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Quantitative measurements of deep-sea channels on the Cocos Ridge, East Central Pacific

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Abstract—Precision depth records taken during Criss-Cross Expedition 1963 show deep-sea channels, about 1 km wide, at depths of 1400 to 2800 m on the Cocos submarine ridge. The channels are near the thalwegs of broad (about 30 km wide) submarine valleys, which trend normal to the long axis of the ridge. A closed depression at the landward end of the ridge and a central saddle prevent continental material from being transported by bottom currents into the region of the channels. The currents that produce the channels carry only oceanic sediments. Local turbidity currents, laden with ash, erupted from the numerous submarine volcanoes on the ridge, possibly carve the channels. Hydraulic functions (LEOPOLD and MADDOCK, 1953) for the channels calculated at bankfall stage are : (1) $W = 11{\cdot}2\ Q^{0{\cdot}39}$; (2) $D = 0{\cdot}43\ Q^{0{\cdot}32}$; and (3) $V = 0{\cdot}21\ Q^{0{\cdot}29}$. The hydraulic functions show that in a downslope direction the channel depth is maintained at the expense of the width, which suggests a channel flow that (1) has its sediment load concentrated near the base, but (2) deposits chiefly on its flanks probably by overbank spillage.

INTRODUCTION

AGASSIZ (1892) first noted a shallow area between the Galapagos Islands and Cocos Islands, which he named the Galapagos Plateau. Later soundings, chiefly by the U.S. Navy Hydrographic Office, demonstrated that the shallow region extended north-east almost to the Central American mainland and was not associated with just the Galapagos Islands. Thus JONES (1950) renamed the feature the Cocos Ridge after Cocos Island, which occupies a median position on the north side of the ridge. SHUMWAY (1954) and SHUMWAY and CHASE (1963) discussed the bathymetry of the Cocos Ridge and surrounding areas using data gathered after World War II. CHASE and MENARD (in press) will incorporate new information gained from a detailed survey of the Cocos Ridge during Criss-Cross Expedition, into a general treatment of the bathymetry of the eastern Pacific off Mexico and Central America.

The Cocos Ridge is a submarine arch that extends from the base of the continental shelf near the Gulf of Dulce, on the Panama–Costa Rican border, to the Galapagos Islands (Fig. 1). The ridge is 965 km long and about 225 km wide. Cocos Island, 480 km from Central America, is the only part of the ridge above water, however, numerous seamounts rise above the general level of the ridge. A closed depression at the base of the continental slope probably would trap erosion products carried by bottom currents from Central America. Any sediment not deposited in the depression or not funneled into the deeper areas that flank the ridge, could not be carried beyond the medial saddle, which crosses the ridge just east of Cocos Island.

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DEEP-SEA CHANNELS

In the spring of 1963, the Criss-Cross Expedition, sponsored by the Office of Naval Research and operated by Scripps Institution of Oceanography, ran Precision Depth Recorder surveys on the Cocos Ridge. During the various crossings of the ridge, I noticed on the record V-shaped echoes near the thalwegs of otherwise smooth-floored sea valleys, which cross the ridge (Fig. 2). Possible explanations for these depressions are : (1) local depressions, (2) fault grabens, or (3) flow channels. Additional crossings of the valleys indicate these features may be linear and are generally parallel to the long axis of the valley. Therefore, local sinking does not explain the V-shaped echoes. Faulting should not be restricted to the center of the valleys; although this possibility cannot be discounted completely. The simplest explanation seems to be that the V-shaped echoes are returns from current-carved channels.

The channels are in valleys that trend normal to the long axis of the ridge. The sense of flow in the channels is off the flanks of the ridge rather than down the long axis of the Cocos Ridge. Two major sea-valleys, delineated by the Criss-Cross survey, are northeast and southwest of Cocos Islands. The most detailed information on the channels comes from the valley northeast of Cocos Island.

The channels on the Cocos Ridge differ from deep-sea channels reported elsewhere, such as the Biscayan (LAUGHTON, 1960) and the Mid-Ocean Canyon (HEEZEN, *et al.*, 1959) from the Atlantic and the Cascadia (HURLEY, 1963), Delgada (MENARD, 1960) and Monterey channels (MENARD, 1960; WILDE, 1965) from the Pacific, as the Cocos channels do not have any apparent connection to the continental land mass either through submarine canyons that cut the continental shelf, or just proximity to the continents. Thus the currents that presumably carve the channels carry mainly sediments of local submarine origin.

Basalt, calcareous ooze, and palagonite tuff encrusted with manganese and iron oxides were dredged from seamounts on Cocos Ridge. The rocks on Cocos Island are basalts, tuffs, and andesites (CHUBB, 1933). Thus the positive relief features on the ridge are volcanic. Unfortunately, no cores were taken of the sediments in the sea valleys. However, WORZEL (1959, p. 352–3) described ash chunks and clay breccia in a core from the ridge, and layered ash from a core on the flanks of the ridge. This suggests that material is being eroded from the ridge and deposited on the flanks of the ridge. The sediments in the sea valleys would be, most likely, a mixture of calcareous ooze and volcanic material, chiefly ash.

Possible causes of the channels of the Cocos Ridge are (1) subaerial streams, which were drowned by the submergence of the ridge; (2) local turbidity currents, triggered by ash from eruptions of submarine volcanoes on the ridge; (3) local turbidity currents set off from unstable slopes; and (4) bottom currents of undertermined origin. Carving of the channels by subaerial streams seems unlikely as the depth of the channels (1400–2800 m) is 14 to 28 times the generally accepted value of recent sea level rise of 100 m (FLINT, 1957, p. 270). VINTON (1951) suggests that at least part of the Cocos Ridge was emergent in Oligocene-Miocene times to provide a partial land bridge for the precursors of the present life on the Galapagos Islands. If the submergence of the ridge is pre-Pliocene, the channel's walls should have slumped inward or the channels should be filled with ooze, as the rate of accumulation

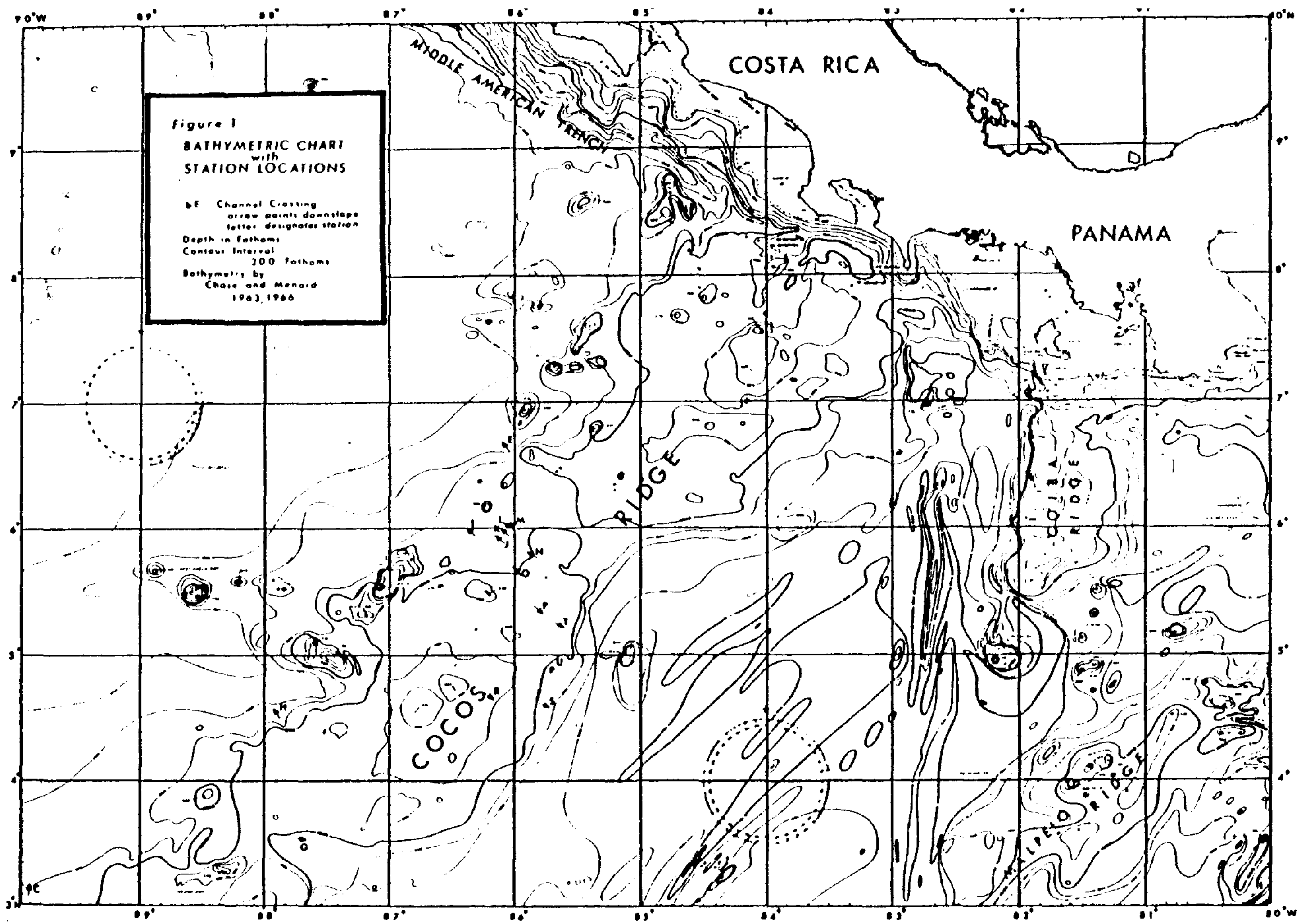

Fig. 1. Locations of stations described in the text superimposed on a bathymetric chart (CHASE and MENARD, in press).

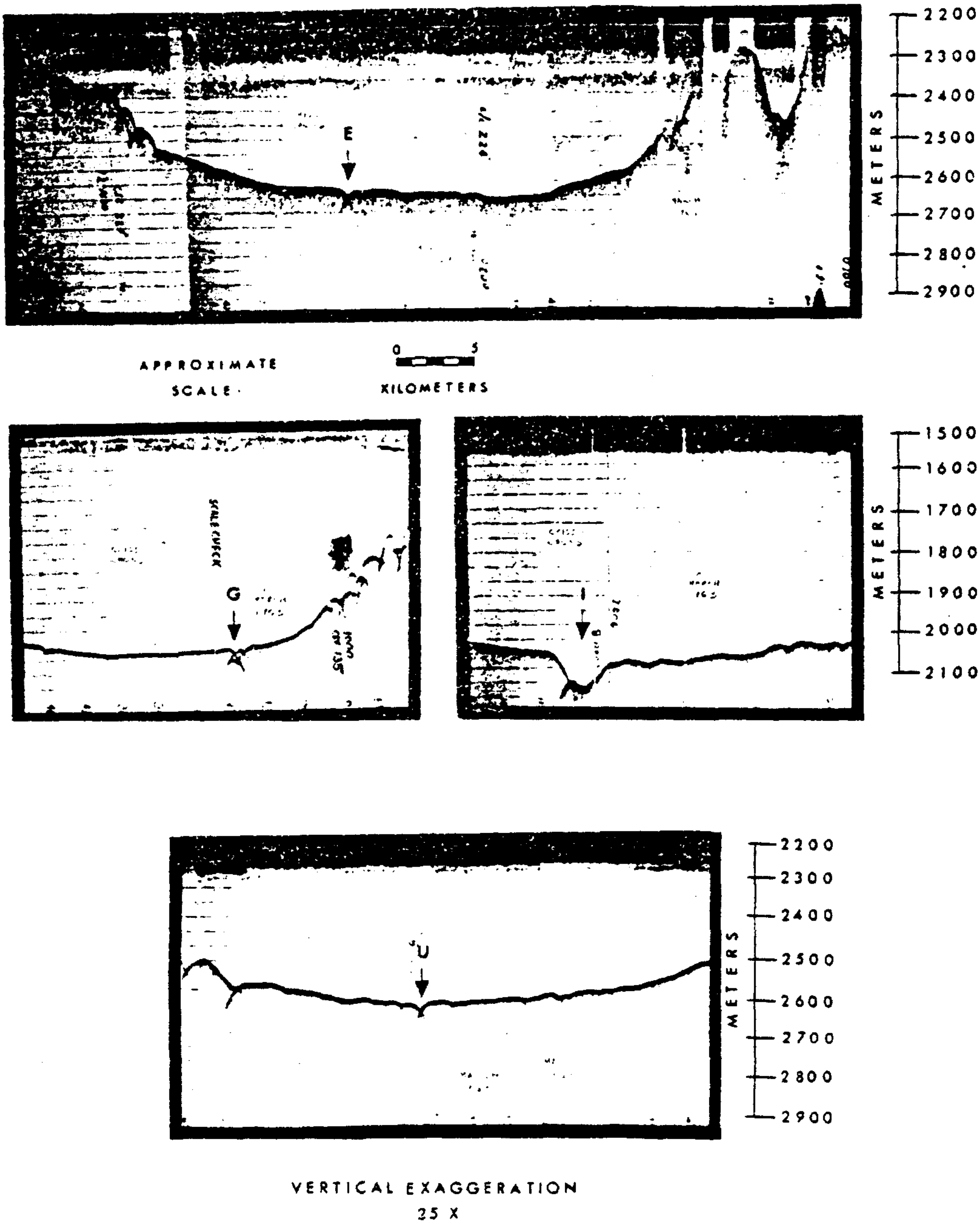

Fig. 2. Representative fathograms of deep-sea channels on the Cocos Ridge. Horizontal lines on records are 20 fms apart (uncorrected for the velocity of sound in water). Letters above arrows are station designations. See Table 1.

of sediment in the equatorial East Pacific is high enough to fill most of the channels (ARRHENIUS, 1961), so that no record of the channels would appear on the fathograms. It is possible that bottom currents could keep the subaerially cut channels open after submergence as any flow would tend to seek the lowest available level. However, the very fact of emergence of a large portion of the ridge is questionable (SHUMWAY, 1954), so that the carving of the channels by subaerial streams must remain a remote possibility. I favour local turbidity currents, initiated by submarine ash flows erupting from volcanoes on the ridge as the agent that carves the channels because (I) volcanoes on the ridge could act as a source of ash, (2) layered ash in the sediments on the flanks of the ridge suggest current deposition, (3) the lack of an abundant land source of sediment to trigger turbidity currents, and (4) the lack of connection between the Cocos channels and the continents indicate that the currents that produce the channels are of local origin. FISKE and MATSUDA (1964. p. 94-5) proposed a similar process of turbidity current deposition for the ash beds in the Tokiwa Formation in Japan. These tuffs are graded and interbedded with marine mudstones.

HYDRAULIC FUNCTIONS

Previous study of deep-sea channels was limited, because of the scarcity of data, essentially to reporting the existence of channels. Recently HURLEY (1964) has attempted to gain some knowledge of the regimes of channel flow by estimating possible velocities and discharges of currents in the Cascadia channels from the Chary-Manning equations. I have extended this effort by quantifying deep-sea channel information by calculating hydraulic functions for the Cocos channels. The data points are from various channels on the Cocos Ridge so that resulting functions are not representative of one channel but of the regime of the Cocos Ridge environment. Whether this is a valid technique will be tested when a large number of crossings of one continuous channel are made. LEOPOLD and MADDOCK (1953) developed hydraulic functions for subaerial streams. I will follow their use of English units so that functions from submarine and subaerial channels may be compared.

The hydraulic functions for the Cocos channels are calculated using the following assumptions : (1) the bankfull cross-sectional area of the triangular, so that the cross-sectional area equals 1/2 times the product of the maximum depth and the maximum width, (2) the mean velocity in the channel during a flow can be determined from the geometry of the channel by the use of a modified Chazy-Manning equation (HURLEY, 1964) :

$$V = \frac{c^* \, (\rho_1 - \rho_2)^{1/2}}{(\rho_1)} \, (ms)^{1/2} \tag{1}$$

where $c^* = \dfrac{1 \cdot 49}{n} \, (m)^{1/6}$

m = hydraulic radius $= \dfrac{\text{cross-sectional area}}{\text{wetted perimeter}}$

n = roughness factor = 0·025 (earth, ROUSE, 1960, p. 219)

ρ_1 = specific gravity of flow = 1·07

ρ_2 = specific gravity of overlying water = 1·02

$\Delta\rho$ = 0·05 (Lake Mead, GOULD, 1951)

s = slope of upper surface of the flow

The wetted perimeter is equal to either (a) the maximum width*, ignoring the shear between the overlying water and the current, or (b) twice the maximum width, including the shears between the sea water and the current, and the channel well and the current. Thus the hydraulic radius, ***m***, is either ½ times the maximum depth, if only the wall friction is considered; or ¼ times the maximum depth if both well and sea water-current shears are considered and approximately equal. KEULEGAN (1955) showed that for non-suspension currents, the shear between two liquids is negligible compared with the shear between the liquid and solid walls. Accordingly, the velocities of the bankfull flow calculated using m as ½ times the maximum depth are preferred as probably more realistic. However, previous workers, KUENEN (1952) and HURLEY (1964) considered shear on all boundaries of the current as important. Therefore Table 1 contains velocities for each channel crossing calculated with a hydraulic radius, ***m***, equal to either ½ times the maximum depth or ¼ times the maximum depth. The mean velocity formula, with all the constants inserted, is :

$$V = 13\,(m)^{\frac{2}{3}}\,(s)^{\frac{1}{2}}\ \text{ft/sec} \tag{2}$$

Discharge is defined as the cross-sectional area times the mean velocity or ½ times the product of the maximum width, the maximum depth, and the mean velocity. The parameter, ½ times the maximum depth or mean depth, the maximum width, and the mean velocity plotted against discharge give the hydraulic functions. Least square analysis of the data from the Cocos channels (Table 1) give the following set of hydraulic functions :

Table* 1. *Hydraulic parameters of Cocos Ridge channels

Station	Measured[1] Width (ft)	Measured[1] Mean depth[2] (ft)	Calculated[3] Mean velocity[4] (ft/sec)	Calculated[3] Mean velocity[5] (ft/sec)	Calculated[6] Discharge"" (10^6 ft³/sec)	Calculated[6] Discharge[5] (10^6 ft³/sec)
E						
F	2432 1748	48 30	17·21 1·9	10·6 7.96	0·624 2·008	0.417 1·237
G	1748	54	16·0	10.3	1·510	0.972
I						
J	9322 5067	145	23.6 10·5	14.4 6·45	23·761 2.394	14·498 1·471
K	2533	30	7·25	4·8	0·551	0.365
L	1900	30	7·7	5·1	o-439	0.29 1
N	2533	45	11·3	6.9	1·288	0·795
Q	3010 912	36	15·7 5·1	10·0 3.2	0.070 1·701	0.044 1·083
R		15				
T	2913 7944	114 60	28·4 21.5	16·9 12.9	25.720 3.749	15.305 2·255
U	4864	45	20.3	12.5	4.443	2·736

(1) From fathograms.

(2) Mean depth $= \dfrac{\text{Maximum depth}}{2}$

(3) From Chazy–Manning equation (HURLEY, 1964).

(4) Using hydraulic radius $= \dfrac{\text{Maximum depth}}{4}$

(5) Using hydraulic radius $= \dfrac{\text{Maximum depth}}{2}$ (preferred)

(6) Using discharge $= W x\, D_v\, V$.

*Ideally the wetted perimeter equals the maximum width divided by the cosine of the side slope angle. As the side slope angle is small its cosine is approximately one. Thus it is within the limits of measurements on the fathograms to approximate the wetted perimeter of the channel walls with the maximum width.

for : $m = \frac{1}{2}$ maximum depth (preferred. This paper)

$$W = 11\cdot 2\, Q^{0\cdot 39} \quad (3)$$
$$D = 0.43\, Q^{0\cdot 32} \quad (4)$$
$$V = 0\cdot 21\, Q^{0\cdot 29} \quad (5)$$

for : $m = \frac{1}{4}$ maximum depth (WILDE, 1964)

$$W = 11\cdot 7\, Q^{0\cdot 40} \quad (6)$$
$$D = 0.43\, Q^{0\cdot 33} \quad (7)$$
$$V = 0.19\, Q^{0\cdot 27} \quad (8)$$

where : W = maximum width (ft)
D = $\frac{1}{2}$ times the maximum depth (ft)
V = mean velocity (ft/sec)
Q = discharge (ft^3/sec)

For deep-sea channels. such as Monterey (WILDE, 1965) and the Cascadia (HURLEY, 1964) the discharge decreases in the downslope or downstream direction. This implies that submarine channels are carved by flows that gain their maximum volume near the head of the channel and dissipate downslope, probably through overbank spillage. The hydraulic functions, using either the hydraulic radius $m = \frac{1}{2}$ or $\frac{1}{4}$, for the Cocos Ridge channels show that the width function decreases at a greater rate with respect to the depth function in the direction of the decreasing discharge. In other words, the agency that produces the channel expends more of its energy maintaining the depth of the channel. The geometry of the type of channel indicated by the hydraulic functions (3) through (8) could be produced by a turbidity current that has its sediment load concentrated near the sole and toe of the flow, similar to the model described by STONELY (1957).

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