The Cromwell Current on the East Side of the Galapagos Islands

HASONG PAK AND J. R. V. ZANEVELD

School of Oceanography, Oregon State University, Corvallis, Oregon 97331

Observations made during October and December 1971 on the Yaloc 71 Cruise of Oregon State University indicate the presence of the Cromwell Current on the east side of the Galapagos Islands. Light scattering, particle size distribution, nutrients, and standard hydrographic parameters were measured in water samples collected at 154 stations. The distribution of water properties shows that the extension of the current to the east side of the islands derives primarily from water flowing around the north side of the islands. This flow consists of two branches that tend to merge into one at about 84°W. There was no clear indication of a branch around the south side of the islands within the area of the observations.

What happens to the Cromwell Current as it passes the Galapagos Islands has been a topic of great interest ever since the discovery of the Cromwell Current itself. *Montgomery* [1962], in a review of the Cromwell Current, concluded that the Cromwell Current is usually weak or absent on the east side of the Galapagos Islands. *Wyrtki* [1966] said that the Cromwell Current disintegrates west of the Galapagos Islands and it splits into north and south branches, with a part of the water extending to the upwelling region off Peru.

Knauss [1966], in his report on the Swan Song Expedition, the specific purpose of which was to study what happens to the Cromwell Current as it moves eastward and beyond the Galapagos Islands, showed weak eastward flow at 87°W centered north of the equator. Using Alaminos cruise data, *White* [1969] demonstrated that the southern branch of the Cromwell Current was present at 84°W at latitudes from 2°S to 4°S on isanosteric surfaces of 120, 160, 200, and 280 cl/ton. The undercurrent was inferred from the distribution of acceleration potential on the isanosteric surface, and was also accompanied by high values of oxygen. *Stevenson and Taft* [1971] measured an eastward velocity of 37 cm/sec at the maximum salinity level at 84°W and near the equator by parachute drogue tracked relative to another parachute drogue 310 meters deep.

The Cromwell Current has been observed at a few points on the east side of the Galapagos

Islands [*Knauss*, 1966; *Stevenson and Taft*, 1971]. *White* [1969] described the circulation on the basis of a network of stations extending to the east of 91°00′W; however, there were few stations close to the islands.

In the present paper, the Cromwell Current circulation pattern will be described in the vicinity of the Galapagos Islands on the basis of the observations made on RV *Yaquina* during the Yaloc 71 cruise.

YALOC 71 CRUISE

The Yaloc 71 cruise, from October 16, 1971, to December 7, 1971, covered the area between 3°N and 3°S and between 93°W and 83°50′W and included observations at 152 hydrographic stations shown in Figure 1. Temperature, salinity, oxygen, light scattering, particle size distribution, and concentrations of four kinds of nutrients (silicate, phosphate, nitrate, and nitrite) were measured at 13 points in the upper 600 meters of water at each station. Nine parachute drogues set 100 meters deep were traced either by radar ranging from the ship's position fixed by a satellite navigation set or by maintaining the ship's position close to the drogue so that the ship's positions determined by satellite navigation could be used as the drogue positions. The water samples, obtained by hydrographic casts with plastic NIO bottles, were analyzed for temperature, salinity, and oxygen. In addition, light scattering was measured with a Brice-Phoenix light-scattering photometer [*Brice et al.*, 1950; *Spilhaus*, 1965; *Pak*, 1970].
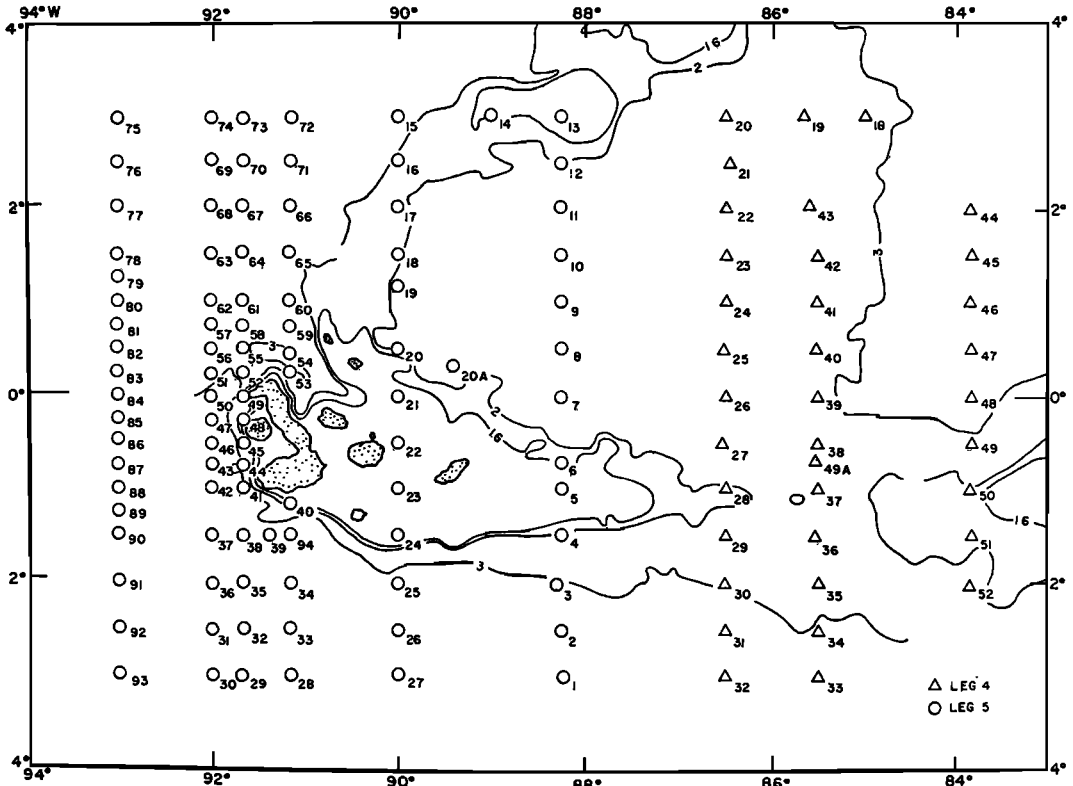
Fig. 1. Yaloc 71 cruise stations with bathymetric contours in kilometers.

Particle size distributions were determined with a Coulter Counter equipped with a 100-μm aperture [*Carder*, 1970], and nutrients were measured with an autoanalyzer.

RESULTS

Observed results are presented to describe the circulation pattern of the Cromwell Current in the region of the Galapagos Islands and to the east of the islands by (1) dynamic topography and drogue observations, (2) distribution of hydrographic properties, and (3) distribution of suspended particles.

Dynamic topography at 100 db and 600 db and drogue data. In order to present the Cromwell Current in the region of the Galapagos Islands and to the east of the islands, dynamic topography of the 100-db surface relative to the 600 db is shown in Figure 2. Nine parachute drogues set 100 meters deep are also indicated in the same figure by arrows corresponding to their velocity vectors, and the tails of the arrows are at the stations where drogues

were launched. In spite of the uncertainty of geostrophic calculations in the equatorial region, measured current directions are in good agreement with dynamic topography, except at one station just south of Isabela Island (the largest of the Galapagos Islands). This agreement lends credence to the complicated flow pattern shown in dynamic topography. The 100-db surface was chosen because drogues were placed at this level.

According to Figure 2, the general flow pattern on the east side of the Galapagos Islands shows eastward zonal flow separated by trains of eddies approximately 50 km in diameter. This pattern of flow has a resemblance to a Von Karman compound vortex street like that described by *White* [1973]. A detailed flow pattern of the Cromwell Current is described according to the dynamic topography, because we find it presents the basic picture of the flow pattern. All the other data are presented and described in reference to that framework. A general picture of the flow pattern was necessary to describe small-scale flows (branches)

in terms of several different parameters. The velocity field is not completely described by the geostrophic approximation. Other lines of evidence tend to conflict with the picture resulting from the geostrophic calculations, and these are discussed later.

On the basis of the dynamic topography of the 100-db surface relative to 600 db, broken streamlines are drawn to indicate the flow pattern without any consideration of speed of the flows (Figure 3). At about 92°00′W, just west of Isabela Island, the Cromwell Current apparently splits into three branches; one heading north (N), the second extending east around the northern coast of Isabela Island (C), and the third heading south off the west coast of the same island (S). From branch N another branch (N-1) splits off and turns at about 02°00′N, 91°30′W. Branch C extends to the east along about 02°00′S after it passes through the islands.

Branch S heads to the south on the west side of Isabela Island beyond 03°00′S, the southern limit of our observations. There is a small branch that turns to the east by going around

the southern coast of Isabela Island to merge into the branch C on the east side of the same island. There is another eastward flow at about 03°00′S starting from about 90°00′S that may be fed by branch S after branch S extends to the south of 03°00′S. The location of this branch (S-1) is similar to that of the 'southern branch of the equatorial undercurrent' reported by *White* [1969.] We cannot, however, verify White's south branch by our data, since our observations extended only to 03°00′S.

In between the zonal streams of eastward flow, we find zonal bands flowing toward the west; one is along the equator (SEQ-1) between the branches N-1 and C, and the other (SEQ-2) between the branches C and S-1. The branch SEQ-1 is much wider than the other branches, and observed current velocity there is about 10–30 cm/sec to the west at 100-meter depth. Observed current velocity of the branch SEQ-2 is about 20 cm/sec to the west at the same depth.

Unfortunately, we do not have any direct current measurements of the Cromwell Current on the east side of the Galapagos Islands. On
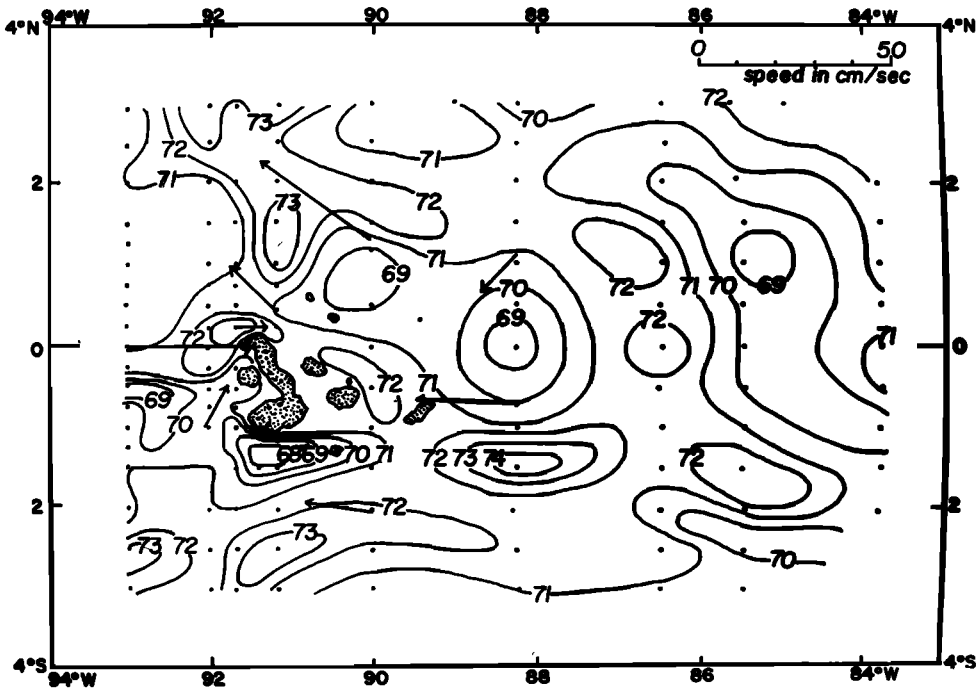

Fig. 2. Dynamic topography in dynamic centimeters relative to 600 db and velocity of current determined by parachute drogues set out 100 meters deep.

the west side of the islands (station 84 at 00°00′, 93′00′W), an eastward velocity of 50 cm/sec was observed at 100-meter depth, and distribution of temperature (Figure 4) in the meridional section at 93°00′W shows that the core of the Cromwell Current is below 100-meter depth.

Both branches SEQ-1 and SEQ-2 turn toward the poles: the first toward the north and the second toward the south, near Isabela Island (at about 92°00′W). It can be seen clearly in Figures 3 and 5 that a part of SEQ-2 goes around the southwest coast of Isabela Island and then extends to the north along the west coast of the island. There is a drogue measurement at station 5-42 (southwest of Isabela Island) which supports the northward flow on the west side of Isabela Island.

Distributions of hydrographic properties. Results of the Yaloc 71 cruise data, primarily the distribution of water properties, are presented to show the extension of the Cromwell Current to the east side of the Galapagos

Islands. The core of the Cromwell Current could not be defined because there were no direct measurements of the velocity profile. However, we can qualitatively estimate the depth of the core by the shape and location of the well-mixed layer indicated in the various parameters of water properties. Such a crude approximation may not be of any value in determining the absolute depth, but it still gives some indication of vertical variation of the current from one meridian to another.

The Cromwell Current, with its high-velocity core, is characterized by intense vertical mixing. For example, above the Cromwell Current the vertical distribution of temperature is characterized by a minimum and below the Cromwell Current it is characterized by a maximum. The core is located at the thermocline. Accordingly, the lines of constant σ_t and isotherms in the meridional sections (Figure 4) bulge upward (ridge) above the thermocline and bend downward (trough) below the thermocline, and the core of the Cromwell Current coincides with the
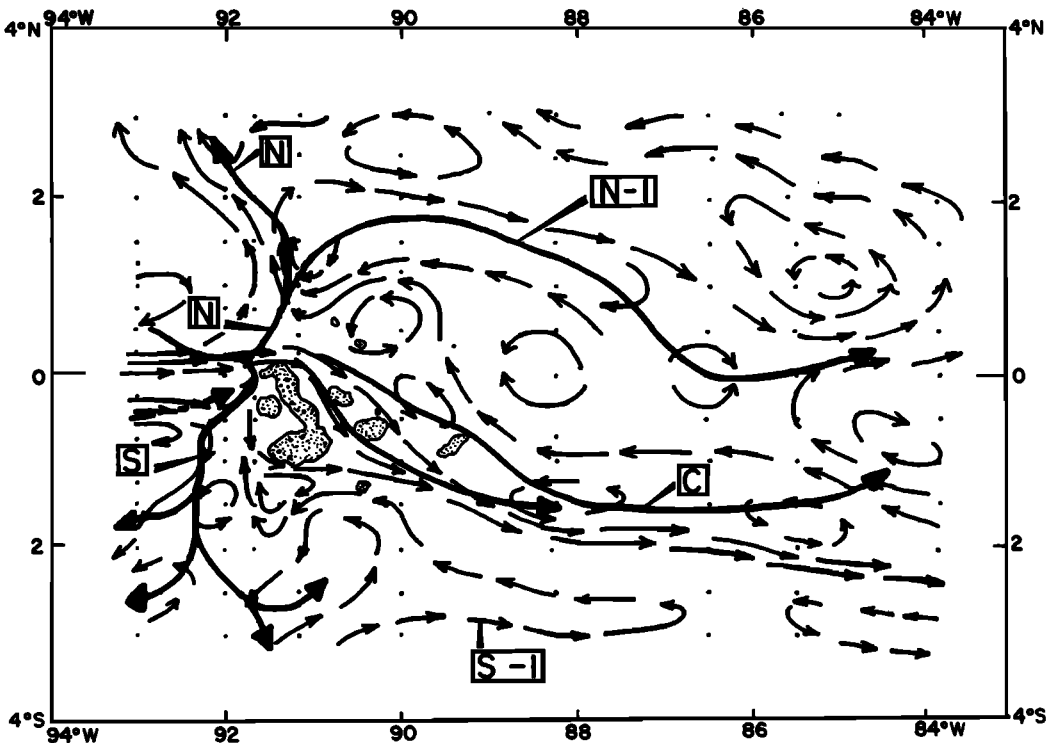

Fig. 3. Streamlines 100 meters deep inferred from dynamic topography (Figure 2) with the axes of the Cromwell Current (heavy lines) determined by the equatorial thermostad.
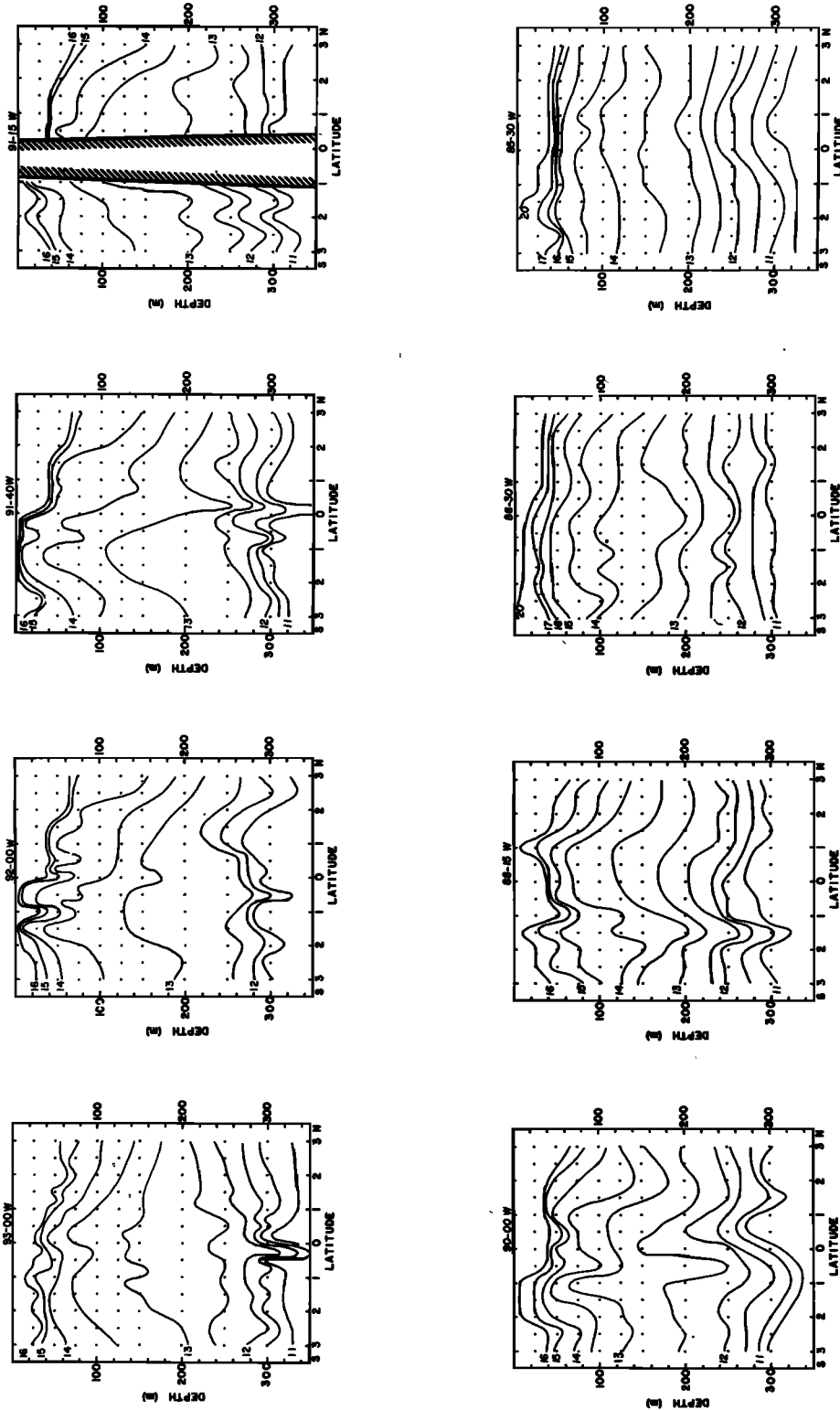
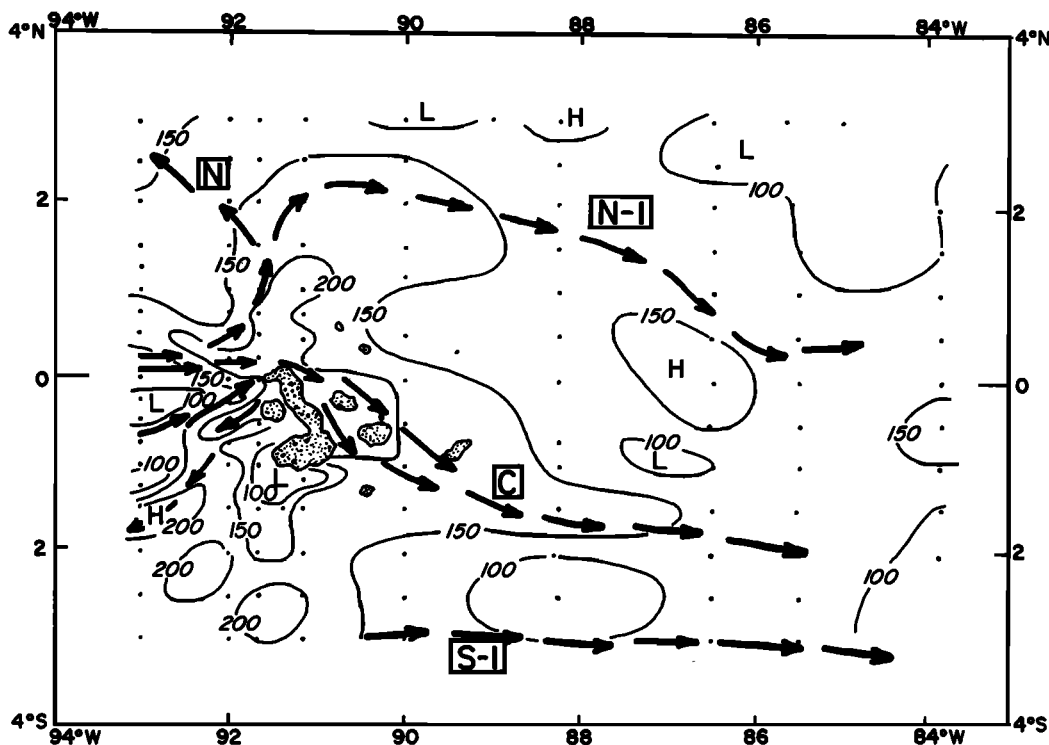Fig. 4. Temperature distributions in 8 meridional sections.

Fig. 5. Thickness (meters) between two isanosteric surfaces; from $\delta_T = 170$ to 190 cl/ton with the axes of the Cromwell Current (heavy lines) determined by the dynamic topography.

level isanostere or isotherm [*Cromwell et al.*, 1954; *Wooster and Jennings*, 1955; *Montgomery and Stroup*, 1962].

The changes in the Cromwell Current as it passes the islands and extends to the east are shown in distribution of hydrographic properties in the meridional sections. Vertical distribution of temperature in eight meridional sections from 93°00'W to 85°30'W are presented in Figure 4. The Cromwell Current is indicated by the layer of relatively well-mixed water (maximum spreading of isotherms), and we can identify the extent of the current, changes in depth, and width of the current as it extends east from the distribution of the mixed layer. The eastward extension of the Cromwell Current is clear as far as 86°30'W. The depth of the Cromwell Current core, estimated by the depth of the most level isotherm, increases slightly as it approaches the islands and then decreases as it extends eastward, contrary to the report by *Knauss* [1966]. The width of the current is also decreased as it extends to the east from the islands.

Owing to the intense mixing within the Cromwell Current, the current is also identified by a relatively thicker layer of water with temperature or density close to that of the core of the current [*Wooster and Cromwell*, 1958; *Knauss*, 1960; *Montgomery and Stroup*, 1962], *Seitz* [1967] proposed the use of the word 'thermostad' to indicate a layer of water with a minimum vertical temperature gradient, and *White* [1969] showed a map of the thickness between isanosteric surfaces of 170 to 190 cl/ton to demonstrate that the equatorial thermostad corresponds to the equatorial undercurrent.

The distribution of the equatorial thermostad determined by the Yaloc 71 cruise data is shown in Figure 5. Arrows indicating the Cromwell Current (from Figure 3), as determined by the dynamic topography, are superimposed on the equatorial thermostad to indicate the agreement between the two sets of data. The axis of the Cromwell Current determined by connecting the equatorial thermostad is drawn in Figure 3 for the same purpose. Locations of the branch N-1 and C in Figure 5 show a fair agreement,

but they are not in exact agreement. For example, the thermostad is slightly south of branch N-1 and slightly north of branch C. From locations of branches N-1 and C in Figures 3 and 5, we can see good agreement between geostrophic flow and the equatorial thermostad. Considering the limitations of geo-

strophic calculations near the equator, the agreement between Figures 3 and 5 seems to suggest that the Cromwell Current can be approximated by geostrophic flow as was reported by *Montgomery and Stroup* [1962] and *Knauss* [1960].
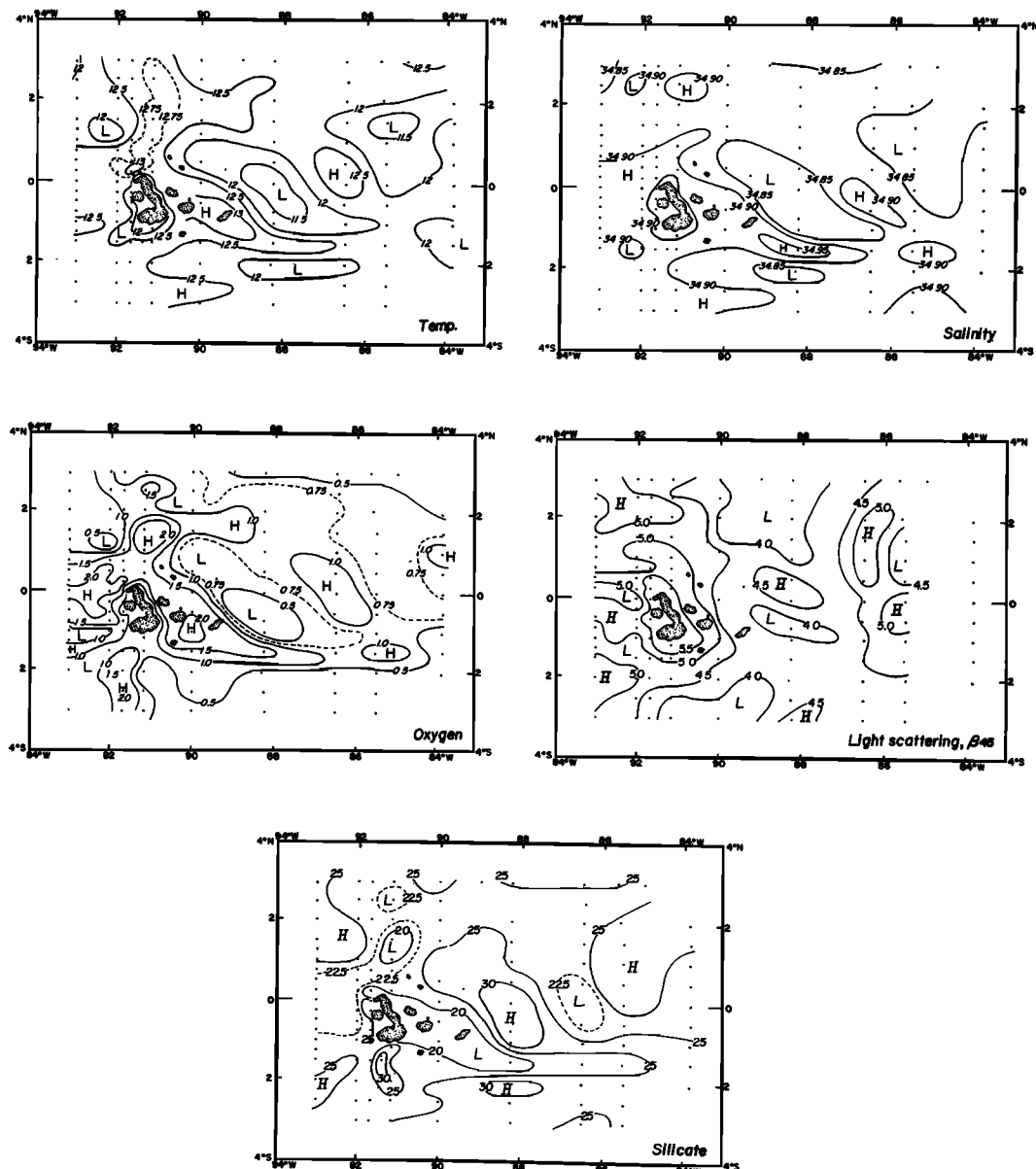
The Cromwell Current is also clearly indi-

Fig. 6. Horizontal distribution at 250 meters depth of temperature (degrees Centigrade), salinity (per mil), oxygen (milliliters per liter), light scattering (1/m ster), and silicate (micrograms per liter).

cated in Figure 6 by a maximum in temperature, salinity, oxygen, and light scattering and by a minimum in silicate in the 250-meter surface. These define the Cromwell Current, at least its lower part, very clearly on the east side of the Galapagos Islands in two branches, N-1 and C. These indications of the Cromwell Current at a depth of 250 meters show a better agreement with the equatorial thermostad than with the geostrophic flow. The two branches separate just north of Isabela Island. The separation may occur simply from blocking of the Cromwell Current by the islands Isabela, Pinta, and Marchena (Pinta and Marchena are about 40 miles northeast of the northern coast of Isabela). Since the width of the Cromwell Current is larger than the longitudinal span of the blocking islands, such separation is likely to occur. While branches N and C are indicated clearly in Figures 5 and 6 and are in good agreement with the earlier interpretations of the Cromwell Current made on the basis of the dynamic topography (Figures 2 and 3), indications of branch S are not as clear as branches

B and C in the same figures. For example, branch S-1 is not supported by oxygen and thermostad distributions, but it is indicated somewhat by temperature, salinity, and silicate distributions. Since branch S-1 is on the border of our observations, our confidence in it may be low.

Distribution of suspended particles. Vertical distributions of suspended particles in the tropical waters normally show a relative maximum at the sea surface and another maximum, normally larger than the surface maximum, at the thermocline. Below the thermocline, particle concentration rapidly decreases with depth to a broad minimum that extends over most of the water column. Near the bottom the particle concentration often increases. The two maximums in the surface layer can be merged into one broad maximum and become indistinguishable when the thermocline is shallow and mixing is intense in the surface layer. The main source of the suspended particles in the open ocean is biological production, which is dependent on the penetration of the sunlight.
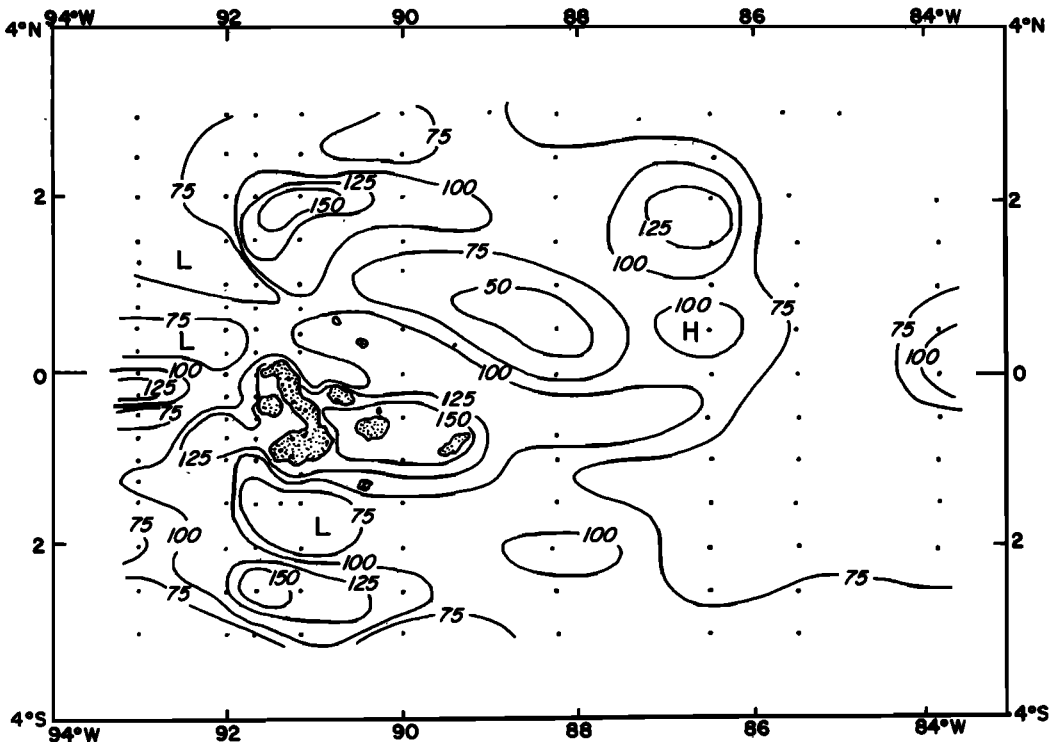

Fig. 7. Total particle volume contained in the layer from 100 to 300 m in ppm/cm³.

The high density gradient associated with the thermocline slows the particles settling from the surface layer, causing the particle maximum usually observed at this depth. The surface layer thus provides a source of suspended particles. The intense vertical mixing associated with the Cromwell Current leads to an increased downward transport of particles, similar to the downward transport of other properties (e.g., heat, dissolved oxygen). The effects of this downward transport are evident at 250 meters which is below the core depth of the current.

Data on light scattering (Figure 6d), which is related to the suspended particles, show branch C of the Cromwell Current by bands of a slight relative maximum 250 meters deep. The same results are observed in the total suspended particle volume in the layer between 100 and 300 meters (Figure 7). Introduction of particles from the islands and subsequent downstream transport are also indicated by the maximum light scattering in a meridional section through Isabela Island and 90°00′W (Figure 8). In Figure 8, we can identify the branches N-1 by another maximum in light scattering, and SEQ-1 and SEQ-2 by minimum light scattering. These maximums in suspended particles are probably related to the Cromwell Current through both intense mixing and turbulent interaction with the islands, resulting in entrainment of particles. Branch C, shown in Figures

3 and 5, passes by the islands where the particle distribution develops a pronounced maximum (Figure 7). It is located to the south of the particle maximum zone, on the east side of San Christobal Island (easternmost island). We cannot find any explanation for this deviation, but we suggest that it is associated with a small-scale phenomenon in time and space not well defined by our observations. The increase in suspended particles is probably caused both by terrigenous particles injected into the water by the interaction of currents with the islands and by an increase in biogenous material contributed by the increased supply of nutrients resulting from the upwelling process associated with the Cromwell Current. Such upwelling is clearly indicated in the horizontal distribution of temperature at 50-meter depth (Figure 9).

The index of refraction of suspended particles is calculated by light scattering and particle size distribution as described by *Zaneveld and Pak* [1973]. The method applies an approximation of a constant linear relation between the total scattering coefficient and volume scattering function at 45° and results in a single value of index of refraction for a given water sample. It is assumed that terrigenous particles have a higher index of refraction than biogenous particles. High values of index of refraction were observed in the Cromwell Current (branch C) and in the general area surrounding the islands
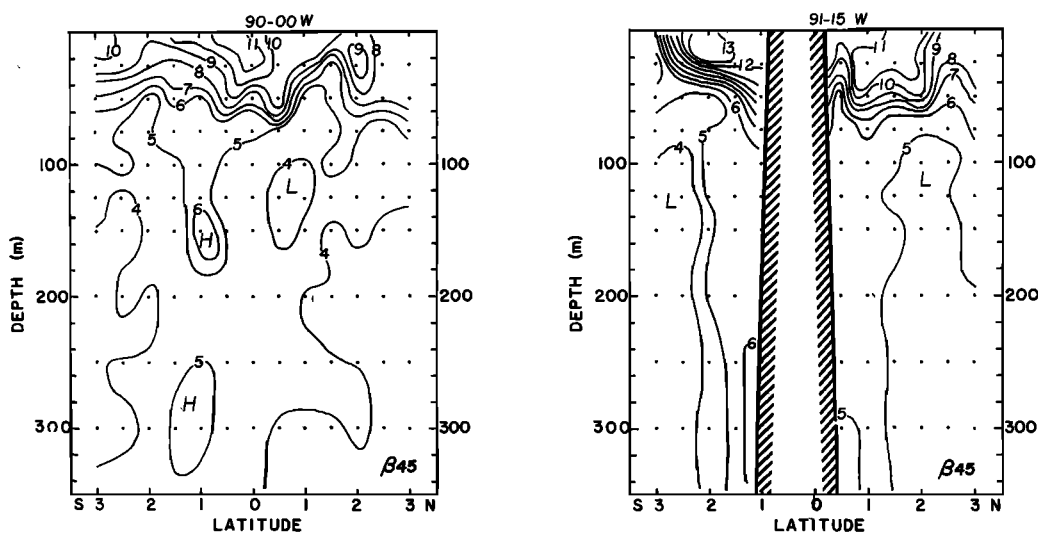

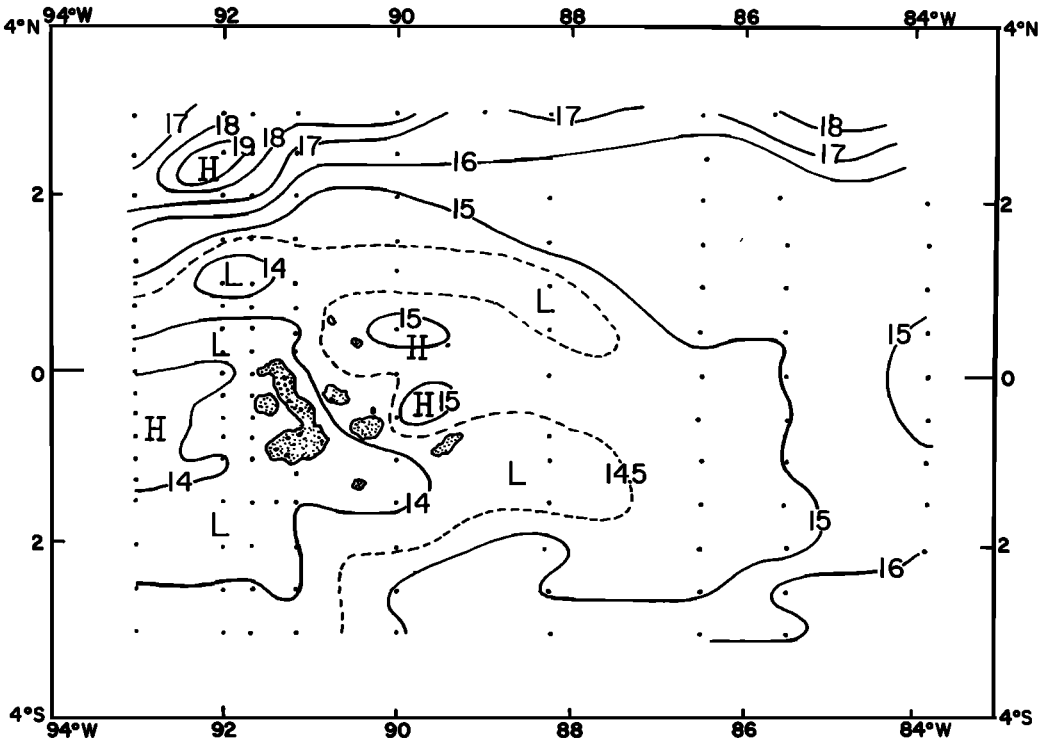Fig. 8. Vertical distribution of $\beta(45)$ (1/m ster) at 91°15′W and 90°00′W meridians.

Fig. 9. Temperature distribution at 50 meters depth.

(Figure 10). Such a distribution of index of refraction suggests that at least a part of the increase in suspended particles in the Cromwell Current is contributed by terrigenous particles, and that the Galapagos Islands are the most likely source of these particles.

On the other hand, high values of index of refraction were not observed in the other branches of the Cromwell Current at 250-meter depth (Figure 10). High values were, however, observed in those branches at shallower depths: 50, 75, and 100 meters. Such vertical and horizontal variations may be regarded as a result of the complex nature of spatial and temporal variations in the interactions between the Cromwell Current and the Galapagos Islands. The Galapagos Islands platform extends farther to the south of the equator than to the north. Thus one would expect the flow patterns of the Cromwell Current, which is symmetric about the equator as it approaches the islands, to be different to the north and south as the current branches and flows around the islands. In addition, the island group may vary from north to

south with respect to the kind and amount of particles they supply to the surrounding waters.

In either case, the distribution of suspended particles shows some indications of the Cromwell Current. We made an estimate of the total mass of suspended particles contained in the layer between 100 and 300 meters deep by assuming an average density of 2.0 g/cc for all the particles counted (Figure 7). If the lowest observed value of particle mass is assumed to be the background value, then the mass of suspended particles introduced by the Cromwell Current is of the order of 1 g/m^2 in the layer between 100 and 300 meters deep and 1.6 g/m^2 in the layer between 50 and 250 meters deep.

DISCUSSION

The Cromwell Current, on the west side of the Galapagos Islands, has been reported to be located at the equator [Knauss, 1960, 1966]. Isabela Island extends roughly from the equator to 1°30′S latitude. Because of the asymmetric location of Isabela Island relative to the equator, the major part of the Cromwell Current
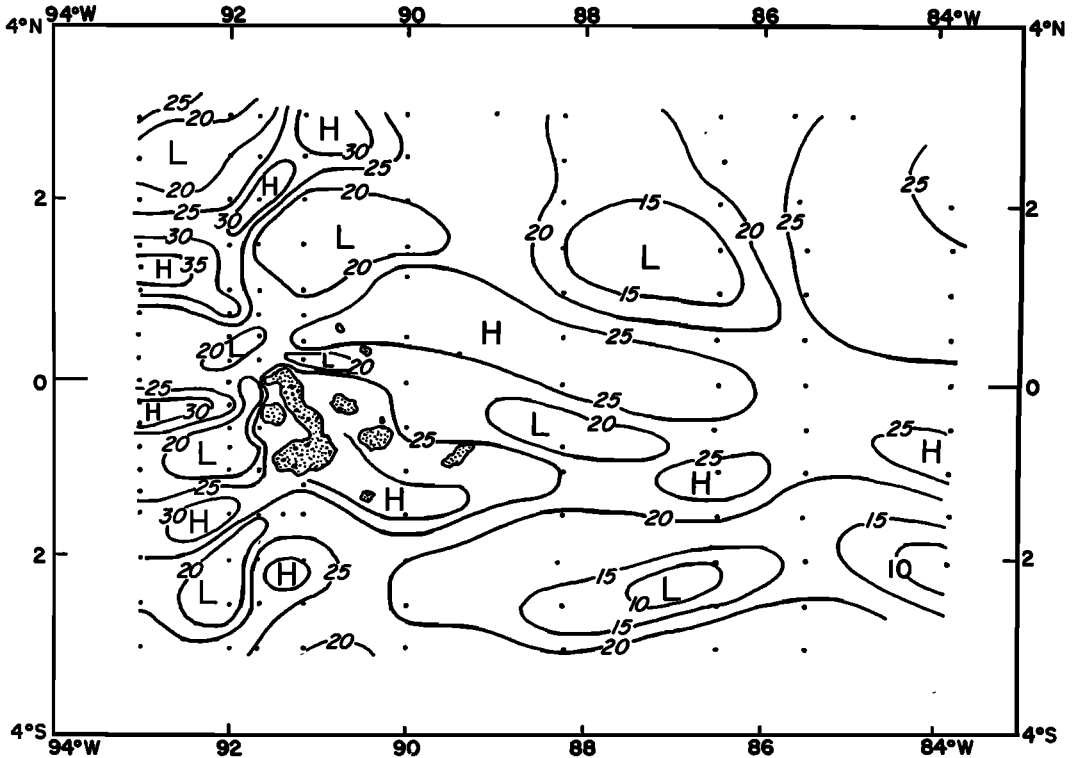
Fig. 10. Distribution of index of refraction at 250 meters depth.

appears to pass around the northern side of it (Figures 5 and 6). A similar result was reported by *Knauss* [1966].

Knauss [1960] reported that, based on the Dolphin Expedition, the Cromwell Current can be accounted for by geostrophic flow. In his later report, *Knauss* [1966] found that the Cromwell Current was not in geostrophic balance based on the data from the Swan Song Expedition.

According to the data presented here, the geostrophic flow pattern was in good agreement with the flow determined by drogues and the distribution of tracers. We found many suspicious values in geostrophic current speed, and we thus feel that these data may not be reliable.

The distribution of temperature at 93°00'W, 92°00'W, and 91°40'W (Figure 4) and the distribution of oxygen at 93°00'W (Figure 11) indicate that the axis of the Cromwell Current on the west side of the Galapagos Islands may be slightly displaced to the south of the equator. On the other hand, the fact that the Cromwell Current does not seem to extend directly around
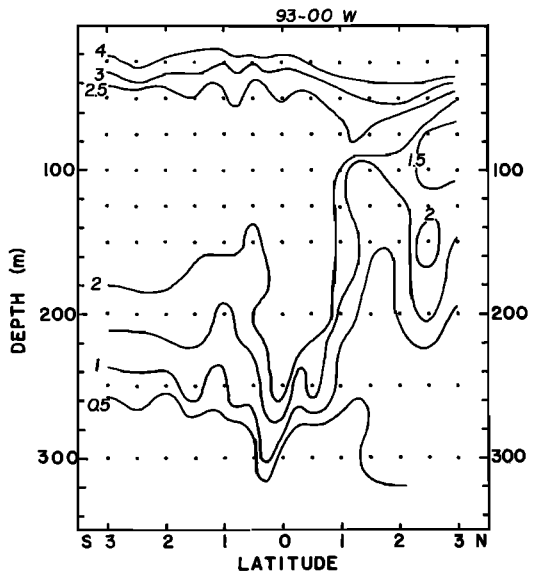

Fig. 11. Vertical distribution of oxygen at 93°00'W meridian.

the southern side of Isabela Island, located near 01°00′S, seems to contradict such displacement. In regard to this problem, we may have to consider the idea that the Cromwell Current is causing strong mixing to generate such a well-mixed layer, but the mixed water can be deflected away from the main stream when a proper deflector is available. There is actually a proper deflector, Isabela Island, and the Cromwell Current (branch S) is deflected to the south of it accordingly. Before branch S reaches the southern coast of Isabela Island, it loses the eastward velocity, and it runs into the south equatorial current (branch SEQ-2), which flows to the west. All the observed data indicate that the south equatorial current (SEQ-2) is present as a zonal band to the south of about 01°30′S and to the east of 91°00′W. The northwestern edge of the SEQ-2 reaches the southern coast of Isabela Island, which effectively blocks off eastward turning of the Cromwell Current (Figures 2, 3, 5, and 7). A branch of westward flow just south of Isabela Island was shown in *White*'s [1969] data, although his picture was based on only a few observations and he did not specifically describe the flow. In this case we can still observe a layer well mixed in temperature and oxygen as indicated in Figure 11, even though the Cromwell Current is not displaced to the south of the equator. An ambiguity of this kind may be one of the weaknesses of studying a current by the distribution of water properties without direct measurement of velocity.

As the Cromwell Current is blocked by Isabela Island and by the southern equatorial current (the branch SEQ-2), the water carried by the Cromwell Current tends to pile up on the west side of the island. The Cromwell Current then may be affected in a way that causes it to split into northern and southern branches at some point farther upstream. If this is the case, the southern branch might extend to the east through the region to the south of 03°00′S until it reaches to about 90°00′W, where it shows as branch S-1. In this case branch S-1 will conform with *White*'s [1969] report of a southern branch of the Cromwell Current between 02°00′ and 04°00′S as far east as the coast of Peru.

On the east side of the Galapagos Islands, the current was observed in two narrow channels. Their locations are not symmetric about the equator, and it is quite possible that the locations of the branches either vary seasonally or as a result of other large-scale dynamic conditions. We could not detect the Cromwell Current with six parachute drogues set 100-meters deep on the east side of the Galapagos Islands (Figure 2). Had we not made observations over a grid of hydrographic stations as well, we would have reported that the Cromwell Current does not extend to the east side of the Galapagos Islands at all.

Distributions of water properties in the level surfaces or isanosteric surfaces in depths less than about 100 meters show a somewhat more complicated picture than in the deeper water. Such a complicated distribution of water properties is believed to be the result of intense mixing caused by the strong internal interaction between the surface water and the Cromwell Current water flowing in the opposite direction, thus creating a large velocity shear, and the interruption of the flow by the Galapagos Islands causing eddies of various sizes. This intense mixing takes place in an area where there is a convergence of the surface water from both hemispheres, which have distinctive water mass characteristics and often form a front.

The equatorial front, the boundary between the surface water of the south equatorial current characterized by low temperature and high salinity (temperature less than 20°C and salinity greater than 34.0%) and the surface water from the northern hemisphere (probably from the equatorial counter current) characterized by higher temperature and lower salinity, is shown in Figure 12. The front contains perturbations of various sizes. These perturbations can be described as intrusions of one water type into the other. This perturbation effect will be superimposed on the effects of the Cromwell Current, and it may be difficult to resolve the two.

Water below the core of the Cromwell Current, on the other hand, is more homogeneous. The Cromwell Current is reflected in the distribution of water properties either as a horizontal maximum in temperature, salinity, oxygen, and light scattering or minimum in silicate with little confusion from other effects (Figure 6).

The interaction between the islands and the currents may create island wakes of terrigenous
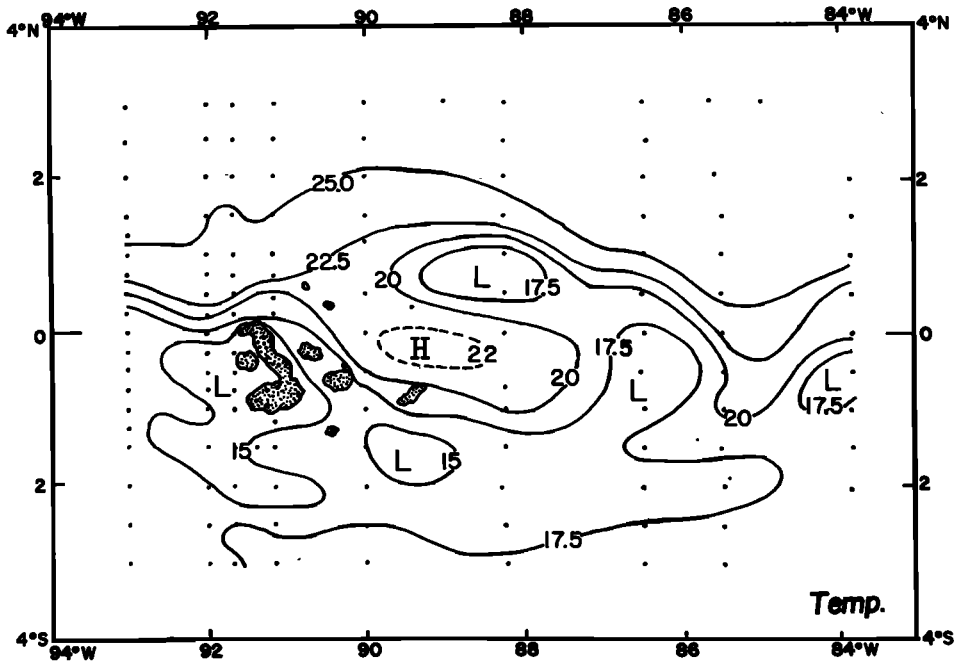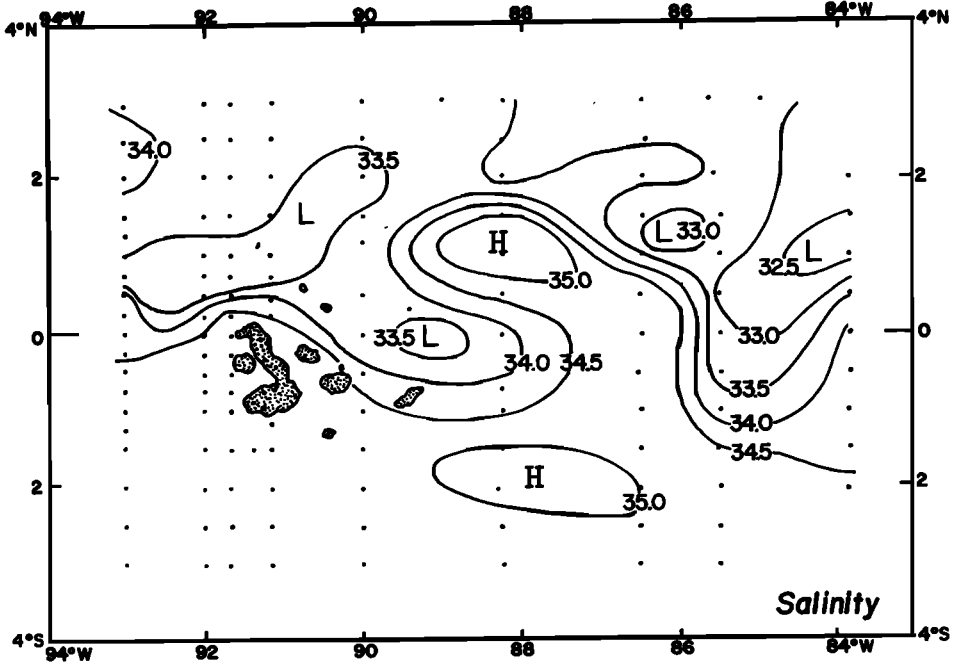
Fig. 12. Horizontal distribution of salinity (top) and temperature (bottom) at 25 meters depth.
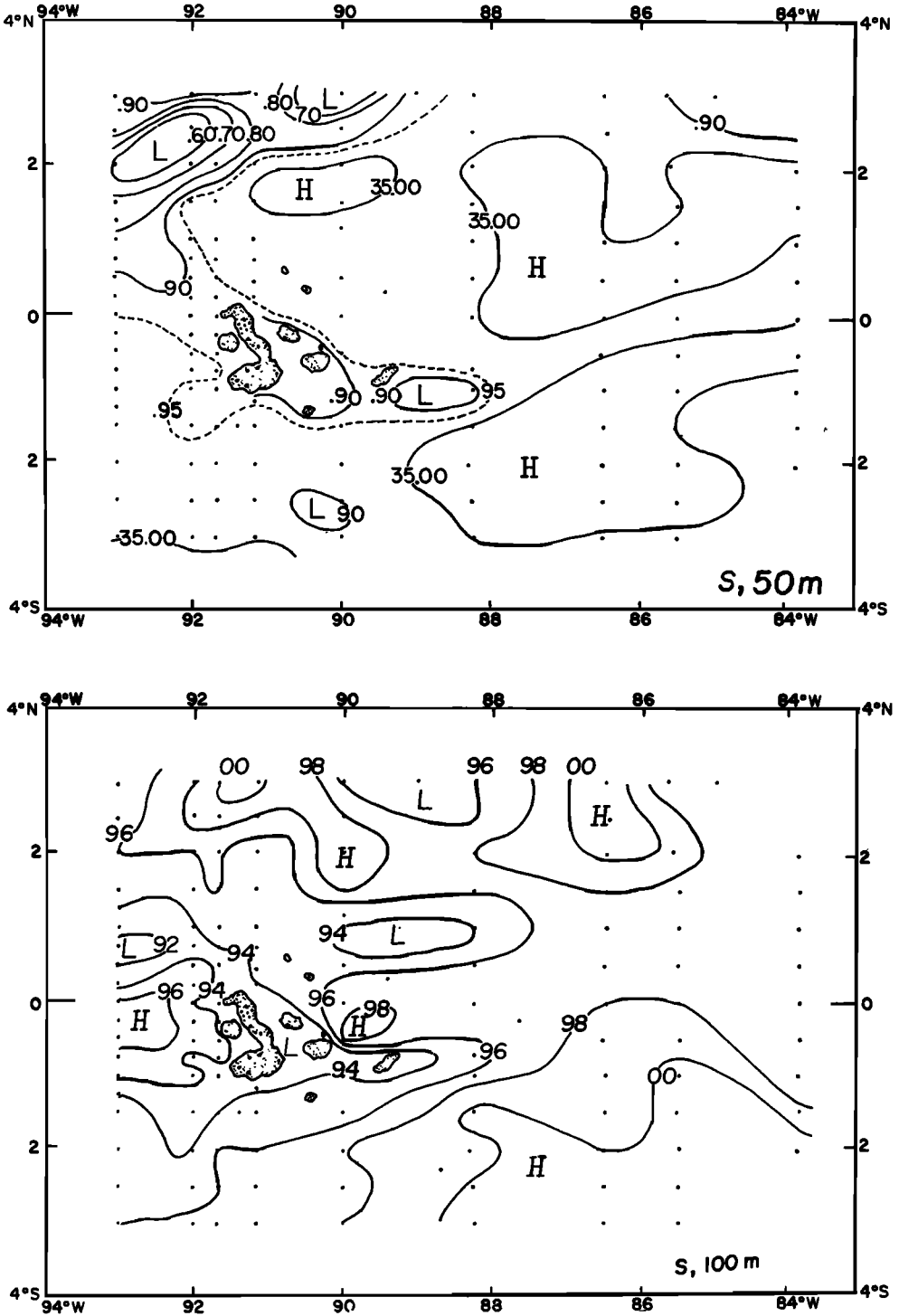
Fig. 13. Horizontal distribution of salinity at 50 meters (top) and 100 meters (bottom) depth.

particles suspended in the water on the lee side of the island. We observed a high concentration of particulate matter and high values in light scattering in the Cromwell Current on the east side of the Galapagos Islands. High values of index of refraction in the region where the Cromwell Current is located support the idea of island wakes of particles, since the index of refraction of the terrigenous particles is larger than that of biological particles.

While the Cromwell Current is identified by a temperature and salinity maximum on the 250-meter surface (Figure 6), the salinity distributions at 50 and 100 meters (Figure 13) do not seem to indicate the Cromwell Current by a salinity maximum as was suggested by *Stevenson and Taft* [1971]. Instead it is indicated by a temperature minimum in the 100-meter surface (not shown), which suggests the Cromwell Current core is located below 100 meters.

CONCLUSIONS

1. The Cromwell Current was observed as far as 86°30'W and was split around the islands. More water seemed to be flowing on the northern side of the islands in two branches (N-1 and C), and a southern branch flowed to the east after a considerable detour to the south (probably beyond 3°00'S).

2. The Cromwell Current deepened slightly as it approached the Galapagos Islands, and it rose to a shallower depth on the east side of the islands.

3. The flow pattern determined by dynamic topography at 100 db relative to 600 db is in good agreement with that determined by the distribution of the distance between 170 and 190 cl/ton isanosteric surfaces, with the movement of nine drogues set 100 meters deep, and with the distribution of other properties (light scattering, temperature, salinity, oxygen, and silicate).

4. Island wakes of suspended particles were observed in the vicinity of the Cromwell Current on the east side of the Galapagos Islands.

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