sides of the North Atlantic, and near Bermuda, show variations in time of current direction and speed (*8*). Current velocities within a few meters of the bottom often exceed 20 cm/sec; speeds are occasionally even greater than 1 m/sec. These currents contain fluctuating components whose amplitudes often exceed the average speed; thus internal waves or wave-induced currents are indicated. Origin and nature of these internal waves are not fully understood. The records show complex spectra of wave motion. Tidal motions seem to play a major role.

No complete theory yet explains what happens to internal waves when they run up a slope; transformation to breakers, surf, or internal bores has been suggested (*9*). Even if internal breakers do not develop, it is conceivable that the particle velocity of the water increases as the layers in which the internal waves travel are narrowed in the upslope direction.

Geologists studying form and structure of slopes, and oceanographers working on water transport, may help each other in analysis of such a complex problem. The idea of linking internal waves to sea-floor topography is not new: for instance, it was suggested (*10*) that sand waves in the western approaches to the English Channel are coupled with internal waves on the basis of relation in wavelengths. Emery (*11*) suggested that sediment near basin sills off California may have been sorted by internal waves: the finer grains winnowed away and the coarser ones left behind. LaFond (*12*) demonstrated quantitatively movement of sediment, in the form of ripples over the shelf, as a function of internal waves; he used thermistors and underwater television to gather the data; water velocities exceeded 7 cm/sec near the bottom.

On submarine slopes, the diverse directions of water velocities, morphologic unevenness, and lamination and cross-bedding may be related to internal waves and associated currents. The speed of the water is the most direct and obvious factor in sediment transport and deposition: velocities of several centimeters per second—often 20 cm/sec and occasionally still greater—may lead to drastic consequences if they can be attributed to waves interacting with the sloping sea floor. Recalling that wave refraction produces longshore drift in shallow water, I suggest that a similar phenomenon may be found on deep slopes: that is, sediment transport due to wave refraction. In fact, a wave-induced "longslope drift" may be the mechanism that fills the heads of deep submarine canyons, analogous to the longshore drift that fills canyon heads in relatively shallow water off California (*11*). The presence of sediment from

Newfoundland off the southeastern United States does not prove the existence of a (continuous) current such as a geostrophic current or a "contour current" per se, as has been postulated (*13*). Currents resulting from internal wave motions also could transport sediment particles over that distance.

Valleys and ridges obliquely crossing deep submarine slopes may be analogous to troughs and banks near the shore, not only in morphology but also with respect to mode of origin—essentially a function of wave interaction with the sea floor. The currents causing the movement of sediment may be generated not by simple sinusoidal waves but by interference of waves having different phases and periods, or by the sum of periodic water motion and a steady current.

Channels and gullies that incise deep-water slopes may have been cut by wave-induced internal currents, analogous to channels carved by rip currents in shallow water. If size and direction of internal waves change less frequently than those of their wind-generated counterparts, the position and size of the rip channels, which are controlled by them (*14*), also may be more stable on deep-water slopes than on shallow-water slopes. Eventually, rip channels on deep submarine slopes may be modified by turbidity currents.

In attempting to draw analogies between nearshore and offshore slopes I am aware of major differences between shallow-water and deep-water provinces. Some processes in either province may enhance these differences: for example, greater variability of topographic forms in time and space, to be expected in the nearshore zone, may contrast with potentially greater dimensions in the offshore zone.

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30 April 1968

Mazama Ash in the Northeastern Pacific

Abstract. *Volcanic glass in marine sediments off Oregon and Washington correlates with continental deposits of Mount Mazama ash by stratigraphic position, refractive index, and radiocarbon dating. Ash deposited in the abyssal regions by turbidity currents is used for tracing of the dispersal routes of postglacial sediments and for evaluation of marine sedimentary processes.*

The cataclysmic eruption of Mount Mazama 6600 years ago (*1, 2*) spread pumice and ash to the north and northeast over at least 900,000 km^2 (*2*) (Fig. 1, inset). Volcanic glass from this eruption is found in the postglacial marine sediments younger than 12,500 years (*3*) of Willapa Canyon, Astoria Canyon, Astoria Fan, Astoria Channel, Cascadia Channel, Cascadia Abyssal Plain, and Blanco Valley (Fig. 1). We now discuss the origin, stratigraphic significance, and relation to submarine topography of the deep-sea layers of ash, and their significance in processes of deposition.

Piston cores taken off Oregon and Washington show that the deep-sea sediments generally are terrigenous and derived from the extensive drainage area of the Columbia River (*3–6*). The marine deposits consist of layers of sand and silt turbidity-current deposits, interbedded with hemipelagic silty clays; volcanic glass is a major component of the layers and a minor component of the interbeds (Fig. 2).

The sand fraction (coarser than 0.062 mm) of the ash-bearing layers can be so classified (*7*): vitric ash (more than 75 percent glass), tuffaceous sand or silt (25 to 75 percent glass), and terrigenous sand or silt (less than 25 percent glass). Tuffaceous sand and silt layers are the most common type in all depositional environments. Only a few of the ash beds in the interchannel areas (regions between channels) and in the upper portions of some of the thick layers in channels on Astoria Fan are classified as vitric ash (Fig. 2).

Generally the marine ash is mainly distributed in the submarine valleys (Fig. 1); it occurs in the sediments of Astoria Canyon and its tributaries and in Willapa Canyon (*8*). On Astoria Fan all ash layers are within 60 km of the apex of the fan in the interchannel regions, but they occur throughout the 160 km of Astoria Channel. Cascadia Channel has appreciable quantities of volcanic glass between its head, near the base of the continental slope, and points at least 400 km down the channel. Ash is found also in cores taken in Blanco Valley off southern Oregon and northern California.

The vertical distribution of volcanic glass varies from distinct coarse beds to ash-rich zones of clayey silt in the different marine environments. Postglacial sediments in Astoria Canyon contain many thin layers of tuffaceous and terrigenous clayey silt (*4*); the deepest layer occurs more than 300 cm below the surface of the sediment (Fig. 2, core 1); tuffaceous sand layers at its mouth are the thickest (thicker than 35 cm) and coarsest in the area studied, containing pebble-sized fragments of pumice (*5*). In Astoria Channel the ash is found in two closely spaced layers of tuffaceous sand or silt 10 to 30 cm thick; the lower occurs at a depth between 125 and 190 cm (Fig. 2, core 2)