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Updated bathymetry of the Anegada-Jungfern Passage complex and implications for Atlantic inflow to the abyssal Caribbean Sea

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ABSTRACT

Recent bathymetric, hydrographic and direct velocity measurements indicate that a previously unexplored deep passage in the northeastern Caribbean Sea may play a significant role in the abyssal ventilation of this basin. The Anegada-Jungfern Passage complex has long been recognized as the sole pathway for deep Atlantic inflow to the eastern Caribbean. The Anegada Passage (sill depth 1915 m) connects the Atlantic Ocean with the small Virgin Islands Basin, while Jungfern Passage (sill depth 1815 m) connects the latter with the large and deep Venezuela Basin comprising the eastern third of the Caribbean Sea. In the region of Jungfern Passage recent bathymetric measurements reveal additional, shallower routes for Atlantic inflow at depths between 1710 and 1630 m. Despite the relatively shallow controlling depths of these passages, direct measurements of velocity and watermass properties reveal an active inflow of water of Atlantic origin. Bathymetric and other oceanographic observations indicate that the previously unexplored Grappler Channel (sill depth 1710 m; located just west of Jungfern Passage) is responsible for up to 20% of the total inflow to the abyssal Caribbean from the mid-depth Atlantic (about 0.2 Sv).

1. Introduction

Unlike several other isolated deep basins in the world ocean (e.g. the Greenland Sea, Mediterranean Sea, Red Sea, and Sea of Japan), the abyssal water of the Caribbean Sea is not produced locally by atmospherically-forced convective processes but is instead imported from the neighboring western tropical Atlantic. Abyssal inflow into the deep Venezuela Basin of the eastern Caribbean Sea is confined to a series of narrow passages in the vicinity of the British and U.S. Virgin Islands (Fig. 1). As the only route for the renewal of deep water in the eastern Caribbean, this passage complex has received considerable attention by oceanographers during the last half-century. Previous investigators (for example, Dietrich, 1963; Frasetto and Northrup, 1957; Wüst, 1963; Sturges, 1965; Worthington, 1966; Stalcup and Metcalf, 1973; Stalcup *et al.,* 1975) have identified the

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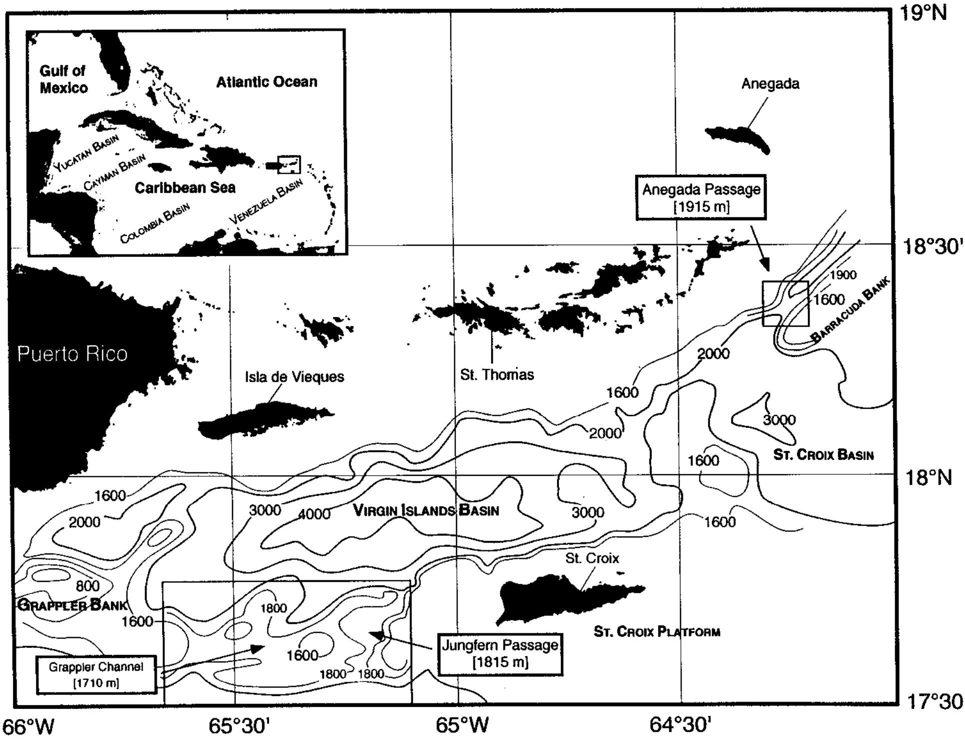

Figure 1. The Anegada-Jungfern Passage complex and surrounding islands. Bathymetry is contoured with an interval of 400 m in areas shallower than 1600 m, and with an interval of 1000 m in deeper areas. Additional contours are shown near passage sills as appropriate. The boxed areas on the inset map and the main chart indicate the domain of the relevant next-larger-scale illustration (Figs. 3 and 4). The St. Croix Basin is isolated on the east by the platform associated with the islands of Anguilla, St. Martin, and St. Barthelemy, and on the south by the Saba Bank. There is no deep connection between this basin and the Atlantic Ocean. This figure is a composite of U.S. Naval Oceanographic Office chart 2644-OA and a subsampled set of our recent bathymetric soundings.

Anegada and Jungfern Passages as the primary pathways for the inflow of Atlantic water to the eastern Caribbean.

Anegada Passage has a sill depth which falls within the depth interval of upper North Atlantic Deep Water (NADW) in the western Atlantic (potential temperature θ near 3.5°C). This cold, relatively saline watermass spreads southward from its origin in the high-latitude North Atlantic in the form of a continuous deep western boundary current (Fine and Molinari, 1988). Low-frequency variability in the production of NADW has been linked to past changes in global climate (e.g. Street-Perrott and Perrott, 1990). Because the inflow from the Atlantic to the Caribbean is driven by the density contrast between waters on the inside and outside of the inflow channel sills, conditions inside the abyssal Caribbean may be modulated by variability in the mid-depth Atlantic (Froelich and

Atwood, 1974). Conditions inside the abyssal Caribbean (including watermass characteristics, anthropogenic tracer concentrations, and the deposition rate of sediments) may thus reflect and preserve past states of the North Atlantic circulation and its response to climate variability. In order to make use of this powerful relationship, the mechanisms and rate of deep water renewal in the abyssal Caribbean must first be understood.

The character and rate of dense Atlantic inflow to the Caribbean Sea are strongly controlled by the bathymetry of the passages through which it flows. Several attempts have been made to accurately survey the bathymetry of the Anegada-Jungfern Passage complex to better define flow pathways and transport magnitudes. In particular, measurements of the sill depths of the Anegada and Jungfern Passages were made by Frasetto and Northrup (1957) and by Stalcup and Metcalf (1973). For reference, and as an introduction to the regional bathymetry, the surveys of Stalcup and Metcalf (1973) are reproduced in Figure 2.

A large volume of regional bathymetric data has recently been collected as part of a multi-year field study to investigate the rate, character, and variability of Atlantic inflow to the abyssal eastern Caribbean. These new measurements substantially enhance our knowledge of the key sills and channels in this region, and indicate the existence of several previously unexplored topographic features. We present here new high-resolution charts of the bathymetry near the Anegada Passage sill and in a larger region surrounding the Jungfern Passage. The latter chart encompasses a significantly wider domain than previous regional surveys and reveals two secondary channels which had previously received little attention. One of these, which we refer to as Grappler Channel, is found to be responsible for a significant fraction of the total deep inflow to the Venezuela Basin.

In the next section the methods used to collect and chart the depth soundings are briefly described. We then discuss our bathymetric findings in the context of abyssal inflow pathways, incorporating supporting hydrographic observations and direct velocity measurements where appropriate to illustrate the impact of the regional bathymetry on deep Atlantic inflow to the abyssal Caribbean Sea.

2. Data

Three field expeditions to the northeastern Caribbean Sea were conducted aboard the R/V *Columbus Iselin* between October 1990 and April 1992. During each cruise several days were devoted to intensive bathymetric surveys. These efforts were concentrated near passage sills and in regions surrounding intended deployment sites for long-term moored instrumentation. Additional bathymetric measurements were acquired during transits between hydrographic stations and during deep-towed ADCP/CTD profiling operations (Fratantoni and Johns, 1996).

Global Positioning System (GPS) satellite navigation was used for determining ship position. GPS fixes were obtained almost continuously during each expedition and were logged directly to a shipboard computer system. The error associated with an individual GPS position is typically less than 100 m. This is an improvement over the $O(200\text{ m})$ position uncertainties in the Jungfern Passage region estimated by Stalcup and Metcalf

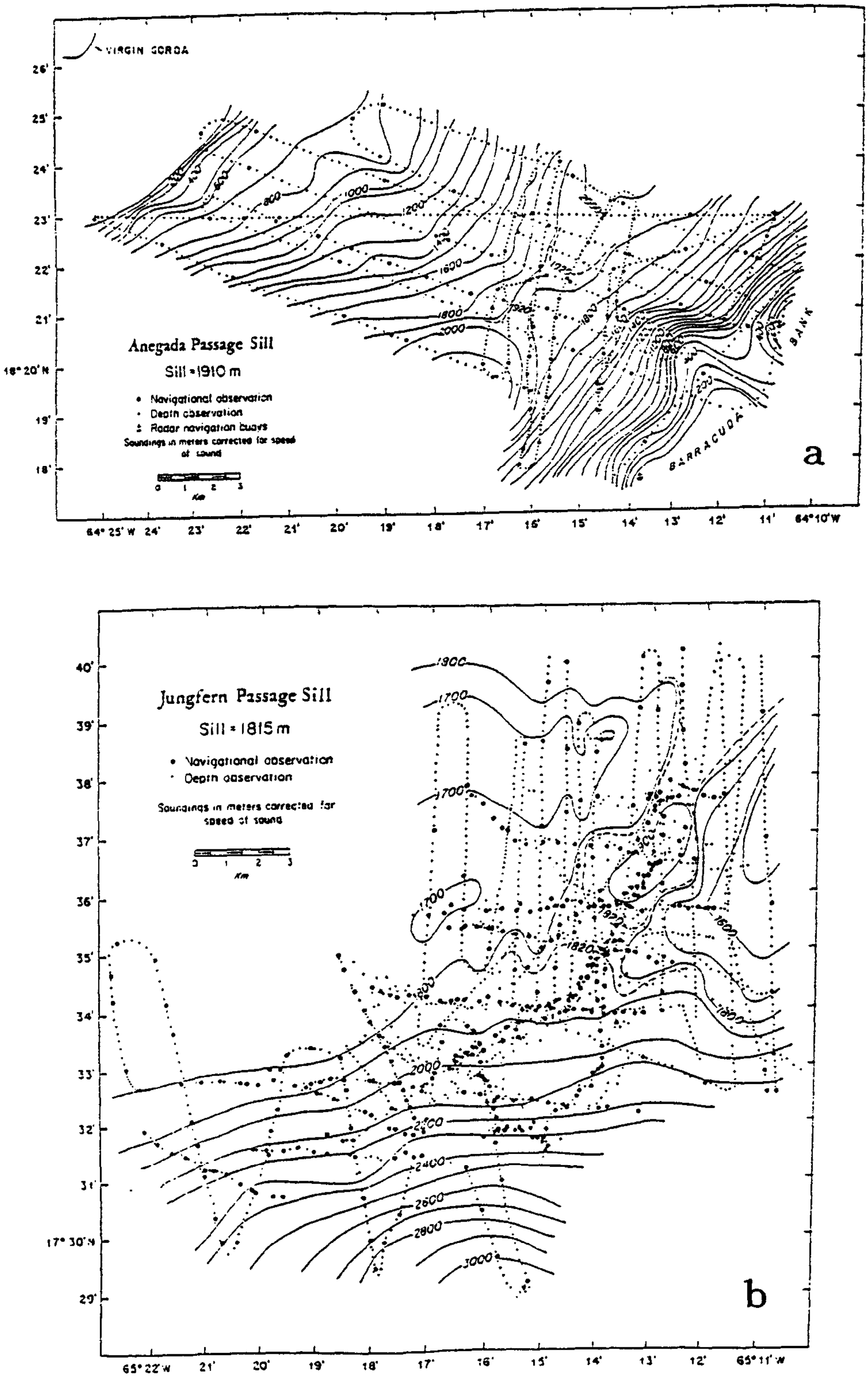

Figure 2. Bathymetry in the vicinity of (a) Anegada Passage sill and (b) Jungfern Passage sill as presented in Stalcup and Metcalf (1973). The small and large dots indicate positions of depth measurements and of the sampling vessel, respectively.

(1973) using radar bearings and ranges relative to a single moored surface buoy. More importantly, the use of modern GPS technology allowed for more rapid and hence higher-resolution survey patterns covering a wider spatial area.

Depth measurements were obtained with a 12 kHz depth sounding system, automatically digitized, and logged to a shipboard computer system. Over a depth interval corresponding to the sills and channels of interest (roughly 1600–2000 m) the regional correction to these raw depth measurements due to integrated sound speed variation is less than 2 m, or 0.1% (Carter, 1980). Above and below this depth interval the required correction is somewhat greater, but does not exceed 5 m (0.4%) within the depth range 1300–3000 m. The relative insignificance of the required correction was confirmed using our own hydrographic station data. Therefore, no sound speed correction was applied to the bathymetric data presented and discussed in this article. The logged data were quality controlled using a combination of automated (e.g. to filter occasional spikes) and manual (e.g. to flag obvious fathometer range errors) methods. The bathymetric charts presented herein were constructed using manual contouring techniques.

A fundamental scientific objective of the field program was to quantify the mean and time-varying rate of inflow from the mid-depth Atlantic to the Venezuela Basin. To accomplish this, several current meter moorings were deployed within the Anegada-Jungfern Passage complex. Moorings were placed at the Anegada and Jungfern Passage sills, in a secondary channel located west of Jungfern Passage (Grappler Channel), and at two locations downslope of Jungfern Passage in the northern Venezuela Basin. Observations at three sites (Anegada, Jungfern, and Grappler Channel sills) relevant to this bathymetry-related study will be briefly introduced and discussed in the following section. A summary of the mooring positions, instrument characteristics, and record-length mean velocity and temperature observations is presented in Table 1. An in-depth examination of the velocity and temperature records at these sites will be presented in a subsequent report. In the remainder of this article, a subset of these data will be used in combination with regional hydrographic and towed profiler observations to support hypotheses on abyssal inflow pathways based on our bathymetric measurements.

3. Results

a. Anegada Passage. The Anegada Passage (AP hereafter) is a relatively long, narrow conduit connecting the Atlantic Ocean with the Virgin Islands Basin (Fig. 1). Between the AP sill and the eastern margin of the Virgin Islands Basin, the passage skirts the northwestern corner of the St. Croix Basin. Stalcup and Metcalf (1973) (SM73 hereafter) thoroughly investigated the possibility of an additional inflow route in the area east of Barracuda Bank and concluded, based on bottom temperature observations, that any such inflow must occur at depths considerably shallower than the AP sill.

The AP sill region itself is geometrically simple with a well-defined saddle point just west of Barracuda Bank (Figs. 2a and 3). Based on our recent bathymetric surveys we have determined a sill depth of 1915 m, in close agreement with the 1910 m depth reported

Table 1. Long-term near-bottom current meter moorings deployed between January 1991 and March 1992 in the Anegada-Jungfern Passage complex. Mooring locations and bottom depth at these locations are shown. Instruments were located approximately 10 m above the bottom. Record length is given in days. The record-length mean speed (standard deviation), direction, and potential temperature are shown.

	Mooring location		Bottom depth	Inst depth	Record length	Speed (cm/s) $\bar{v}$	Speed (cm/s) σ	Dir	Pot Temp °C
Anegada	64°15.7′W	18°21.4′N	1915	1905	419	11.98	(12.10)	223	3.64
Jungfern	65°14.8′W	17°35.0′N	1780	1770	421	6.53	(10.28)	211	3.82
Grappler	65°27.8′W	17°36.4′N	1800	1790	604	9.32	(8.25)	204	3.85

earlier by SM73. Our estimate of the sill position, 18°21.5′N, 64°15.6′W, is approximately 1 km east of that reported by SM73. As both the present survey and that of SM73 had adequate sampling density within a radius of several kilometers of the sill position (see Fig. 2a) and exhibit excellent agreement in sill structure, this offset may be indicative of a systematic bias in the radar-ranging navigational system employed in the previous survey.

Below a depth of 1900 m, the passage narrows to approximately 0.5 km in the immediate vicinity of the sill. Downstream from the sill the passage widens to about 3 km, then expands further as the AP and the St. Croix Basin merge. Away from the sill region the density of our bathymetric soundings decreases. This necessitated the occasional use of SM73's surveys (appropriately shifted for the spatial offset) for contouring guidance in a few regions of Figure 3.

b. Jungfern Passage and vicinity. A topographic ridge forming the southern boundary of the Virgin Islands Basin links Grappler Bank on the west with the St. Croix Platform and the island of St. Croix on the east (Fig. 1). There are three breaks or interruptions in this ridge with sill depths at or below 1630 m (Fig. 4a). The deepest of these, Jungfern Passage, lies along the western edge of the St. Croix Platform. Bounded on the west by a small seamount rising above 1500 m, Jungfern Passage (JP hereafter) contains the controlling sill for the entire passage complex joining the Atlantic Ocean with the deep eastern Caribbean.

The JP sill (depth 1815 m) is located at 17°35.1′N, 65°14.2′W in our survey (Fig. 4a), in excellent agreement with the previous surveys of SM73 (Fig. 2b). The passage is narrowest about 4 km northeast of the sill position. Just south of this constriction is an isolated depression with a maximum depth of 1980 m. The northern portion of the passage is considerably wider, with the western boundary formed by a low ridge with depths between 1730 and 1760 m. South of the sill JP widens rapidly, merging with the steep northern wall of the Venezuela Basin. Between the 2000 and 3000 m isobaths just south of the Grappler Bank-St. Croix ridge, this wall has a mean slope of approximately 1:6, or 17%. Farther downstream, the Venezuela Basin reaches a maximum depth greater than 5500 m in the

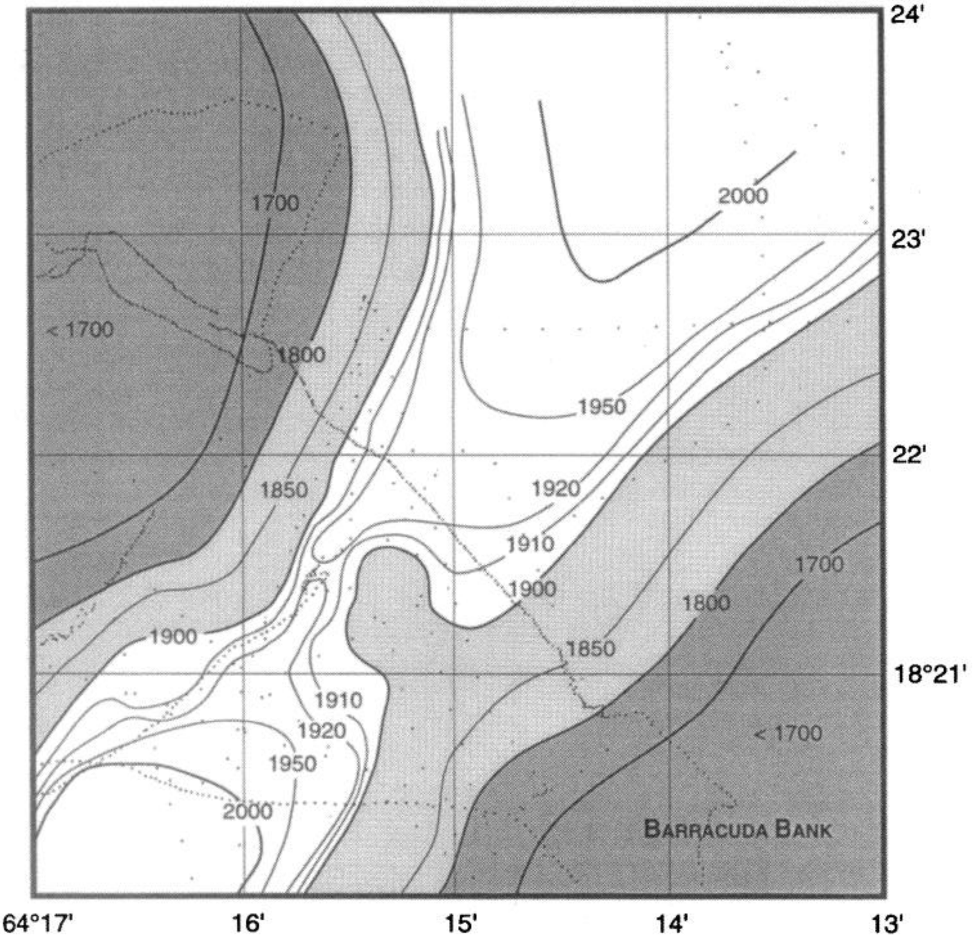

Figure 3. Bathymetry of Anegada Passage sill. Areas shallower than 1900 m are indicated by shading. This figure is a composite of new bathymetric soundings (described herein and indicated by dots) and historical observations by Stalcup and Metcalf (1973).

Muertos Trough, south of the islands of Puerto Rico and Hispaniola (see U.S. Defense Mapping Agency Chart 25000 for a wider view of the region).

Though the deepest pathway between the Virgin Islands Basin and the Venezuela Basin is along the axis of JP, with water entering in the far northeastern corner of Figure 4a, there are at least two other routes available for inflow in the 1710 to 1630 m depth range. After JP, the next deepest inflow route is the dogleg-shaped channel located about 20 km farther to the west. This feature was identified previously by Frasetto and Northrop (1957) as the "western channel" of Jungfern Passage though it was poorly resolved in their survey and no sill depth was determined. The areal coverage and spatial resolution of bathymetric data

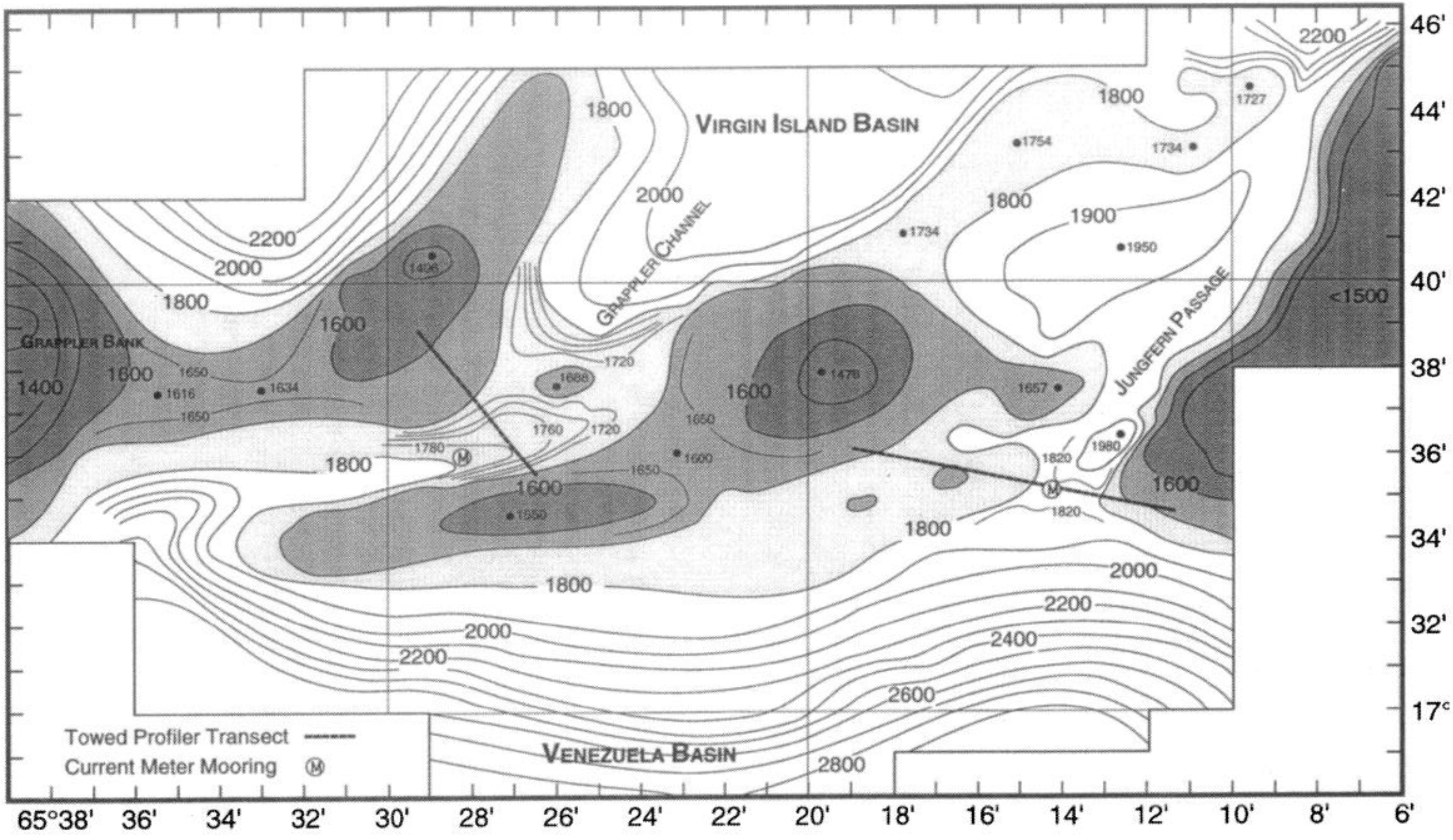
Virgin Island Basin
Venezuela Basin
Grappler Bank
Grappler Channel
Jungfern Passage
Towed Profiler Transect
Current Meter Mooring Ⓜ
<1500
1400
1600
1800
1900
2000
2200
2400
2600
2800
1426
1476
1550
1600
1616
1634
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Figure 4a

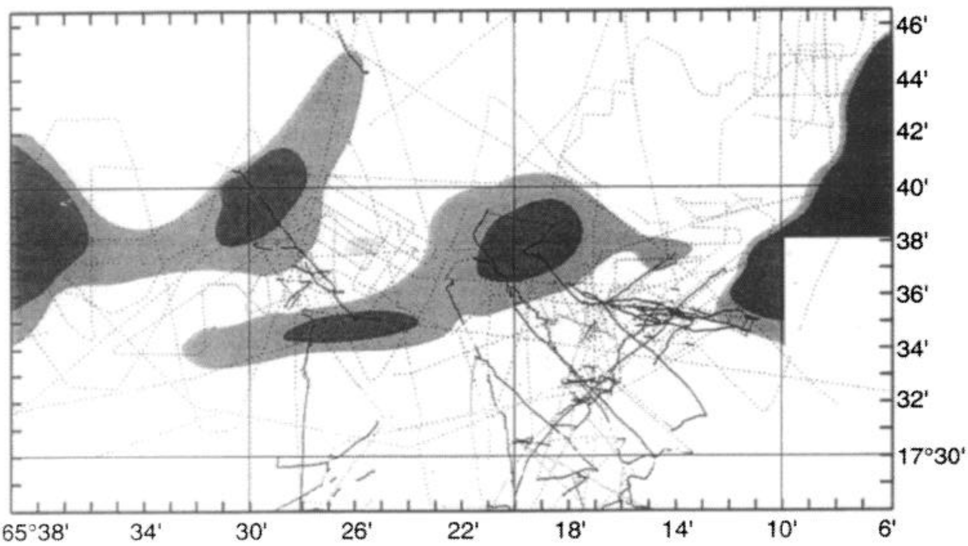

Figure 4. (a) Bathymetry of Jungfern Passage, Grappler Channel, and neighboring channels and sills. The contour interval is 100 m, with additional contours added near the sills as appropriate. Areas shallower than 1800 m are indicated by shading. Areas with insufficient sounding density were not contoured. (b) Sounding locations used in constructing Figure 4a. The shading of Figure 4a is repeated here for spatial reference. Dots indicate sounding locations. Line segments result from closely-spaced soundings during deep-towed ADCP/CTD profiling operations, or while drifting on station during mooring deployment/recovery operations.

in this region are significantly improved in the present study (see Fig. 4b). There is sufficient separation between these two channels to warrant the assignment of a unique identity, and we hereafter refer to the western channel as the Grappler Channel (GC). GC is bounded on the west by a peninsular extension of Grappler Bank and on the east by a pair of small seamounts. The channel is divided into two subchannels by a small hill rising above 1690 m in its center with each subchannel having a maximum depth of 1710 m (Fig. 4a).

To the west of GC lies a still shallower channel with a sill depth of approximately 1630 m, and to its immediate east a small depression in the ridge separating JP and GC with a sill depth of approximately 1680 m (Fig. 4a). These secondary channels were not surveyed with the same level of detail as JP or GC, and additional measurements in this area are required to fully describe their geometry.

4. Discussion

Following entry at Anegada Passage, the inflow of NADW from the mid-depth Atlantic circulates cyclonically (anti-clockwise) around the Virgin Islands Basin. Because of the earth's rotation, the temperature field associated with an intermediate-depth boundary

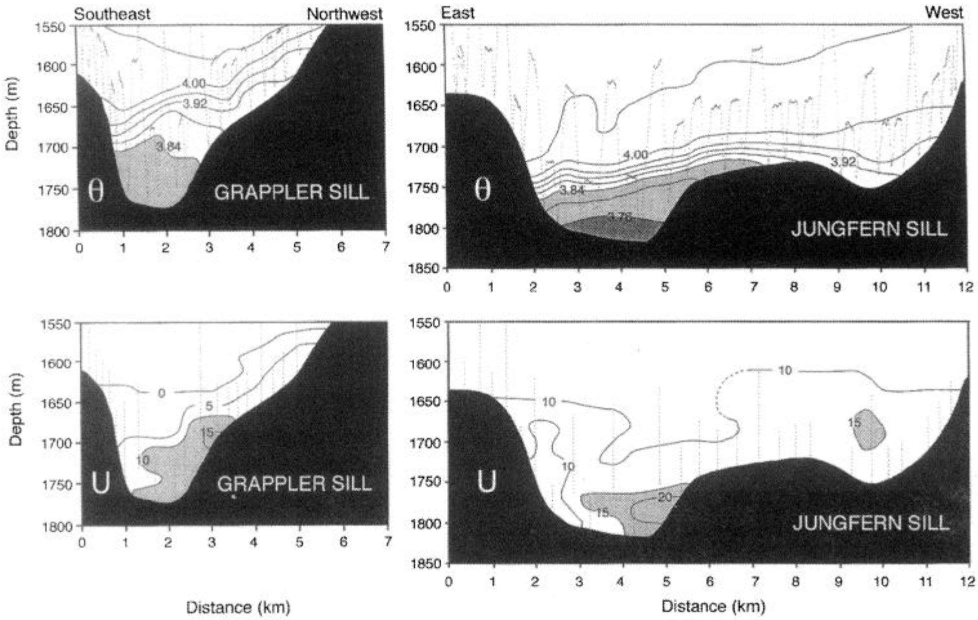

Figure 5. Cross-sections of potential temperature θ (°C) and along-channel velocity *U* (cm/s) obtained during deep-towed ADCP/CTD profiling operations across the Grappler Channel and Jungfern Passage sills (see Fratantoni and Johns, 1996). The direction of flow is to the southwest (Grappler) and to the south (Jungfern), or into the page. Dots indicate actual data point locations for velocity and a small subsample of the data point locations for temperature. The Grappler and Jungfern sections were occupied on March 12 and 13, 1992, respectively.

current circulating in this manner is distorted such that the isotherms slope upward into the boundary. Thus at a given depth, the coldest water is found along the right-hand side of the flow. This effect persists within the inflow passages connecting the Virgin Islands Basin and Venezuela Basin, as illustrated in Figure 5. Note that both the velocity and temperature fields indicate a deep current leaning against the topography on the right-hand side of the channels. For example, the 4°C isotherm in GC rises from 1650 m on the southeast side of the channel to 1500 m on the northwest side. While the coldest water ($\theta < 3.76$°C) is found in JP, the 50–75 m thickness of the $\theta < 3.84$°C layer is similar in both passages. The transport of water colder than 4°C (approximately the top of the highly-stratified layer separating the inflow water from the weak background stratification of the deep Virgin Islands Basin) is approximately 130 and 40×10^3 m^3/s for JP and GC, respectively. Previous observations (confirmed by our recent measurements) indicate a deep inflow through AP of approximately 200×10^3 m^3/s.

The considerable overflow of Atlantic water observed through GC suggests that this passage, and possibly the shallower one to its west, may play a more important role in deep outflow from the Virgin Islands Basin that would be anticipated from their relatively shallow sill depths. Owing to the cyclonic pathway of the Atlantic waters around the Virgin Islands Basin, and the rotationally inclined nature of this boundary flow, these upstream channels may bleed off portions of the Atlantic inflow that is transiting around the Virgin Islands Basin toward JP. In this sense they may serve as a type of "weir" control on the overflow through JP. For example, it can be seen in Figure 5 that the isothermal surfaces corresponding to cold Atlantic overflow waters are elevated some 50–100 m in GC compared to those in JP, suggesting that the uppermost portion of the boundary flow is being diverted through GC. The top of the overflow layer in GC lies at depths of less that 1600 m, suggesting that some (probably small) amount of Atlantic inflow water could also escape over the 1630 m sill at the very western end of this ridge. Because the distortion of the density field is proportional to the inflow velocity, variability in the influx of NADW through Anegada Passage, perhaps triggered by events farther upstream in the western North Atlantic, could lead to an even larger relative contribution by these secondary channels during strong inflow events.

In addition to the synoptic temperature and velocity sections presented in Figure 5, long-term current meter records collected in these passages show evidence of persistent flow of Atlantic waters through GC (Table 1, Fig. 6). Figures 6a–6c illustrate the low-frequency correlation between temperature and velocity at the three primary inflow sills. Note that the coldest water observed at each near-sill mooring site is, as expected from the dynamical considerations above, coincident with the strongest inflow velocities. The minimum potential temperatures recorded at the AP, JP, and GC sill moorings were 3.52°, 3.69°, and 3.72°C, respectively. Record-length mean potential temperatures are shown in Table 1. The JP and GC velocity-temperature correlations (Figs. 6b and 6c) are similar in form, with a predominance of cold inflow occuring near 3.8° with a speed of 10–25 cm/s. The maximum inflow speed in GC is significantly smaller than that in AP or JP. In all three passages, relatively warm outflow is occasionally observed. The magnitude of this outflow is greatest at AP.

Figures 6d–6f compare temperature-salinity relations derived from towed ADCP/CTD profiling operations along the passage sills (see Fig. 5). At the AP sill (Fig. 6d), a salinity anomaly of about 0.015 ppt relative to the abyssal water of the interior Caribbean is due to the presence of relatively saline mid-depth Atlantic water. The Atlantic-origin inflow through AP appears to mix vertically through a temperature range of about 0.3°, between 4.2° and 3.9°C (note the change in slope of the AP temperature-salinity relation near 4.2° and again near 3.9°C). Below this temperature, watermass characteristics tend toward those of the mid-depth western Atlantic. At the time corresponding to these measurements Atlantic-origin water was present at all three passage sills. At JP (Fig. 6e), the anomalously saline Atlantic inflow is contained below a temperature of approximately 4°C, consistent with the moored velocity and temperature measurements described above (Fig. 6b). Figure 6f clearly demonstrates that the previously unexplored GC exhibits watermass characteristics of deep Atlantic inflow comparable to those in the other two major inflow passages.

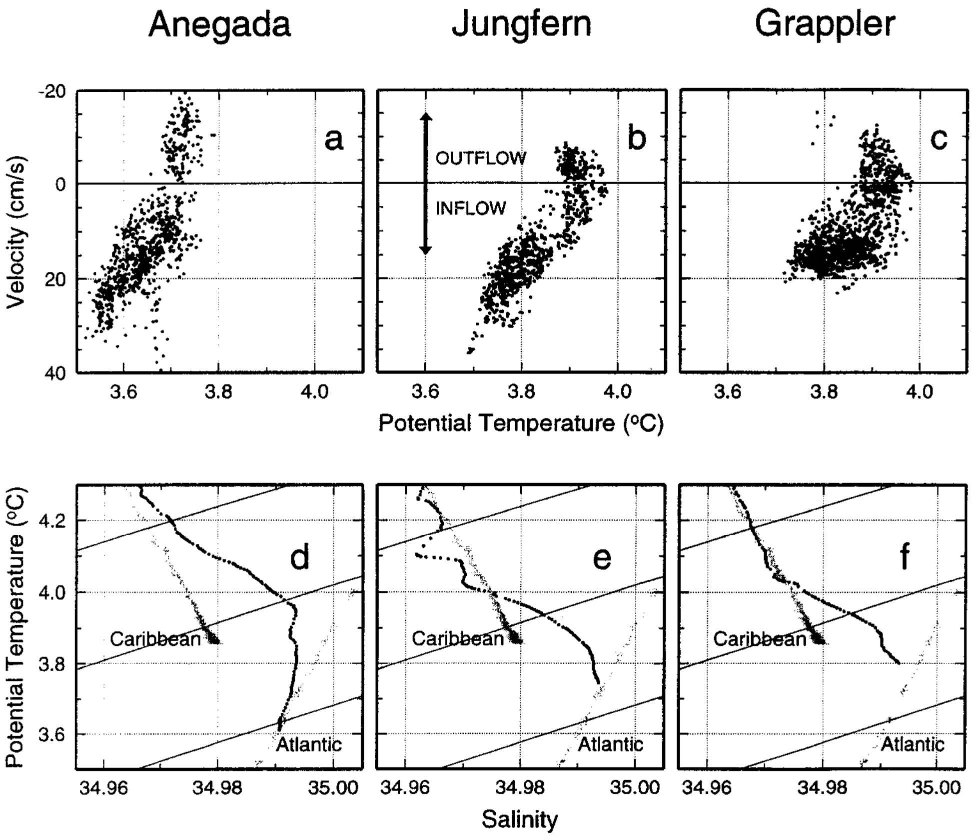

Figure 6. Upper panel: Low-frequency correlation between near-bottom velocity and potential temperature at (a) Anegada Passage, (b) Jungfern Passage, and (c) Grappler Channel sills as measured by long-term near-bottom current meter moorings (see Table 1). Instrument height above bottom at each sill was approximately 10 m. The velocity and temperature records shown here have been low-pass filtered with a 40-hour Lanczos filter and subsampled at 12-hour intervals. Lower panel: (d, e, f) Correlation between potential temperature and salinity at the three sills as measured during deep-towed ADCP/CTD profiling operations. The diagram for each sill consists of three profiles (labeled): the relation just outside of the Anegada Passage in the western Atlantic (a mid-depth Atlantic source-water reference), the relation in the interior of the Venezuela Basin (a far-field Caribbean reference), and the relation at the specified sill. The diagonal lines are contours of constant potential density referenced to 2000 dbar.

5. Summary

In this article new bathymetric measurements of the Anegada-Jungfern Passage complex were described. These measurements clarify several details of the regional bathymetry, including the locations and depths of key passage sills, and indicate the presence of previously uninvestigated bathymetric features that may be of oceanographic significance. The Anegada Passage is the sole route by which mid-depth Atlantic water in the

1650–1915 m depth range enters the isolated Virgin Islands Basin in the northeastern Caribbean. From this intermediate basin, dense Atlantic-origin water overflows a topographic ridge west of the island of St. Croix and enters the deep Venezuela Basin. Jungfern Passage had previously been identified as the dominant pathway for renewal of abyssal water in the eastern Caribbean.

The new bathymetric measurements presented here, when combined with recent hydrographic and direct-velocity observations, strongly suggest that there are other significant pathways for flow across the ridge separating the Virgin Islands Basin and Venezuela Basin. In particular, observations indicate a significant inflow of cold, saline Atlantic-origin water through a secondary channel west of Jungfern Passage (Grappler Channel), even though the sill depth of this channel is 100 m shallower than Jungfern Passage. Preliminary calculations indicate that Grappler Channel is responsible for approximately 40×10^3 m^3/s of Atlantic inflow, or 20% of the 200×10^3 m^3/s total estimated to pass through the Anegada-Jungfern passage complex. These results are applicable to continuing efforts to reconcile watermass characteristics of the abyssal Caribbean Sea with long-term changes in the Atlantic meridional overturning circulation and associated global climate variability.

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