Strike-Slip Tectonic Processes in the Northern Caribbean Between Cuba and Hispaniola (Windward Passage)

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Abstract. Marine geophysical data including Seabeam, seismic reflection, magnetics, gravimetry and side-scan sonar have been recently collected along the northern Caribbean strike-slip plate boundary between Cuba and Hispaniola, in the Windward Passage area. The analysis of this comprehensive data set allows us to illustrate active strike-slip tectonic processes in relation to the kinematics of the Caribbean Plate. We show that the transcurrent plate boundary trace runs straight across the Windward Passage, from the southern Cuban Margin in the west (Oriente Fault) to the Tortue Channel in the east. The Windward Passage Deep is thus not an active pull-apart basin, as previously suggested. The plate boundary geometry implies that the motion of the Caribbean Plate relative to the North American Plate is partitioned between a strike-slip component, accommodated by the Windward Passage active fault zone, and a convergence component, accommodated by compression at the bottom of the Northern Hispaniola Margin. On the basis of a correlation with onland geological data, an age is given to the stratigraphic sequences identified on seismic profiles. A kinematic reconstruction is proposed that follows the tectonic unconformities recognized at sea and on land (Late Eocene, Early Miocene, Middle Miocene and Late Pliocene). Each one of these tectonic events corresponds to a drastic reorganization of the plate boundary geometry. We propose to correlate these events with successive collisions of the northern Caribbean mobile terranes against the Bahamas Bank. During each event, the plate boundary trace is shifted to the south and a part of the Caribbean Plate is accreted to North America.

Introduction

The Caribbean domain and Central America form a small lithospheric plate inserted between North and South America (Molnar and Sykes, 1969), that is moving eastward relative to North America (Figure 1A). Its northern boundary is a left-lateral strike-slip fault system extending from Honduras to Puerto Rico, over 3000 km and connecting the Lesser Antilles and the Central America subduction zones. The Windward Passage (Figure 1B) is a critical area of the northern Caribbean Plate boundary zone located at the junction between a domain which was lately incorporated into the North American Plate (Cuba, Cayman Ridge and Yucatan Basin) and the typical North American domain. It is crossed by the present-day trace of the northern Caribbean strike-slip plate boundary which continues to the west along the southern Cuban Margin (Oriente Fault) and to the east along the northern margin of Hispaniola and on land, in the northern Dominican Republic.

During the Seacarib II and Oriente oceanographic cruises (*R/V Jean Charcot*, December 1987, and *R/V Le Suroit*, January 1990), a geological and geophysical study of the Windward Passage was undertaken (Figure 2). The collected data include full Seabeam coverage of the area, 30 single channel seismic reflection profiles with magnetic and gravity recordings and full, high resolution side-scan sonar imaging of the active fault trace. This comprehensive data set allows us to precisely map the geometry of a major strike-slip fault system and to image its associated structures. The enhanced study of this critical segment of the northern Caribbean Plate boundary illuminates active strike-slip tectonic processes and gives significant constraints to the present-day kinematics of the Caribbean Plate. Moreover, because of its location between Cuba and Hispaniola, the Windward Passage has recorded the tectonic events associated with the Caribbean Plate drifting relative to North America during the Cenozoic. It is thus a critical witness of the Caribbean Plate kinematics in the past.

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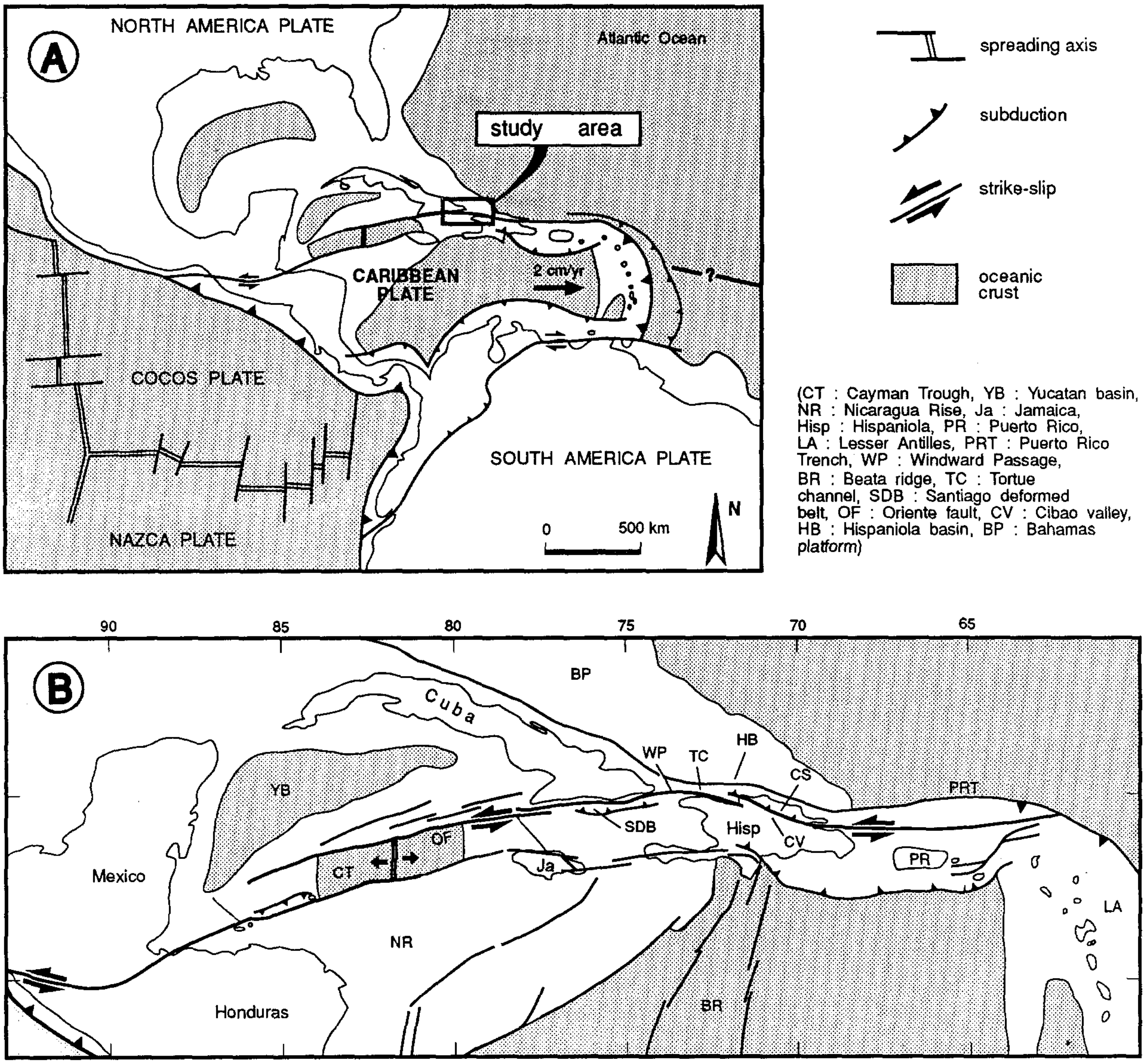


Fig. 1. A. geodynamic setting of the Caribbean Plate (the study area is indicated). B. Tectonic map of active structures along the northern Caribbean Plate boundary.

Previous Data

Prior to the Seacarib II and Oriente cruises, few marine studies had been undertaken in the Windward Passage area. In 1980, two multichannel seismic lines crossing the whole area were shot during the CT2 cruise of the University of Texas at Austin, Institute for Geophysics (*R/V F.H. Moore*). We publish here one of them (Figure 8). Two other seismic profiles have been made by the Woods Hole Oceanographic Institution (*R/V Atlantis*, 1978) and were interpreted and published by Goreau (1983). These data allowed him to define the main morphostructural units of the Windward Passage area, the Windward Passage Sill and the Windward Passage Deep (Figure 2). On the basis of these results, Goreau (1983) and Mann and Burke (1984) interpreted the Windward Passage as an active pull-apart and assumed the Tortue Channel to be the eastward prolongation of the Oriente Fault. Other authors, however, claimed the Oriente Fault was connected with the western extremity of the North American Plate subduction under Puerto Rico and Hispaniola (Mascle *et al.*, 1985, 1990). In 1985, during a transit between northern Hispaniola and the Cayman Trough, the *R/V Farnella* recorded one GLORIA side-scan sonar track covering the eastern quarter of the Windward Passage.

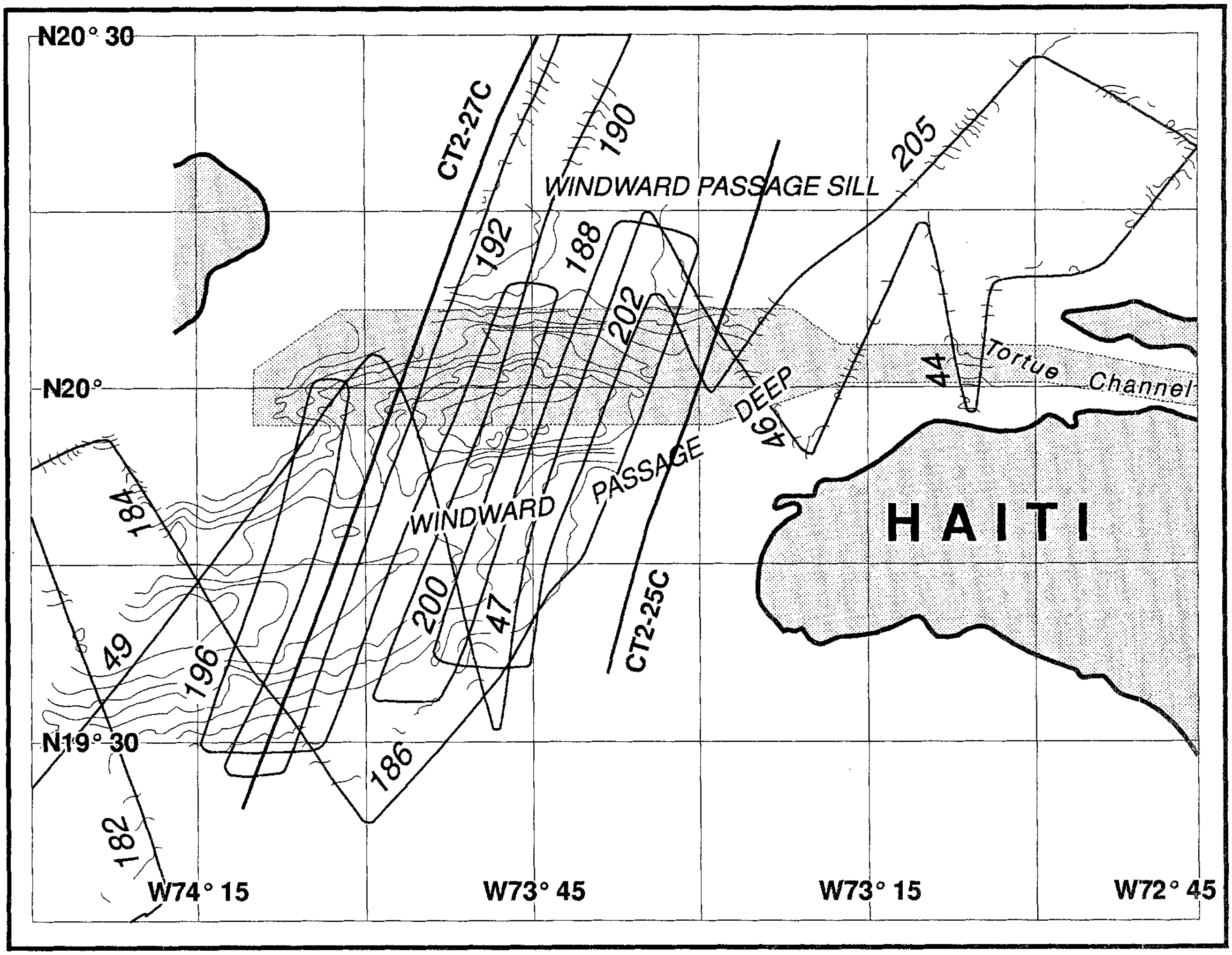


Fig. 2. Location of the seismic reflection profiles and of the area covered by side-scan sonar imaging (shaded area).

This swath complements our data along the Haitian coast.

Seabeam Imaging of the Windward Passage

The Windward Passage is a 90 km wide strait between the southeastern Cuban coast and the northwestern peninsula of Haiti, one of the main gateways between the Atlantic Ocean and the Caribbean Sea (Figure 1B). A precise bathymetric map of this area (Figure 3) was obtained by full multibeam echo sounder coverage (Seabeam), and two 3-dimensional views were produced at the Ifremer Centre of Brest, France (Figure 4). These data allow us to analyze in detail the morphologic domains defined by Goreau (1983).

THE WINDWARD PASSAGE SILL

The Windward Passage Sill is a narrow east–west trending submarine plateau (25 km wide and 125 km long), extending between the Punta Maisi of Cuba and the northwestern peninsula of Haiti. It is located between 1500 and 2000 m deep and progressively shallows toward the east. The Tortue Island represents its emerged eastern termination. This plateau displays a slight dip to the north (0.5°) toward the Hispaniola Basin. Its northern edge is a steep scarp (10°, 2500 m of difference in level) dipping into the Hispaniola Basin. Its southern border is a N100 trending scarp dipping into the Windward Passage Deep and made of two successive steps. The first step (the wider; 4 km wide) is located around 2700 m deep and extends along the whole scarp. The second step is located around 3800 m and progressively disappears to the east within the Windward Passage Deep.

THE WINDWARD PASSAGE DEEP

The Windward Passage Deep is an east-west trending rectangular-shaped basin, parallel to the Windward Passage Sill and bounding it to the south. It is 50 km long and 15 km wide with the depth ranging between 3500 and 3800 m. It is bounded to the south by a steep uniform scarp coming down from the Gonave Ridge. A small narrow east-west trending depression follows the northern edge of the deep at the toe of the Windward Passage Sill scarp. There is a small east-west trending ridge located within the basin. South of this small ridge, the basin bottom slightly rises to the south (0.5°).

THE PUNTA CALETA AND TORTUE CHANNELS

The Punta Caleta Channel is a narrow east-west trending valley located between 19° 58′ N and 20° N. It separates the Cuban coast from a submarine 250 m deep ovoid mole. The Tortue Channel extends in an east-west direction between Tortue Island and the Haitian coast. It is 5 km wide and 1200 to 1500 m deep, located between 20° N and 20° 02′ N. It is to be noted that both channels are exactly colinear and that they do not correspond to the southern edge of the Windward Passage Sill, but to the first step of its northern border.

Magnetics and Gravimetry

MAGNETICS

The map of Figure 5 displays the magnetic anomalies after regional field correction using the IGRF80 model. The Windward Passage is characterized by elongated east-west trending positive anomalies, with amplitudes greater than 350 nT. They are parallel to the east-west bathymetric escarpments mapped with the Seabeam in this area. They can be attributed to a topographic effect or to east-west trending faults shifting basement blocks. The Windward Passage Sill does not display any transverse anomaly, but a continuity between southeastern Cuba and northern Hispaniola. The western end of the Punta Caleta Channel shows a high positive anomaly (350 nT) with an east-west trend. The same type of anomaly is exhibited in the eastern end of the Tortue Channel. The most prominent magnetic trend across the Windward Passage is thus clearly east-west, in agreement with the structural pattern (see below).

GRAVIMETRY (FREE AIR)

The free-air gravimetric anomaly is closely correlated with the bathymetry, as expected (Figure 6). The Windward Passage Sill displays a −100 mgals negative anomaly and very smooth gradients, except along its northern and southern borders. It is interrupted in its middle part by a north-south relative negative of −120 mgals. The Windward Passage Deep shows a significant negative anomaly. The −180 mgals isogal follows the basin's borders and corresponds more or less with the 3500 m isobath. Despite its two topographic steps, the gravimetric expression of the northern border of the Windward Passage Deep is a single gradient. The lower step displays the same gravimetric signature as the basin itself, suggesting that it corresponds to an uplifted part of the basin rather than to a downdropped part of the Windward Passage Sill.

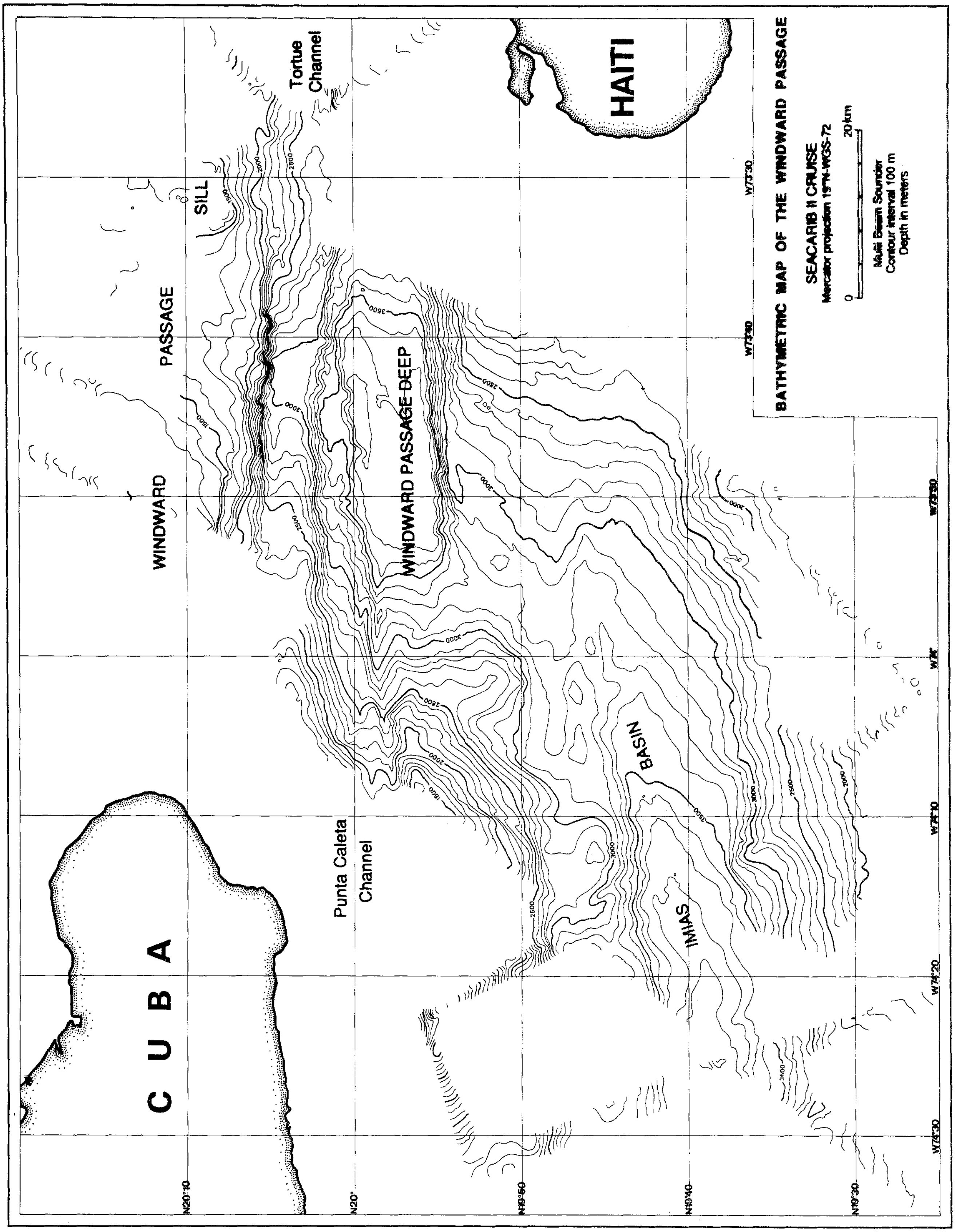
Seismic Reflection Profiles

We interpreted the 30 single channel seismic profiles performed during the Seacarib II and Oriente cruises and two multichannel profiles of the CT-2 cruise. Isopach and isochron maps were derived from this dense seismic coverage. Six structural domains can be identified from the seismic profiles analysis.

HISPANIOLA BASIN

The Hispaniola Basin displays a great sedimentary infilling, thicker than 1.5 stwtt (Figures 7 and 8). It is bounded to the north by a steep but irregular scarp that displays mostly a chaotic seismic configuration with many diffraction hyperbolas. In the eastern part of the Windward Passage area, the profiles crossing the southern edge of the Hispaniola Basin show basin reflectors underneath this scarp, suggesting compressive deformation in this area. Compressional structures in this area have been documented and clearly imaged by a recent multichannel seismic and GLORIA survey along the northwestern Hispaniola Margin (Dillon *et al.*, 1992).

Fig. 3. Bathymetric map of the Windward Passage.


BATHYMETRIC MAP OF THE WINDWARD PASSAGE
SEACARIB II CRUISE
Mercator projection 19°N-WGS-72
0
20 km
Multi Beam Sounder
Contour interval 100 m
Depth in meters
HAITI
Tortue Channel
SILL
WINDWARD PASSAGE
WINDWARD PASSAGE DEEP
IMIAS BASIN
Punta Caleta Channel
C U B A
W73°30
W73°40
W73°50
W74°
W74°10
W74°20
W74°30
N20°10
N20°
N19°50
N19°40
N19°30
1500
2000
2500
3000
3500

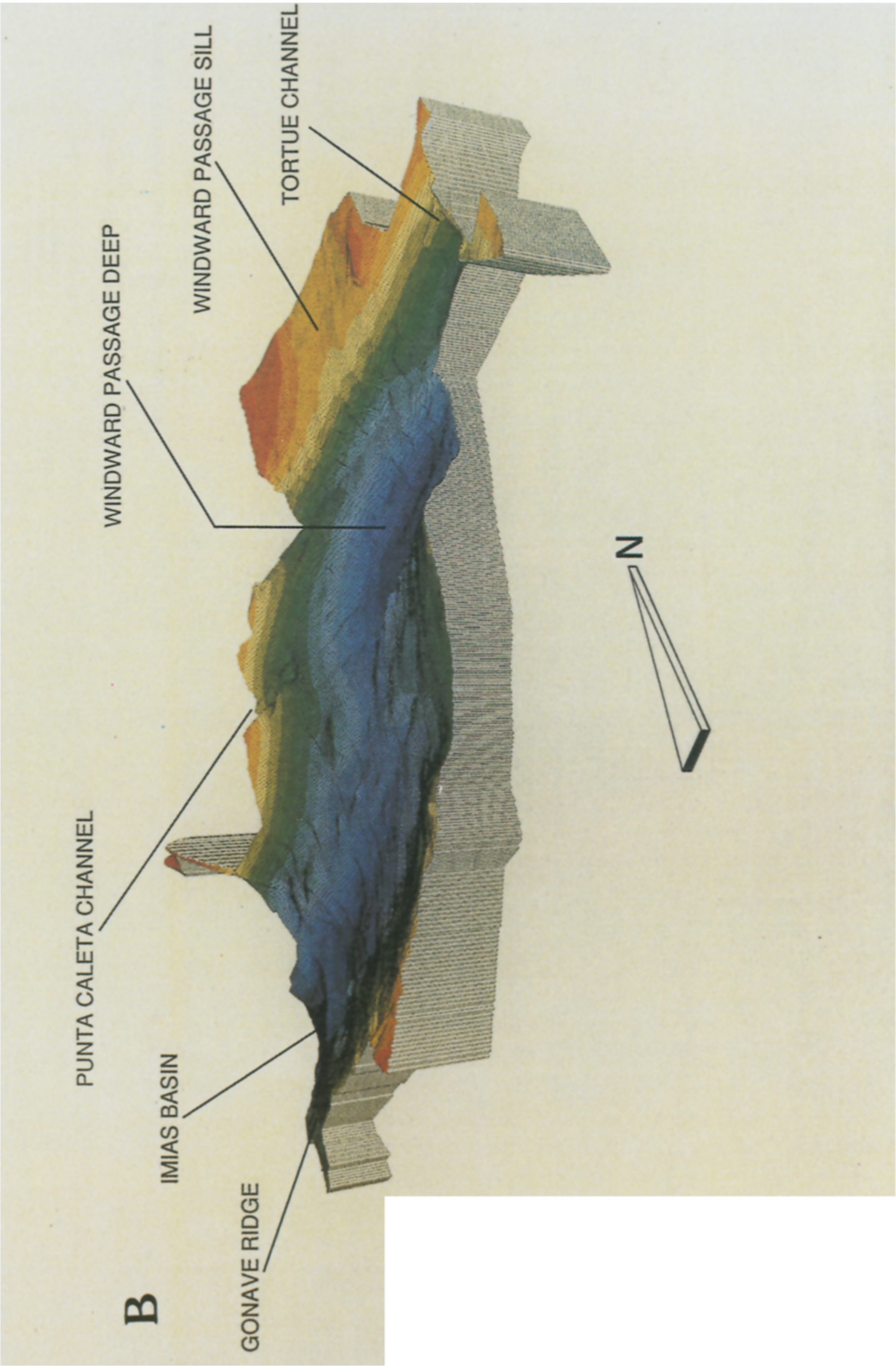


Fig. 4. Three-dimensional views of the Windward Passage.

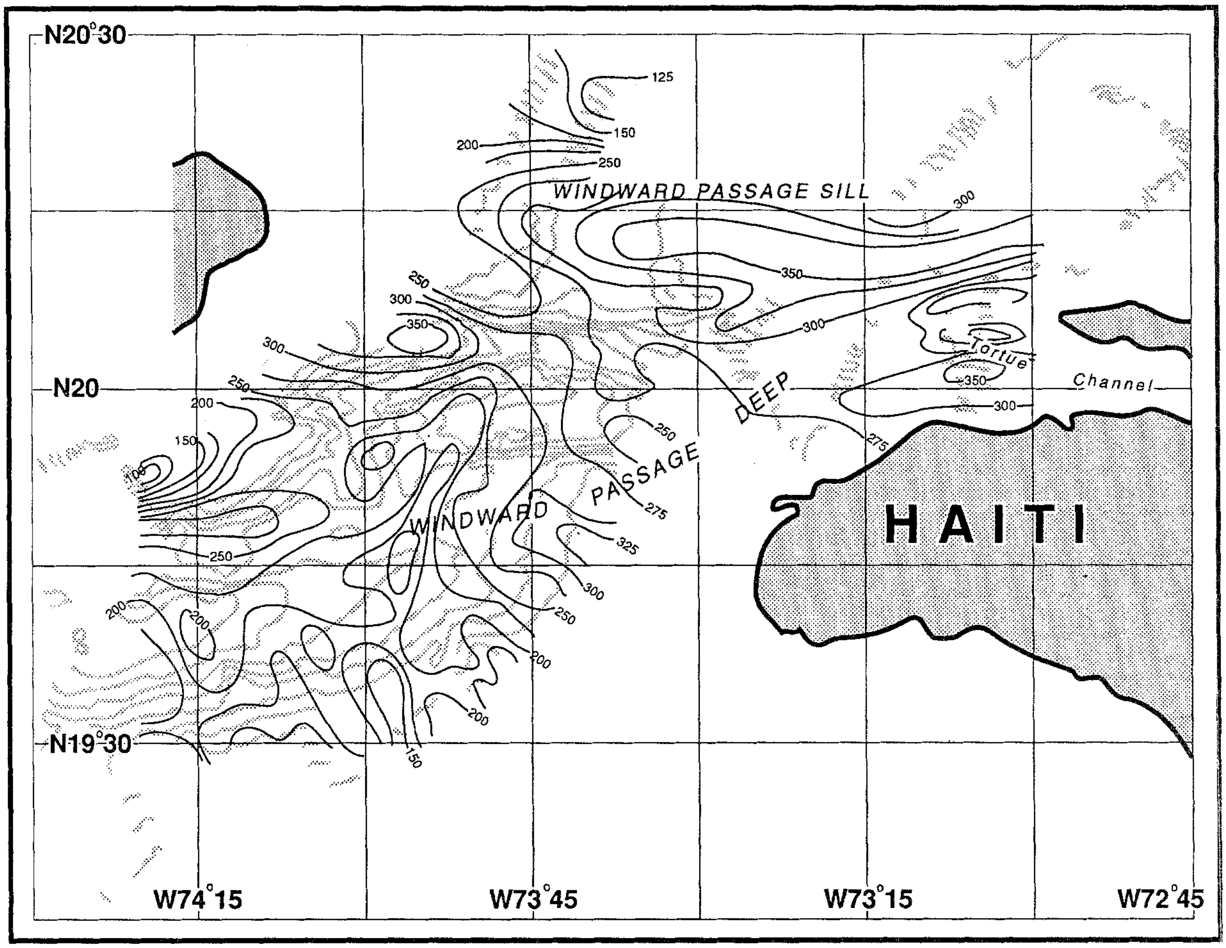


Fig. 5. Magnetic map of the Windward Passage (contour interval 25 nT).

WINDWARD PASSAGE SILL

Three main seismic sequences can be identified:

a. The lower sequence (B) is a thick series (>1 stwtt) of well-defined high frequency reflections, with a parallel configuration. This sequence is folded with synclines clearly visible on Figures 8 and 9. The top of the B sequence is eroded, as shown by the systematic absence of the anticline crests on the seismic profiles. Isochron and isopach maps (Figure 10) display the east–west trend of the folds: three anticlines are bounding the southern edge of the sill; two synclines are located along its northern edge. On the basis of the depth of the synclines (around 0.5 stwtt) and of the geometry of the folded layers, we can infer a difference in level of more than 1 stwtt between the top of the anticlines and the bottom of the synclines. This suggests the presence of prominent topography in this area after the folding and before erosion (around 1000 m of relief).

b. The middle sequence (A′) is separated from the B sequence by a prominent angular unconformity (Figure 11). Its thickness varies laterally from 0 to 0.5 stwtt. It fills up the syncline depressions of the B sequence. This sequence has poorly defined reflectors and is onlapping the B sequence. It sometimes shows a divergent configuration.

c. The upper sequence (A) displays strong, parallel and continuous reflectors. This sequence overlies A′ with a slight unconformity at some places. The A sequence is not restricted to the infilling of the synclines, as was A′ (Figure 12). It unconformably overlies B over the entire area, covering up eroded anticlines. The A sequence does not show any evidence of significant deformation, suggesting the Windward Passage Sill to be quiescent during its deposit as well as at the present time.

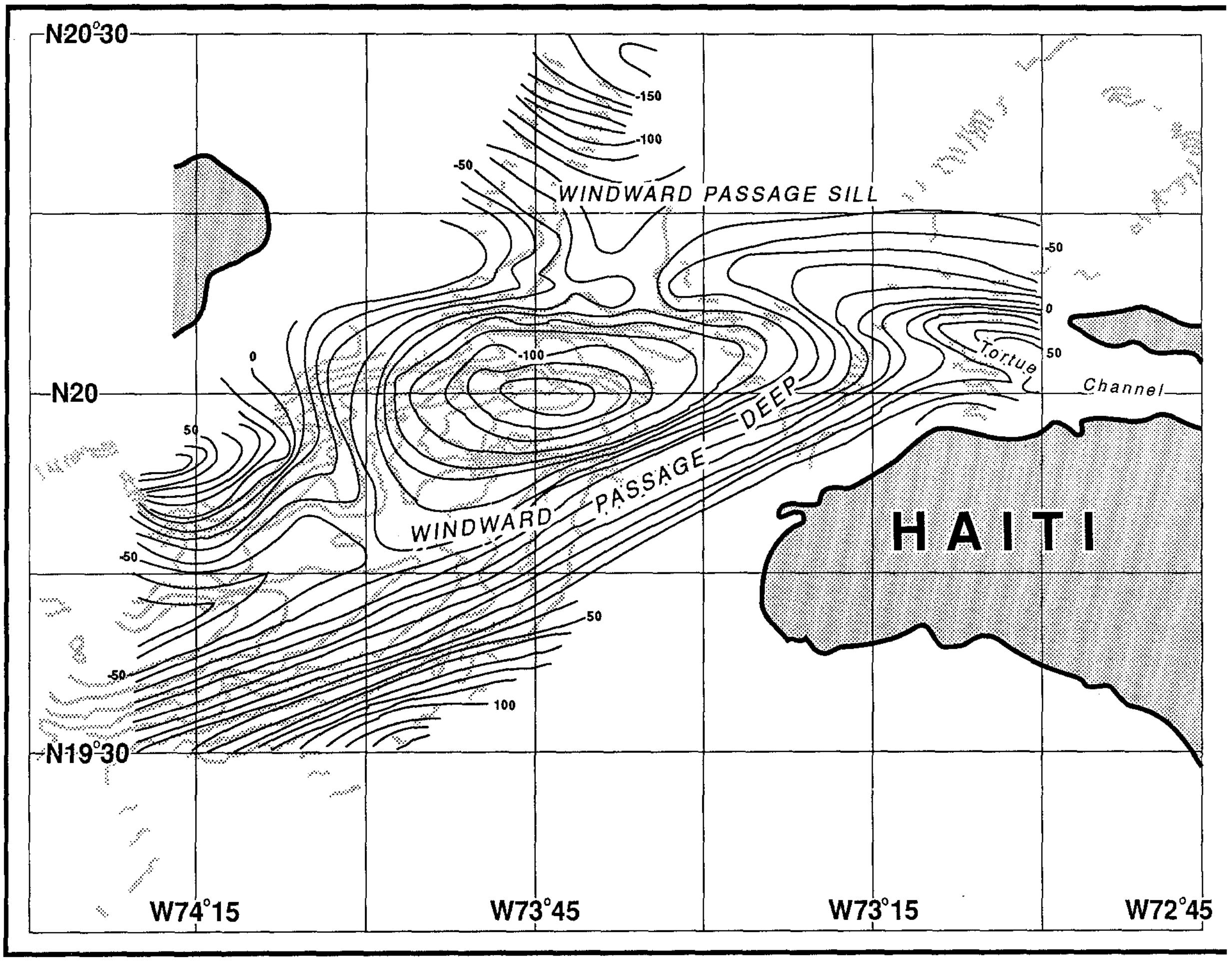


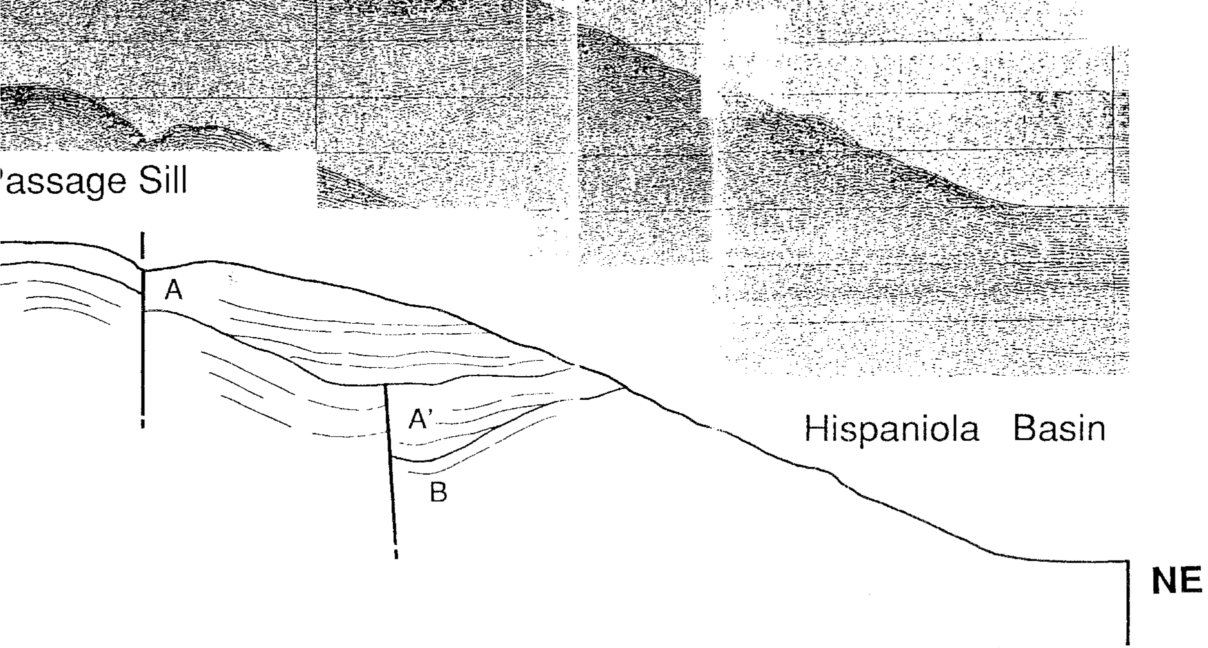
Fig. 6. Free-air gravity map of the Windward Passage (contour interval 10 mgals).

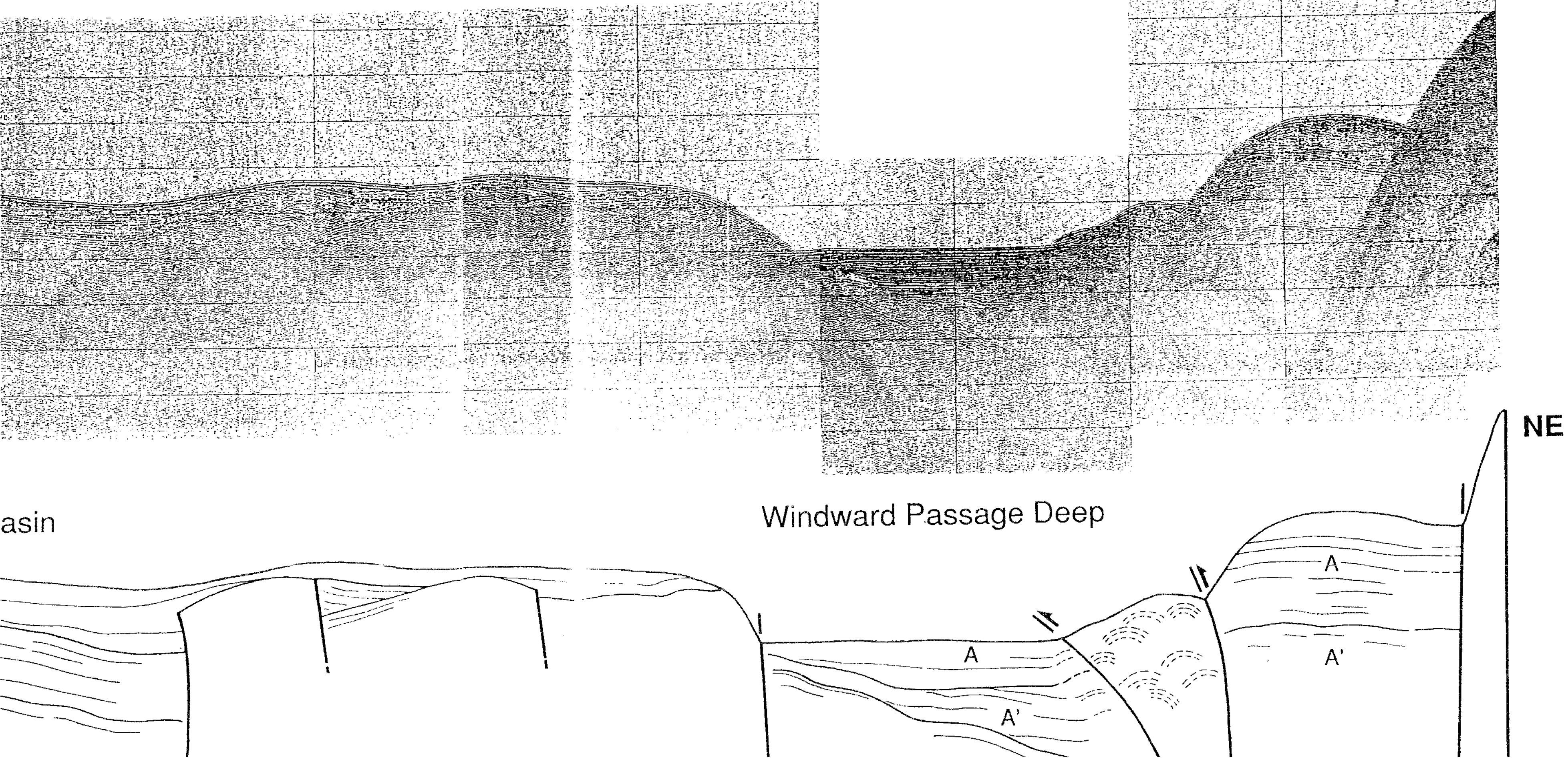
WINDWARD PASSAGE DEEP

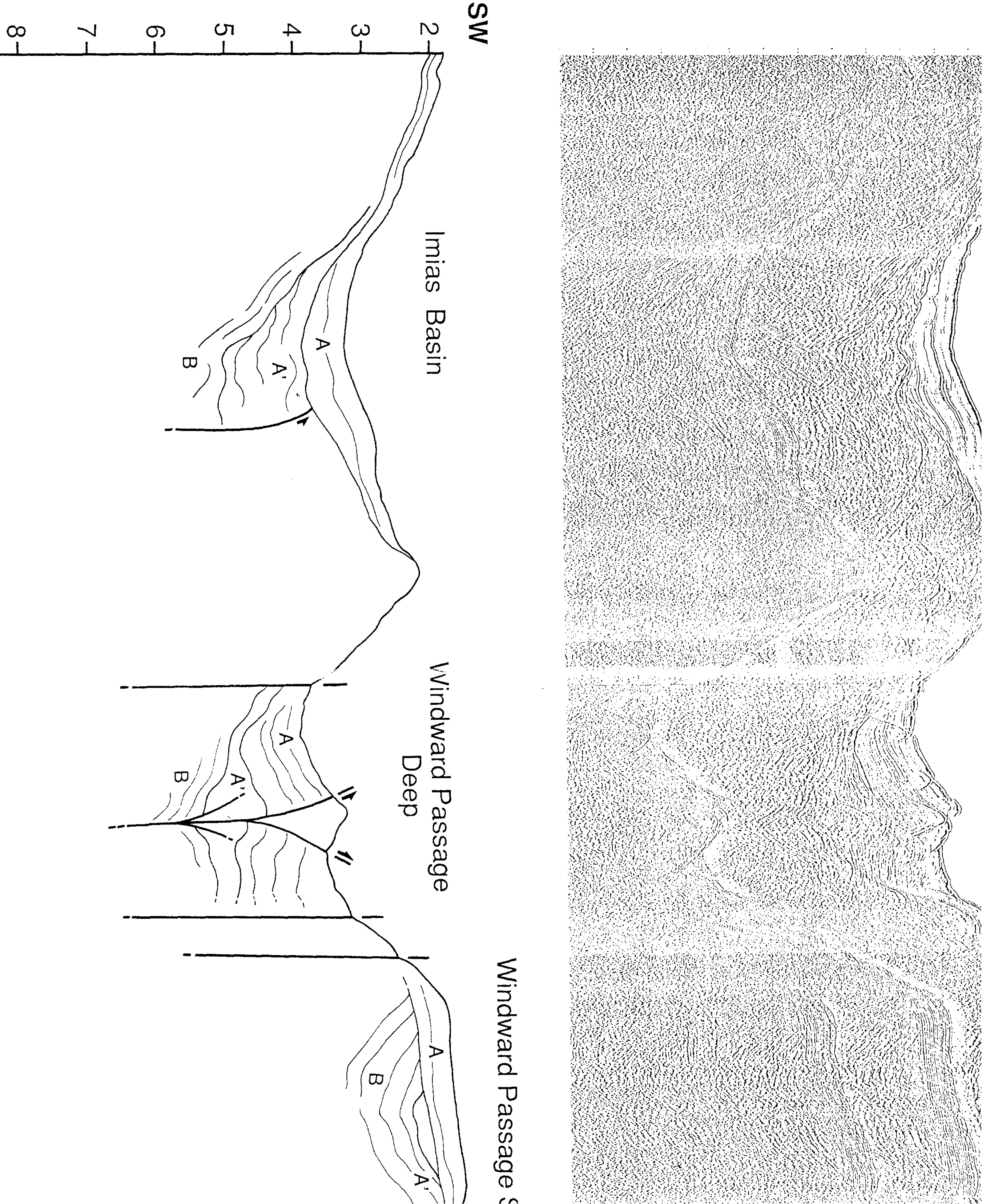
a. The central part of the Windward Passage Deep displays a thick sedimentary infilling (> 1.5 stwtt). The same seismic sequences as those found in the Windward Passage Sill can be distinguished (Figure 7 and 8), with the same seismic characteristics. However, B is not folded and A′ and A are thicker (up to 0.7 stwtt and 1 stwtt, respectively).

As suggested by the gravity data (Figure 6), seismic reflection profiles show that the lower step of the northern basin scarp is made of Windward Passage Deep sediments. This lower step is thus an uplifted part of the Windward Passage Deep, not a downdropped part of the Windward Passage Sill. As a consequence, the topographic depression of the Windward Passage Deep does not exactly coincide with the sedimentary basin itself.

b. Along the northern edge of the Windward Passage Deep, sediments (including the A sequence) are involved in folding and reverse faulting. Figure 13 shows a small anticline in the sediments of the northern edge of the basin. Figure 14 shows a steeper anticline, slightly verging southward, involving the sediments of the lower step of the northern basin scarp. This step actually corresponds to an anticline fold, bounded to the south by a high angle reverse fault (Figure 15). This fault can be continuously followed in the morphology as well as on the seismic profiles across the Windward Passage Deep. It is located within the basin, running in an east–west direction from the Punta Caleta Channel to the Tortue Channel. In the central part of the basin, this fault is associated with a spectacular positive flower structure, as illustrated in Figure 16. The Windward Passage Deep therefore appears to be a formerly subsiding basin that has been undergoing folding and faulting tectonics for a recent time.


Passage Sill
A
A'
B
Hispaniola Basin
NE


NE
asin
Windward Passage Deep
A
A'
A
A'


SW
2
3
4
5
6
7
8
Imias Basin
A
A'
B
Windward Passage Deep
A
A'
B
A
B
A'
Windward Passage

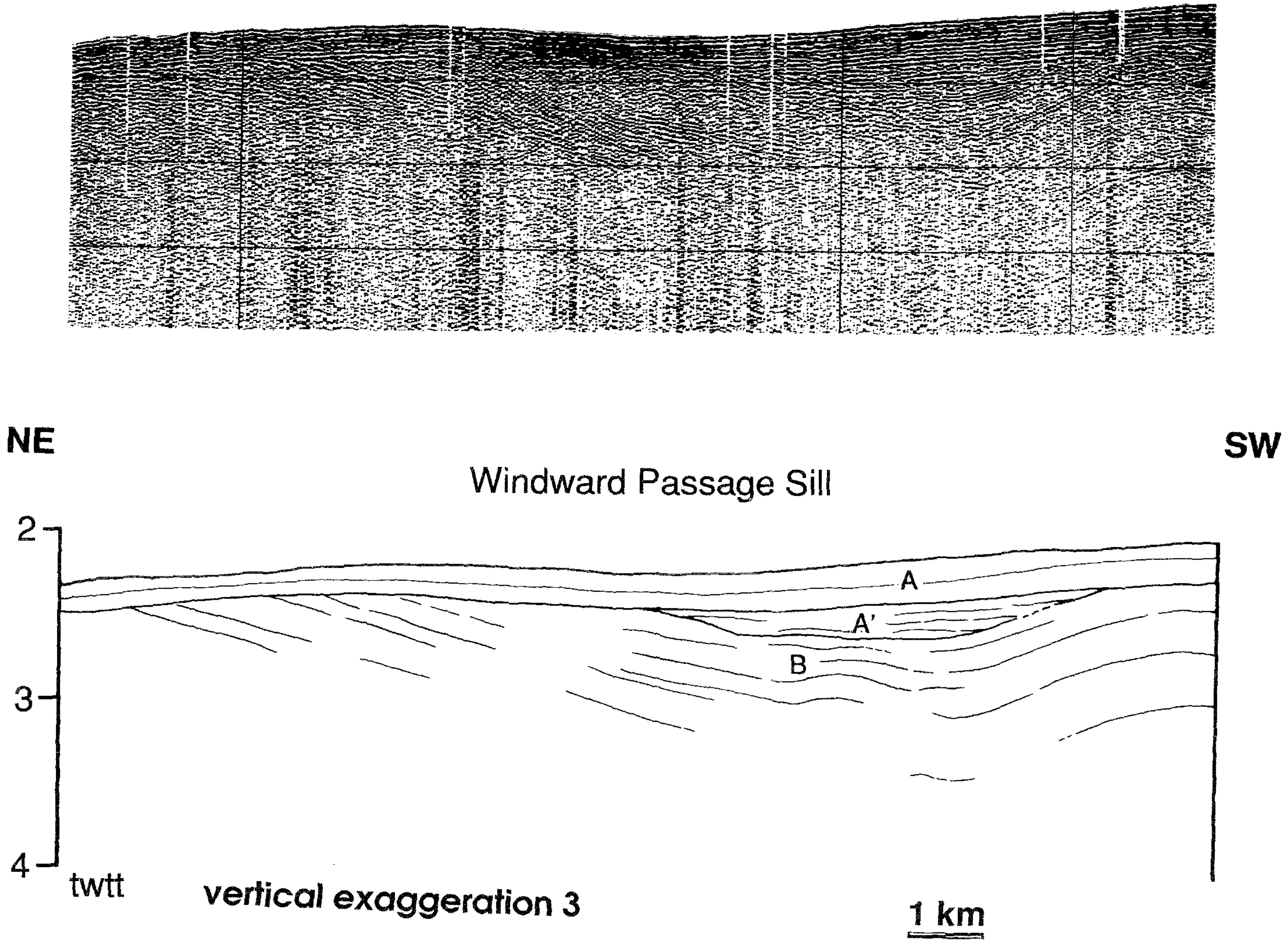


Fig. 9. Seismic profile 46 and its interpretation.

IMIAS BASIN

The same three seismic sequences as those previously identified are distinguished in the Imias Basin. The B sequence is dipping to the north but is not folded. It is overlapped by the A′ sequence. A′ shows a small south-verging anticline along the northern border of the basin. The A′ sequence itself is onlapped by the A sequence. In the western part of the basin, the A sequence is folded and affected by a reverse fault (Figure 17). In the eastern part, this reverse fault is buried under the underformed A sequence (Figure 18). The Imias Basin represents the eastern end of the Santiago Deformed Belt (Calais and Mercier de Lépinay, 1990), an active zone of transpression developed along the southern Cuban Margin. The tilting of the B sequence probably occurred along normal faults that were later reactivated as high angle reverse faults. The onlap and the divergent configuration of the A′ sequence seem to indicate that the tilting occurred during its deposit.

Synthetic Structural Map of the Windward Passage

The Seabeam, seismic reflection, and side-scan sonar data (Figures 19 and 20) allowed us to establish a precise structural map of the Windward Passage (Figure 21). Its most prominent tectonic features are three east–west trending faults, located along both edges of the Windward Passage Deep and within the basin itself.

1. The northernmost fault limits the Windward Passage Sill to the south. It corresponds to a 500 m high scarp. Its trace disappears to the west in the morphology as well as on seismic profiles. This fault continues to the east along the northern border of the Tortue Channel.

2. The southernmost fault forms the southern border of the Windward Passage Deep. It takes a N70 to N60 trend to the west, in the direction of the Imias Basin, but rapidly disappears in the morphology as well as on seismic profiles. To the east, this fault is buried before reaching the Haitian coast.

3. The main fault system crosses the middle of the Windward Passage Deep. It is made up of two main faults which are both active, since they affect the youngest sediments of the Windward Passage Deep.

a. The northern fault segment runs in a N80 direction up to the middle part of the basin. Its trend shifts slightly at about 73° 40′ W and its trace disappears. This fault corresponds to the southern border of the upper step of the basin edge scarp (750 m of average difference in level). It seems to be a nearly vertical fault.

b. The second fault crosses the whole length of the Windward Passage Deep. It corresponds to the southern border of the lower scarp of the northern basin edge. This fault segment strikes N80 along its western part, N90 along its middle part and N95 along its eastern part. It continues to the east into the Tortue Channel, as shown by the GLORIA track along the Haitian coast (Figure 20). Seismic profiles show that this fault corresponds to a south-verging reverse fault in the western part, becomes more vertical in its middle part and continues as a north-verging reverse fault in its eastern part. It is associated with folding and minor faulting displaying positive flower structure at depth (Figure 16). This fault itself is made of several segments (3 or 4) with small offsets giving the appearance of one continuous fault trace. The high resolution side-scan sonar images show that these segments are rectilinear. Each change of strike occurs at the relay areas between them (Figure 19) and ranges from 4 to 7°. These relay areas are marked by intense deformation over a 500 m to 1 km wide domain, contrasting with the low deformation level along the rectilinear part of the fault segments. The deformation is characterized by numerous *en échelon* sigmoidal tensional fractures; their "S" shape indicates left-lateral motion.

In the eastern part of the Windward Passage, an east–west trending canyon comes down from the Tortue Channel into the Windward Passage Deep. It is probably tectonically controlled by active faulting.

Present-Day Plate Boundary Trace Across the Windward Passage

Side-scan sonar data as well as seismic reflection profiles allowed us to clearly image a major east–west trending fault system crossing the Windward Passage Deep (Figure 21). This fault system is the eastward prolongation of the Oriente Fault (Figure 1B), previously mapped in detail along the southern Cuban Margin and to the Punta Caleta Channel (Calais and Mercier de Lépinay, 1991). Since the Oriente Fault represents the

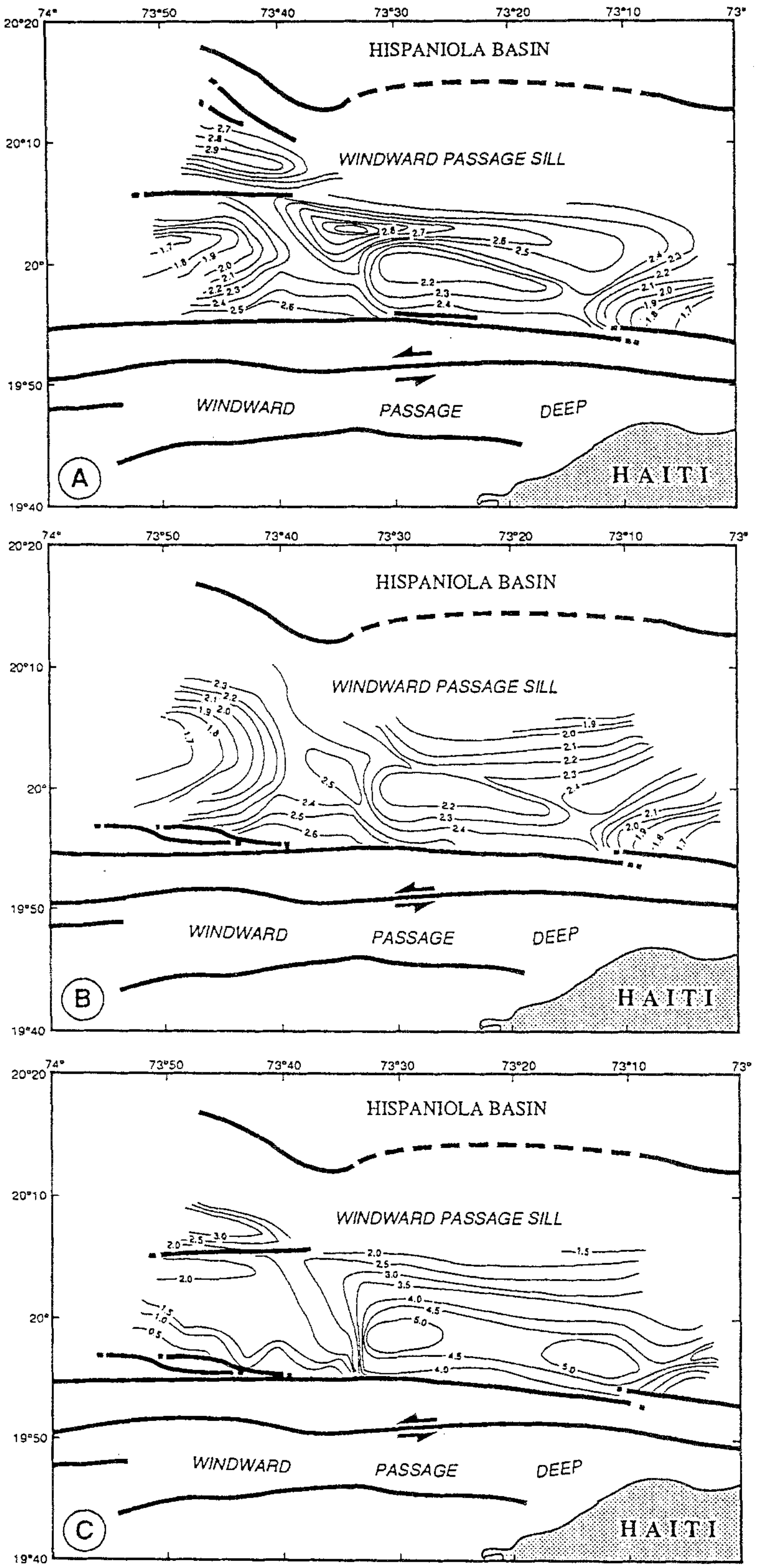


Fig. 10. A. Isochron map of the top of the B sequence (values in stwtt). B. Isopach map of the A′ sequence (values in stwtt × 10). C. Isopach map of the A sequence (values in stwtt × 10).

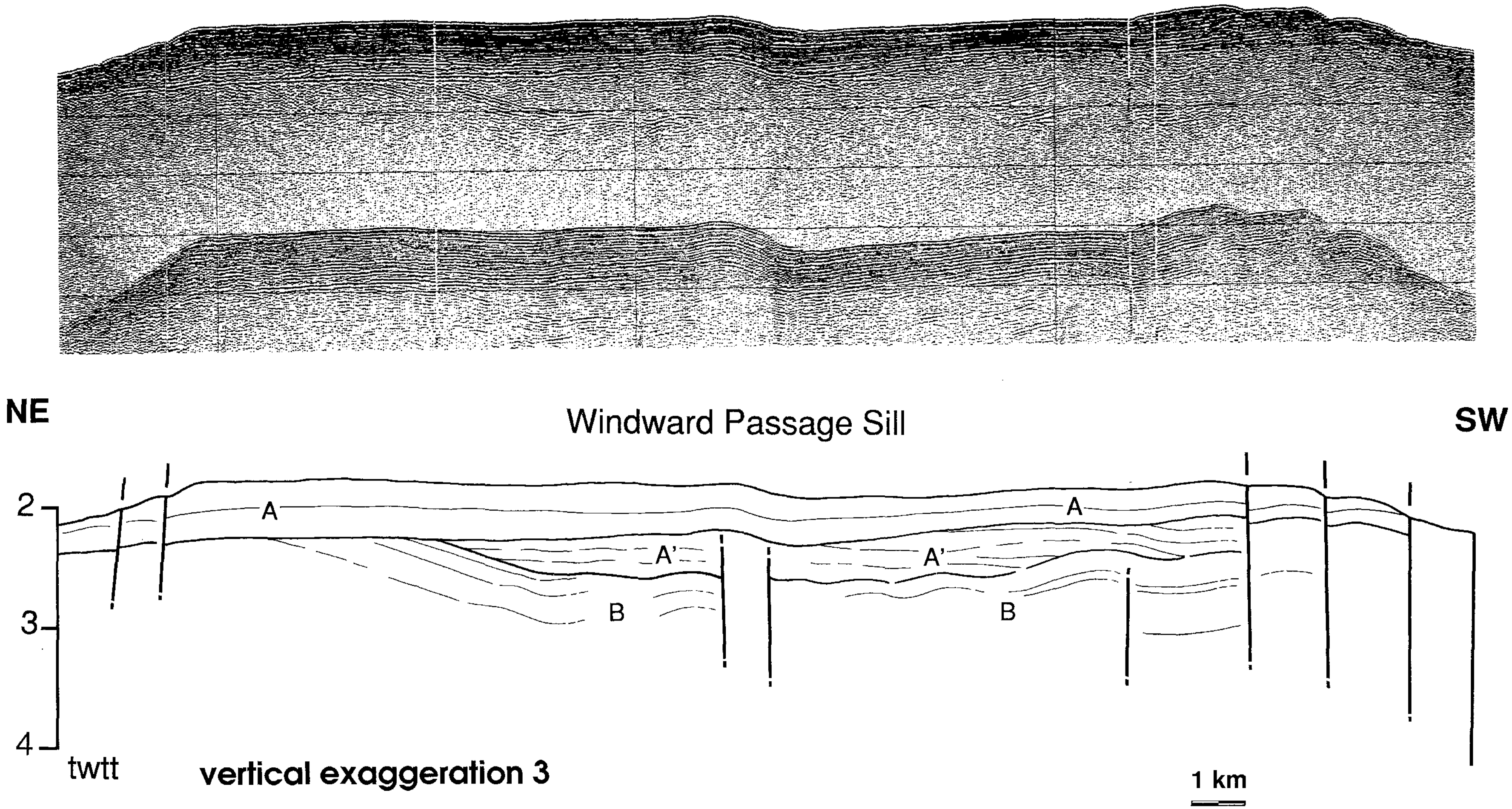


Fig. 11. Seismic profile 205 and its interpretation.

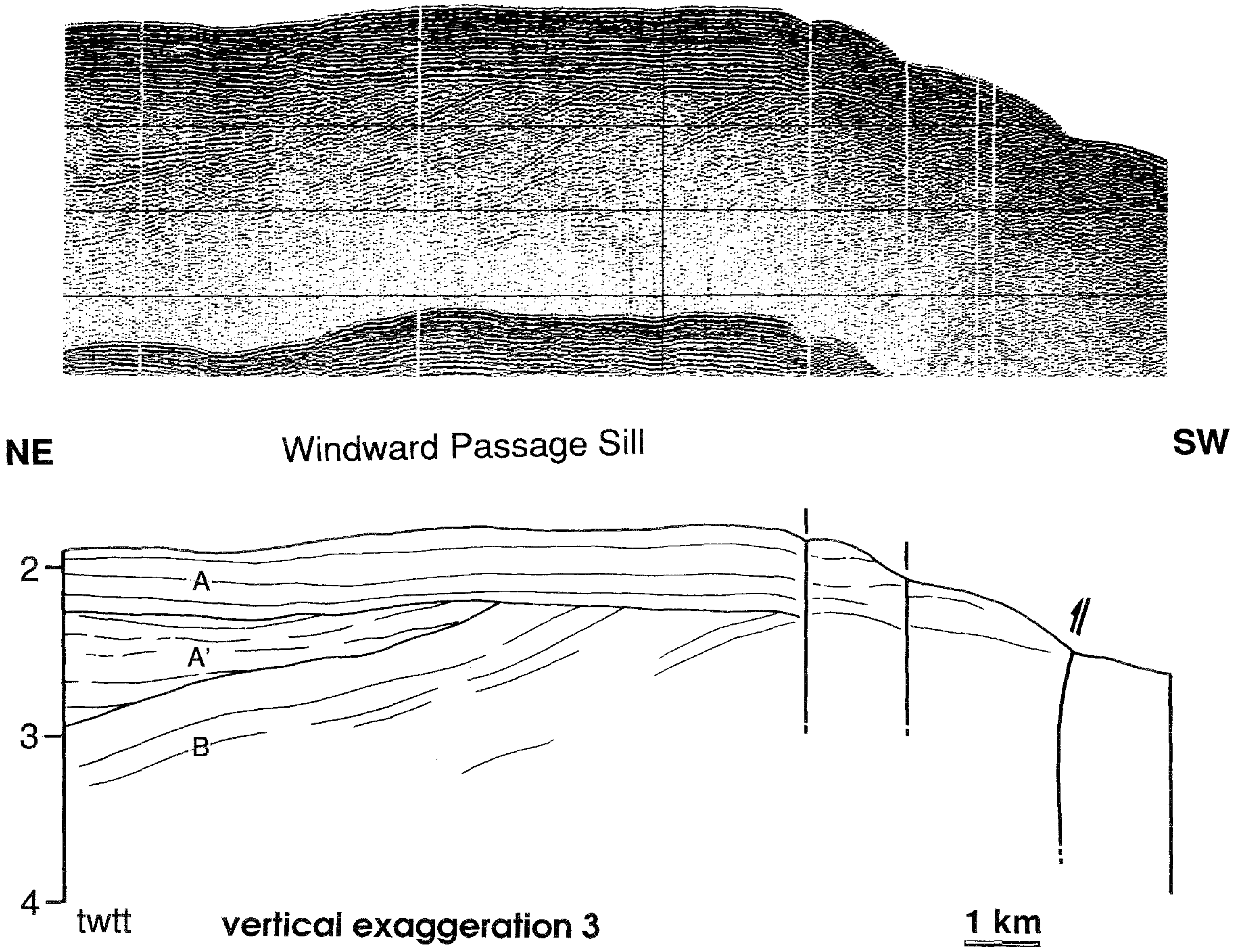


Fig. 12. Seismic profile 186 and its interpretation.

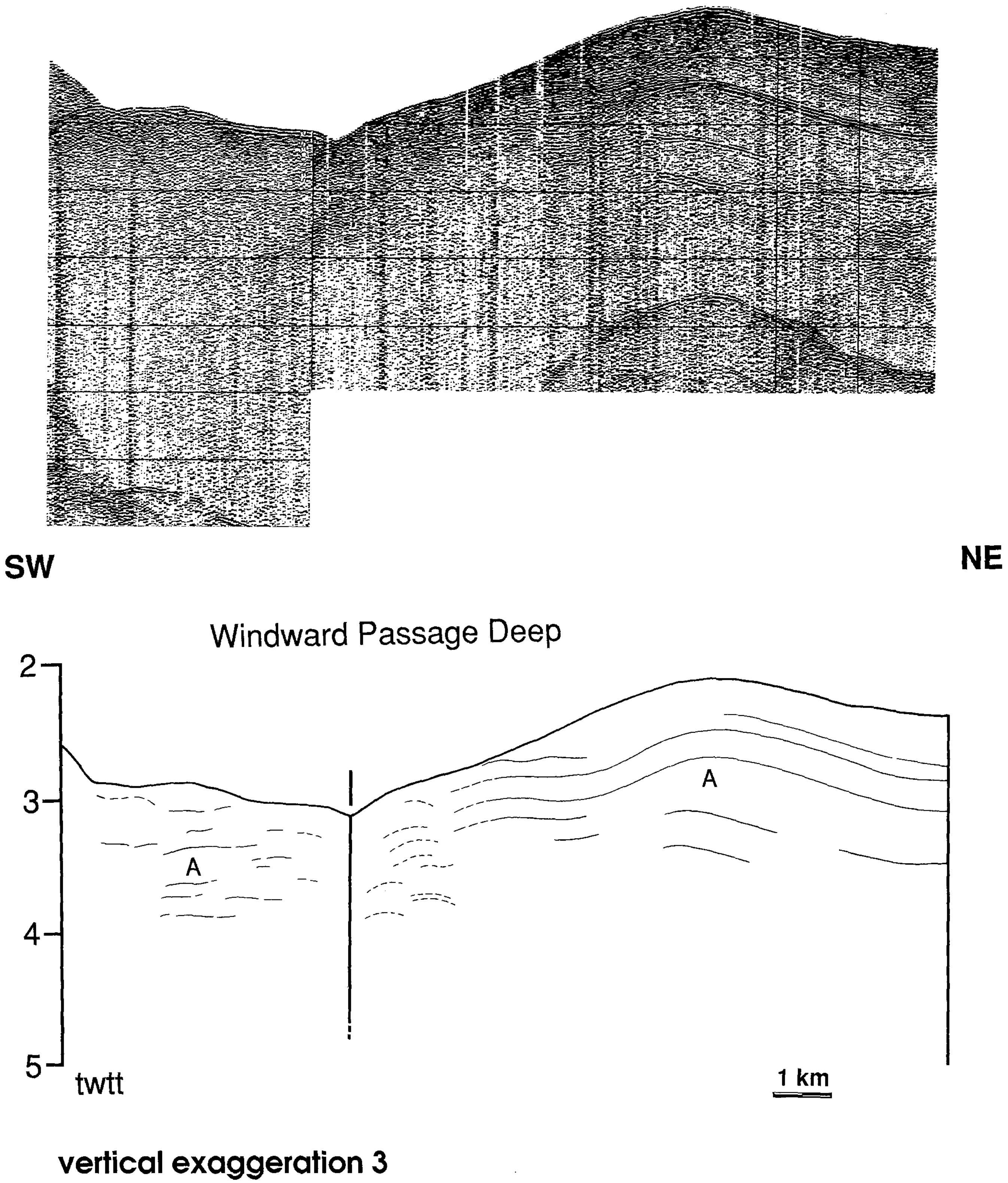


Fig. 13. Seismic profile 49 and its interpretation.

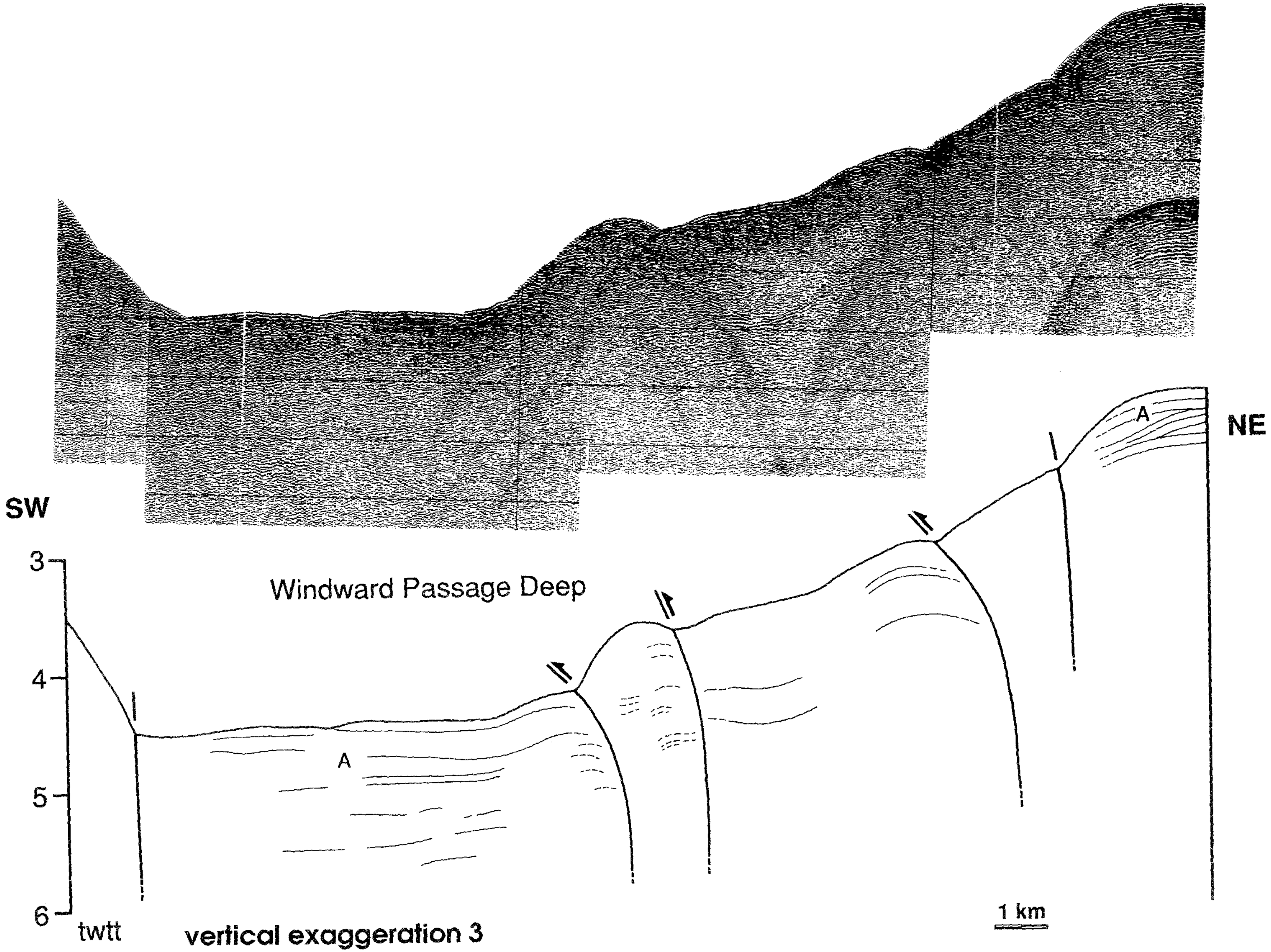


Fig. 14. Seismic profile 47 and its interpretation.

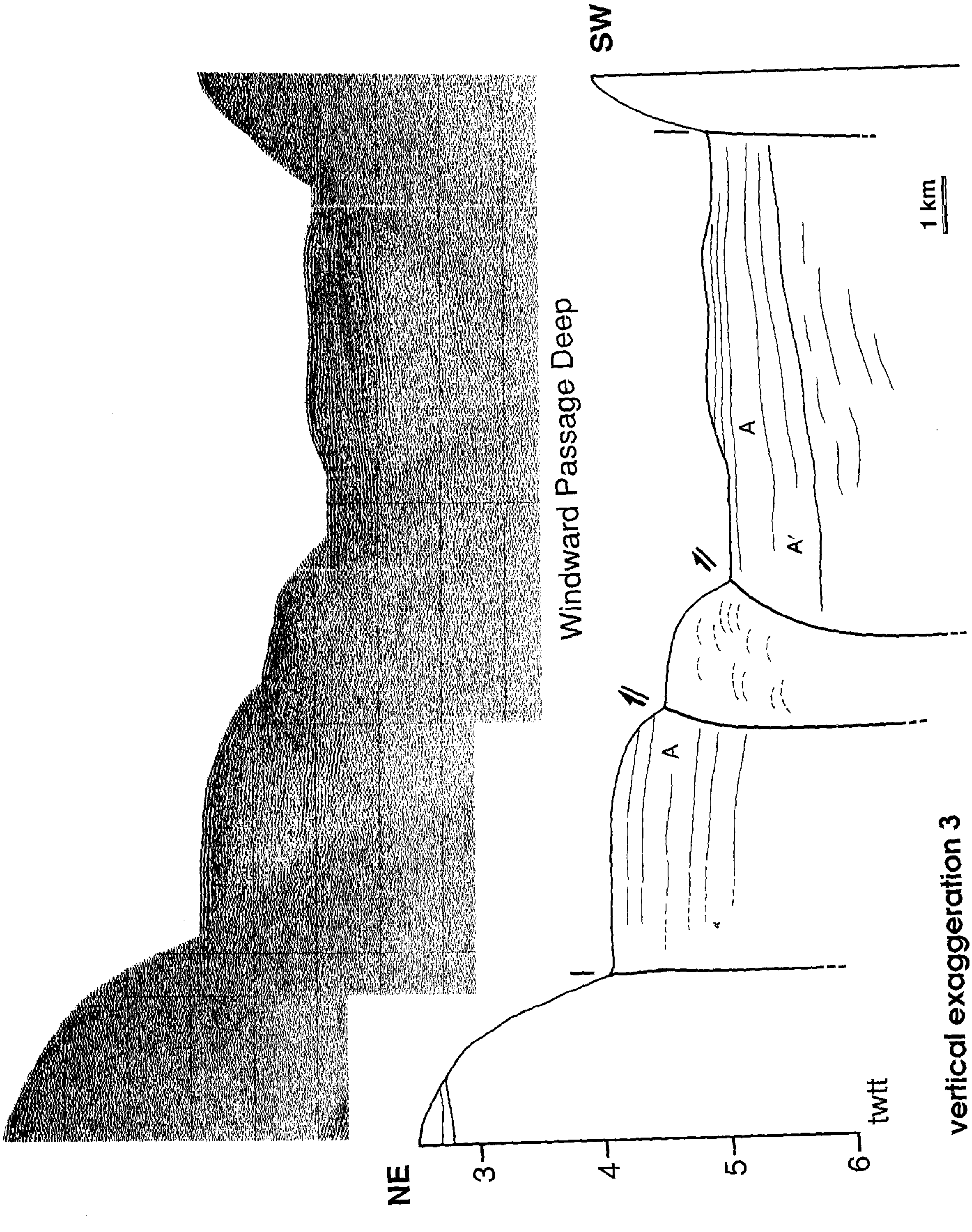


Fig. 15. Seismic profile 188 and its interpretation.

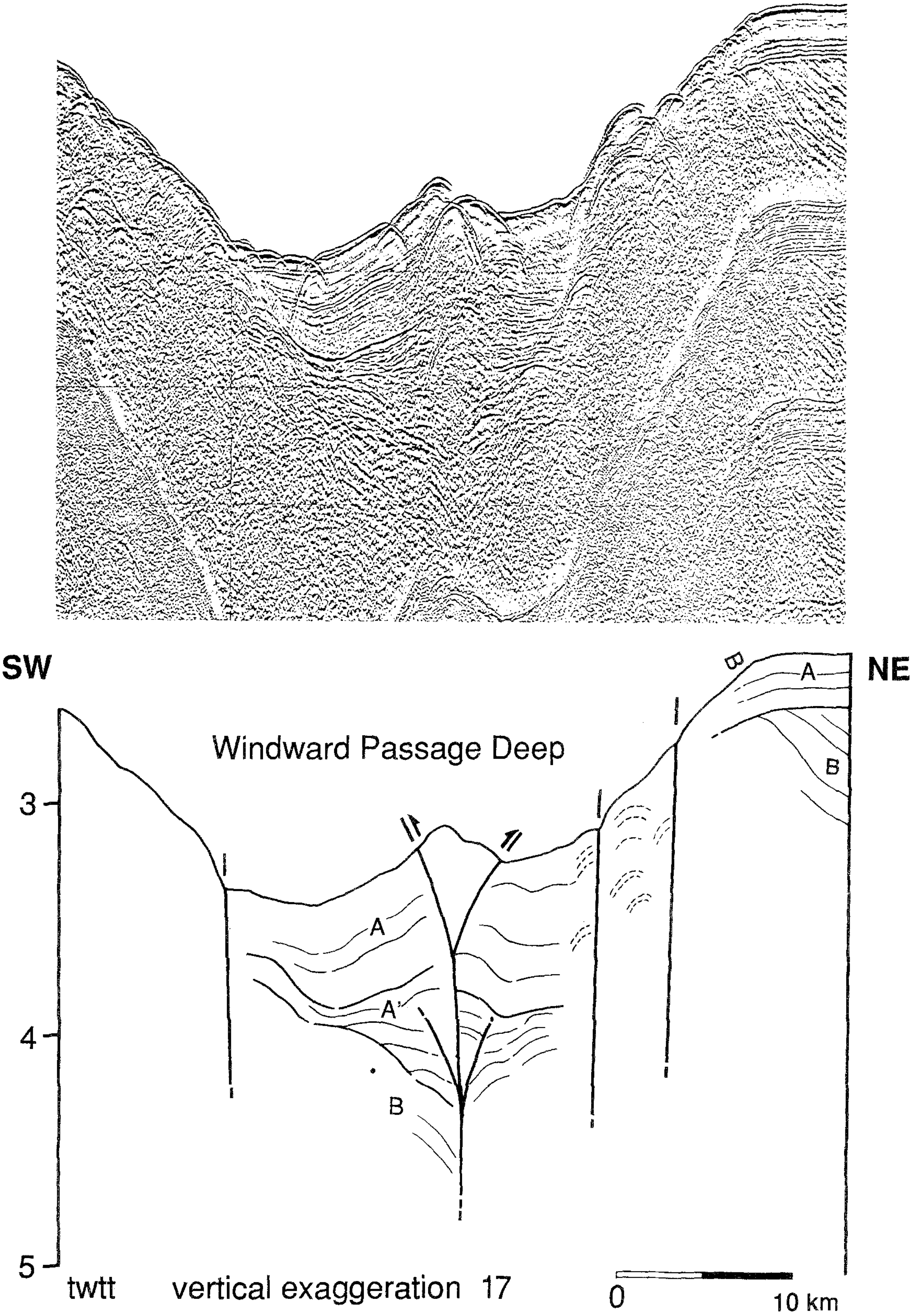


Fig. 16. Seismic profile CT2-25C (detail) and its interpretation (shown with permission of the University of Texas Institute for Geophysics).

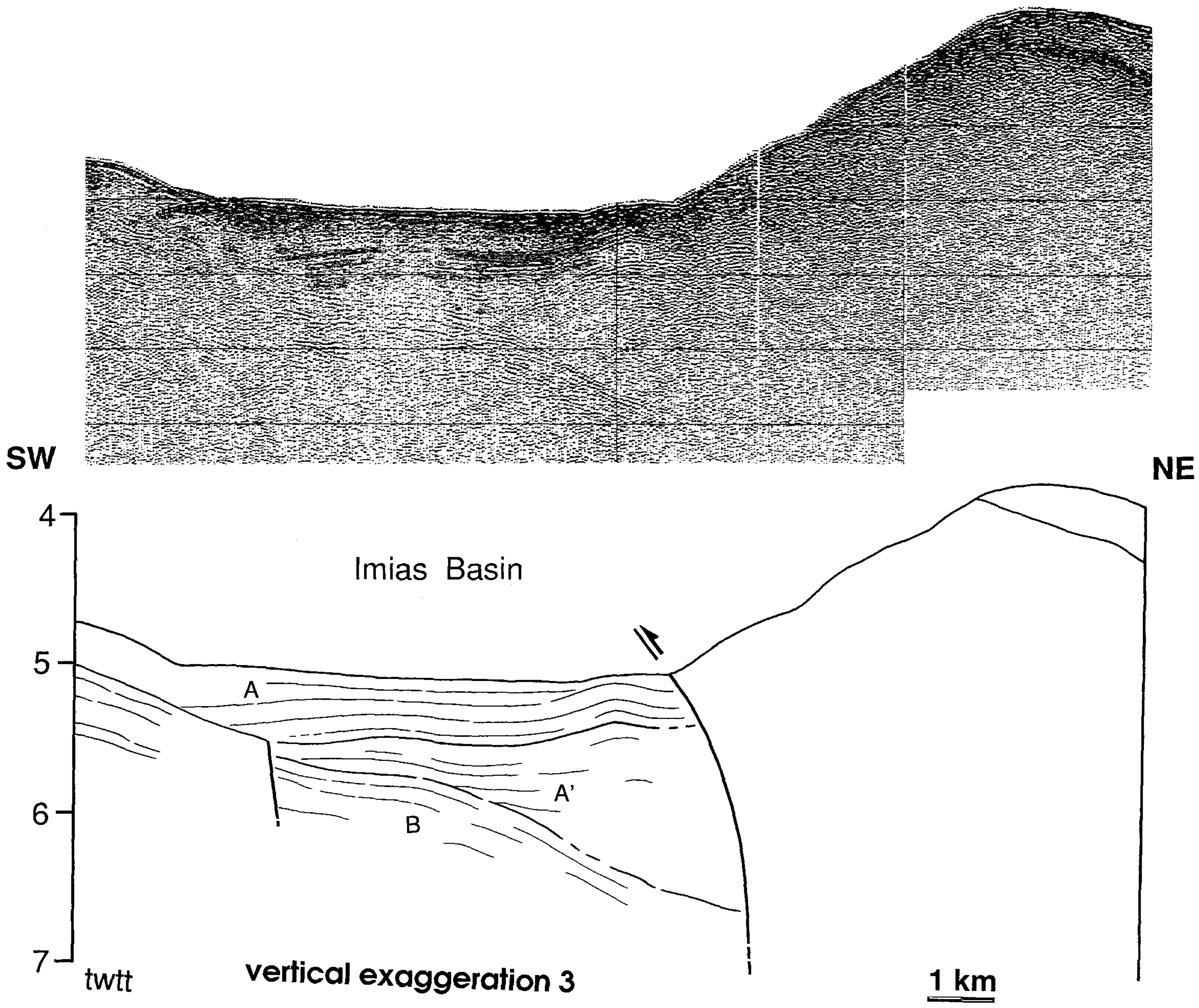


Fig. 17. Seismic profile 196 and its interpretation.

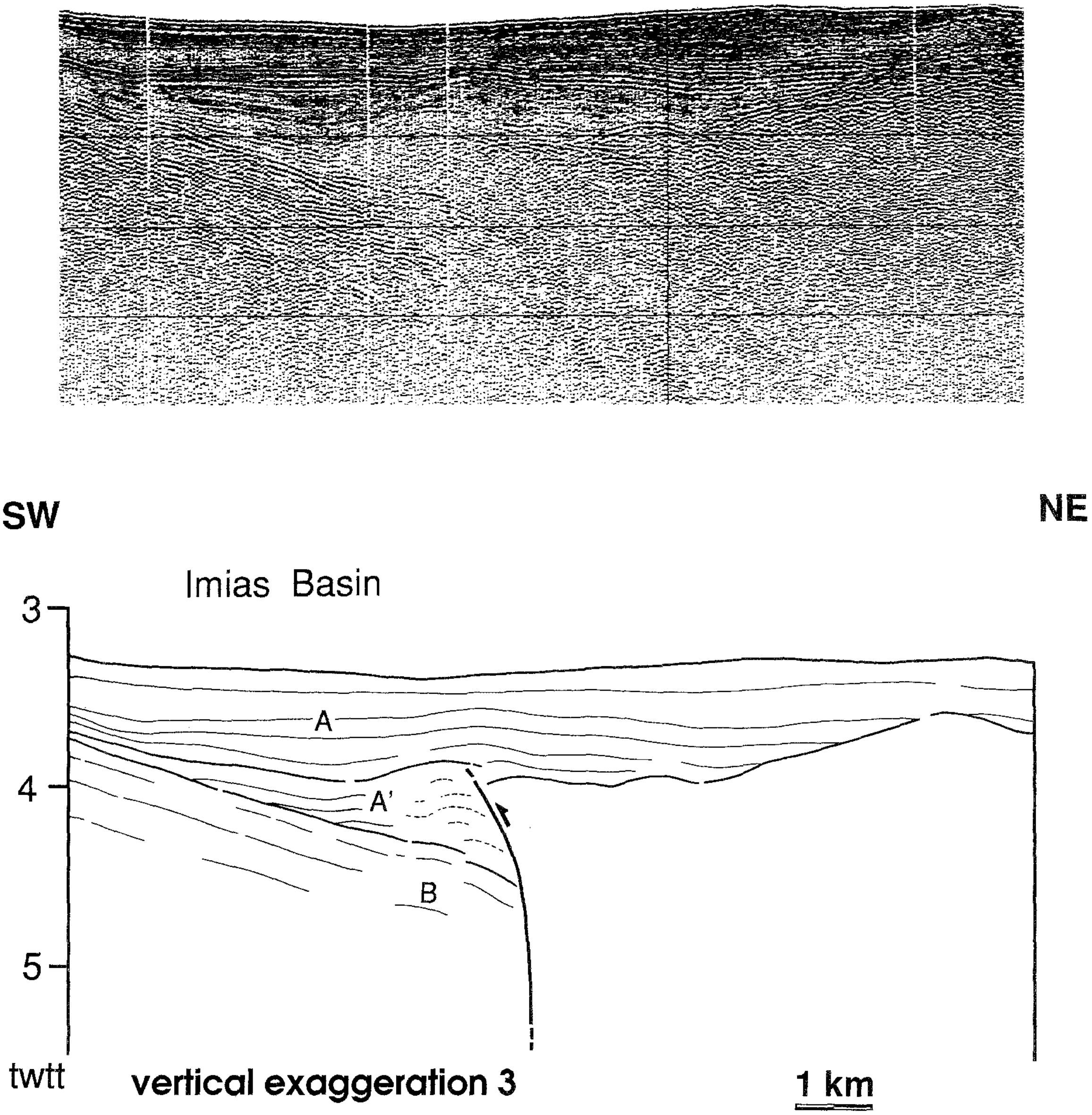


Fig. 18. Seismic profile 202 and its interpretation.

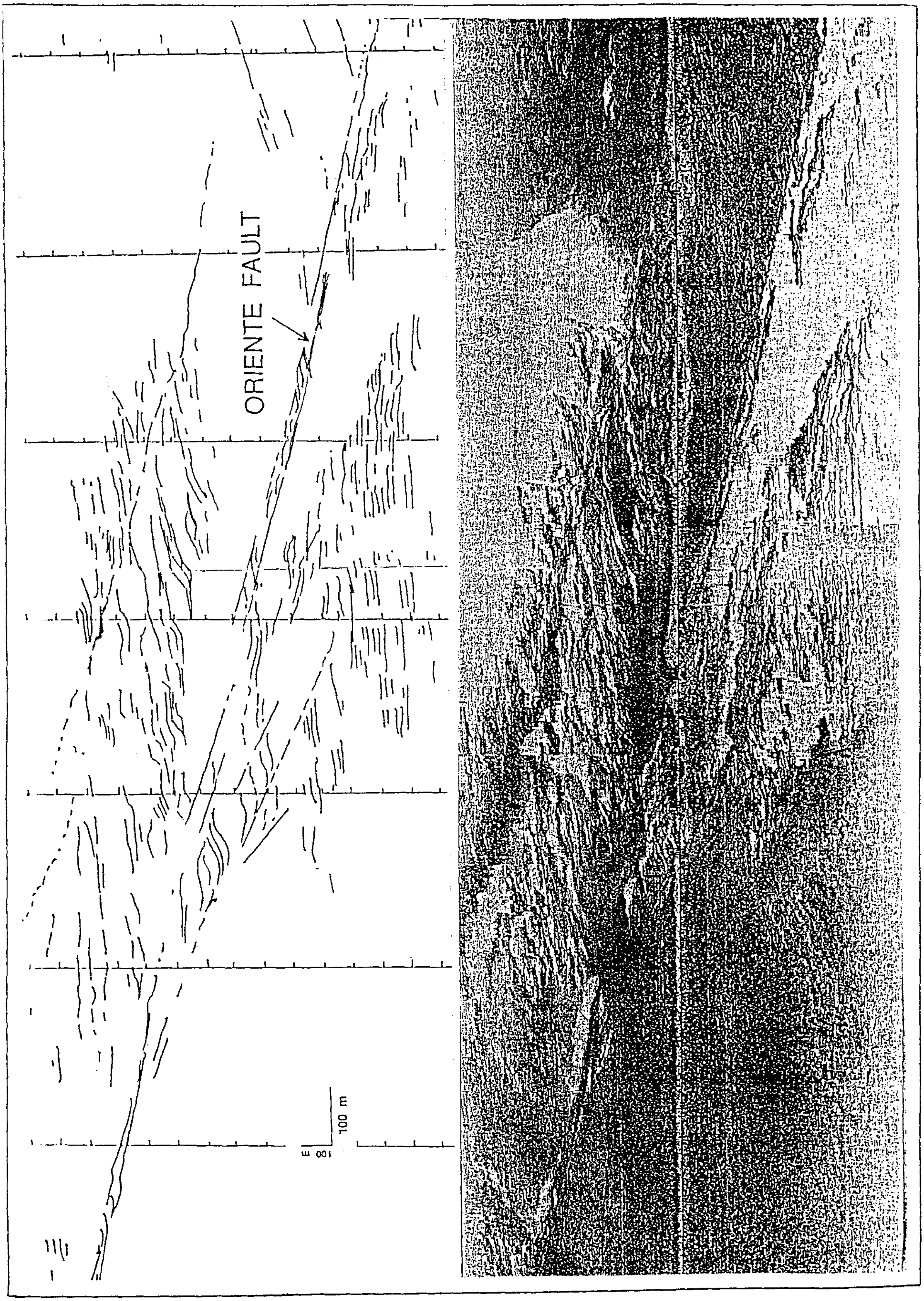


Fig. 19. SAR side-scan sonar image of a segment of the Oriente Fault in the Windward Passage Deep.

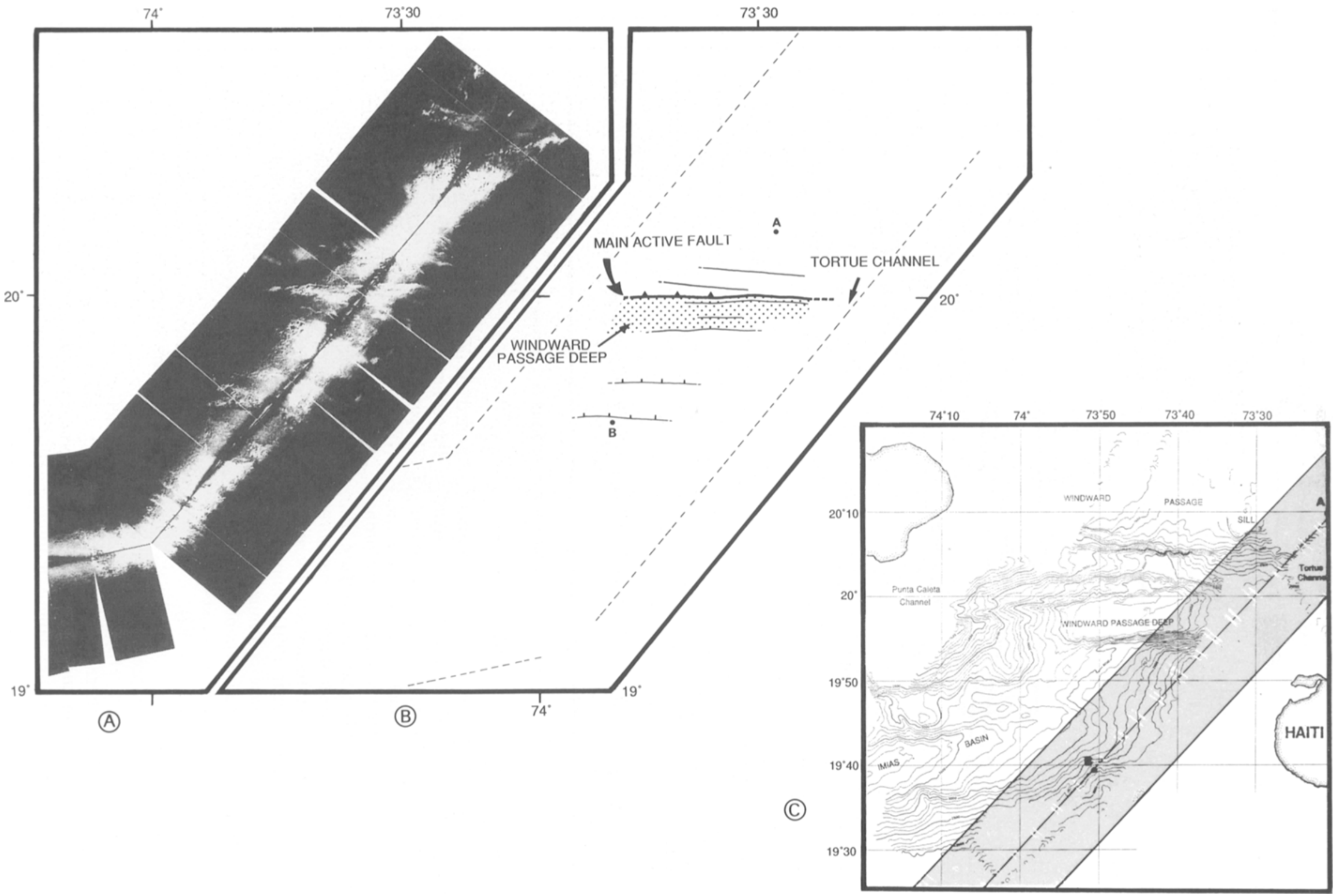


Fig. 20. GLORIA side-scan sonar image of the eastern part of the Windward Passage (used with permission of N. T. Edgar, U.S. Geological Survey).

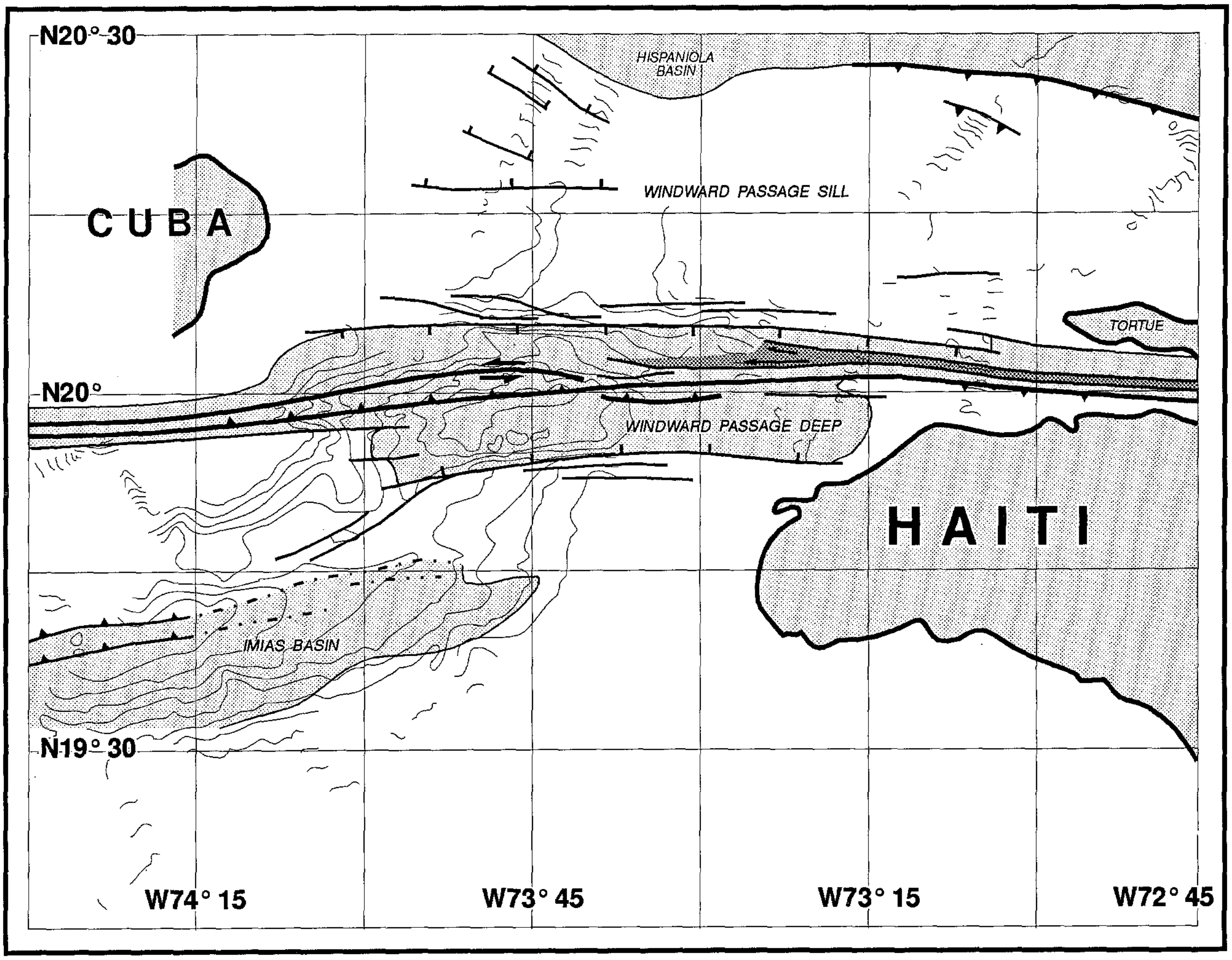


Fig. 21. Structural map of the Windward Passage.

northern Caribbean Plate boundary trace (Molnar and Sykes, 1969), our results show that the plate boundary trace runs straight through the Windward Passage and continues eastward into the Tortue Channel. The plate boundary trace probably follows the northern Haitian coast (Figure 1B), as suggested by the very linear shape of the shoreline and by seismic reflection studies off the western edge of the Cibao Valley (Edgar, 1991). More to the east, the plate boundary trace continues on land into the northern Dominican Republic along the Cordillera Septentrional active strike-slip zone (Mann *et al.*, 1984; Calais *et al.*, 1992).

There is thus no connection between the Oriente Fault and the active compressional structures of the base of the northern Hispaniola Margin (Dillon *et al.*, 1992). Since there is no Benioff zone under Hispaniola (McCann and Sykes, 1984; Calais *et al.*, 1992), these structures cannot be interpreted as the deformation front of the Atlantic lithosphere subduction under Puerto Rico and Hispaniola. Moreover, as shown by Dillon *et al.* (1992), the geometry of these structures is not that of a typical transpressional area (*en échelon* folds, faults rotations; Sylvester, 1989). The compressional structures of the Hispaniola Basin seem rather to be related to north–south convergence, so that "the main locus of transcurrent motion [along the plate boundary] probably occurs either on land or near the coast" (Dillon *et al.*, 1992). Since the Oriente Fault can be continuously tracked from the southern Cuban Margin across the Windward Passage into the eastern Dominican Republic, we believe that it is the major structure responsible for the left-lateral transcurrent motion of the Caribbean Plate relative to North America. This interpretation is in good agreement with the earthquake distribution and focal mechanisms in the northeas-

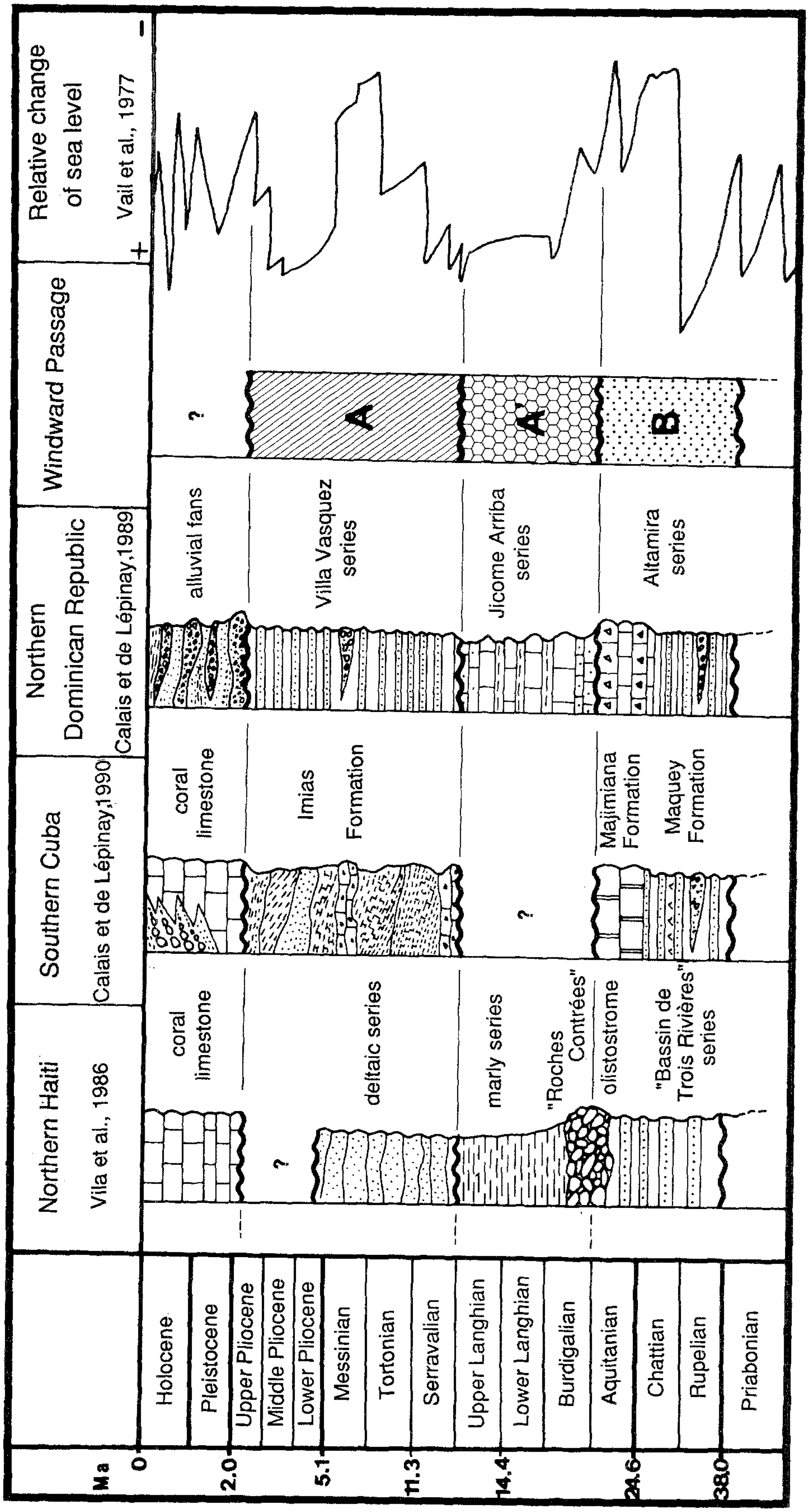


Fig. 22. Synthetic stratigraphic columns of the northern Caribbean.

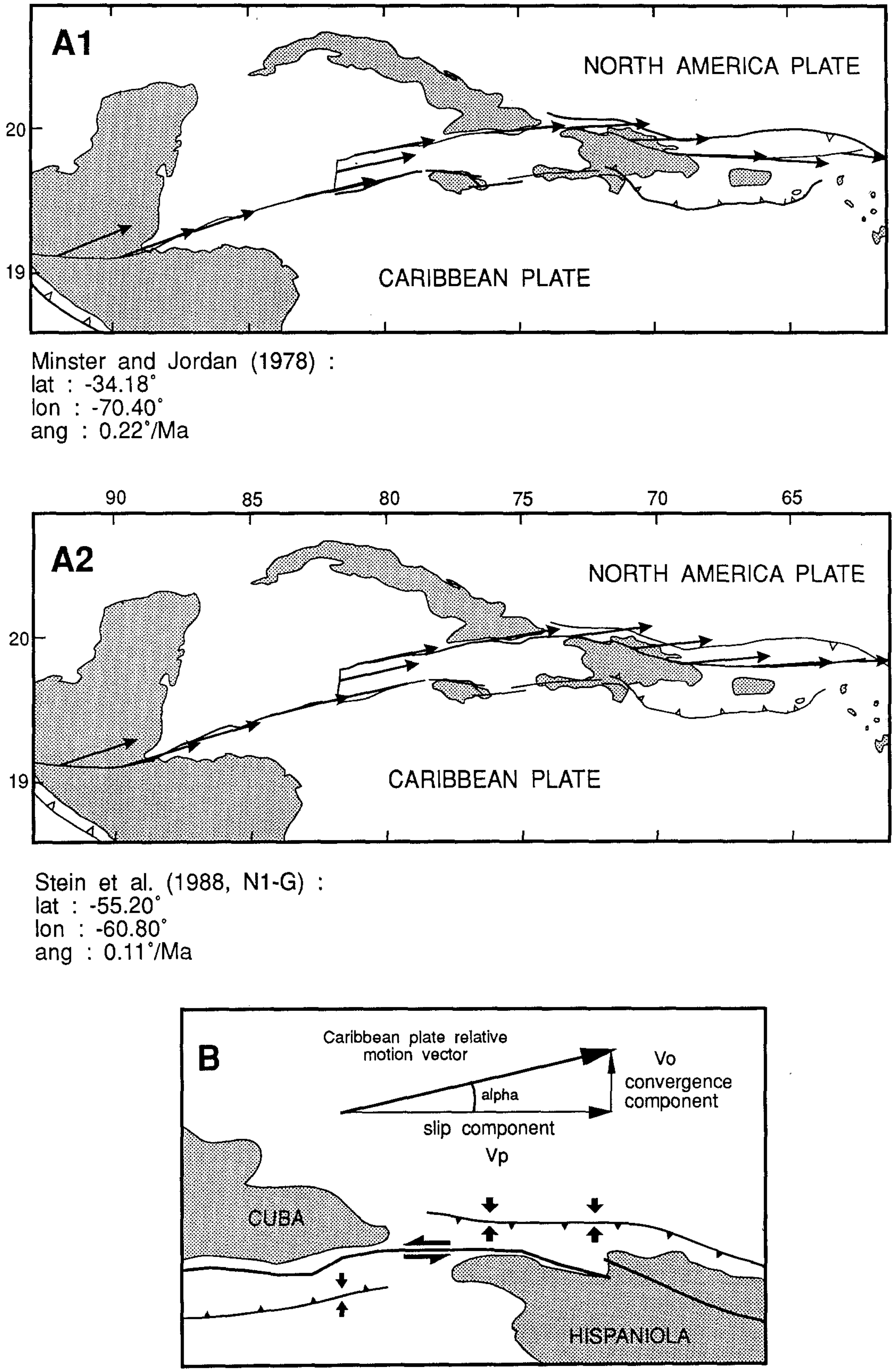


Fig. 23. A. Plate motion vectors of the Caribbean Plate relative to the North American Plate along the northern Caribbean Plate boundary (pole locations and angular velocities are indicated); A1 after Minster and Jordan's (1978) model, A2 after Stein *et al.'s* (1988) model. B. Hypothesis of kinematic partitioning.

TABLE I

Strike-slip and convergence components of the Caribbean/North America relative motion vector according to the plate kinematics models of Minster and Jordan (1978) and Stein *et al.* (1988) (see Figure 23).

		N90 fault strike					N95 fault strike				
Author	Rate (cm yr^{-1})	a (deg.)	v_p (cm/yr)	v_o (cm/yr)	v_o/v_p (%)	conv. (km)	a (deg.)	v_p (cm/yr)	v_o (cm/yr)	v_o/v_p (%)	conv. (km)
Minster	2.03	3.4	2.02	0.12	5.96	2.4	8.41	2.01	0.30	14.78	5.9
Stein	1.19	7.6	1.18	0.16	13.29	3.12	12.57	1.16	0.26	22.30	5.2

tern Caribbean (McCann and Sykes, 1984; Calais *et al.*, 1992).

We calculated the motion vector of the Caribbean Plate relative to North America in the Windward Passage area (Figure 23) using the global kinematics models RM-2 (Minster and Jordan, 1978) and Nuvel-1 (Stein *et al.*, 1988). Since the plate boundary trace between Cuba and Hispaniola trends N90 to N95, we geometrically split this vector into a component parallel to the fault (v_p) and a component normal to the fault (v_o). Table I displays the v_p and v_o values that we obtained. In both cases the calculated plate motion vector is oblique to the plate boundary trace in the Windward Passage area, with an angle ranging between 3.4° and 12.6°. This obliquity implies a convergence component between the Caribbean and North American plates ranging from 6% (1.2 mm yr^{-1} to 22.3% (2.9 mm yr^{-1}). Over 2 Ma (the possible age of the present-day plate boundary geometry; see below), these values correspond to 2.4 km to 5.9 km of crustal shortening perpendicular to the fault trace.

According to our structural observations, no significant transpression occurs across the Windward Passage. The present-day compressive deformation is restricted to the relay zones of the Oriente Fault. Moreover, the smooth folding that we observed can be explained in the frame of pure strike-slip motion, as shown by analog tectonic models (Odonne and Vialon, 1983; Richard and Cobbold, 1989; Sylvester, 1989). We believe that the amount of convergence predicted by the kinematic models is too large to be attributed to the small amount of compressive deformation observed along the Oriente Fault across the Windward Passage. The lithosphere in the Windward Passage area and along the northern Hispaniola Margin seems to behave as if the convergence and strike-slip components of the global motion were completely decoupled. In this case, the Oriente Transcurrent Fault would specifically account for the major east–west left-lateral motion, while a compressional area developing at the bottom of the Hispaniola Basin would account for the small north–south convergence component.

Such a partitioning process has been proposed to explain the structural pattern of central California (Mount and Suppe, 1987) and, at another scale, that of the Sumatra Margin (Fitch, 1972) and that of the Philippines Archipelago (Pinet and Cobbold, in press). In all three cases, almost pure strike-slip motion is accommodated along a single narrow transcurrent zone, while convergence is accommodated at a broader scale by compressive structures (thrusts and reverse faults) or frontal subduction.

Tectono-Sedimentary Synthesis

MARINE DATA

On the basis of the seismic, side-scan sonar, gravity and magnetic data analysis described above, we propose the time-succession of five tectono-sedimentary steps in the Windward Passage area, as follows:

a. The first period corresponds to the B sequence deposit. Its seismic characteristics do not show any sedimentological disturbance and seem to indicate a quiet tectonic regime.

b. The second period corresponds to the folding of the B sequence on the Windward Passage Sill. Positive and negative topographic features (anticlines, synclines and basins) form during this period, which appears to be that of a tectonic crisis and strong physiographic reorganization.

c. The third period corresponds to the erosion of the folded B sequence, in particular on the Windward Passage Sill, which was probably above sea level at this time. The synclines are filled up with material eroded from the anticlines (A′ sequence). A thick sedimentary sequence fills up the Imias

Basin and the Windward Passage Deep, which are strongly subsiding.

d. The fourth period corresponds to the A sequence deposit, unconformably overlying the A′ and B sequences in the Windward Passage Sill. The unconformity at the base of A is probably not of tectonic origin, but rather corresponds to a sudden subsidence or to a strong positive eustatic variation.

e. The fifth period corresponds to the present-day transcurrent tectonic regime. The normal faults bounding the Imias Basin to the north are reactivated as reverse faults. The reverse faulting is still active only in the western edge of the basin. In the eastern part the faults are buried under the most recent sediments. A major east–west trending strike-slip fault crosses the middle of the Windward Passage Deep. Its northern and southern edges are inherited from a previous tectonic setting, but are not active faults anymore. This fifth period corresponds to a strong reorganization of the plate boundary geometry and tectonic regime in the Windward Passage area.

Since no absolute age for these events can be inferred from marine data in the absence of direct sampling, we extrapolate in the following onland geological data in order to time-correlate the marine observations.

CORRELATION WITH ONLAND DATA

Onland field work in southern Cuba and northern Hispaniola (Haiti and Dominican Republic) show that the tectonic evolution of these domains is marked by the same three unconformities (Late Eocene, Early Miocene, Late Pliocene), separating four different paleogeographic and tectonic regimes (Figure 22):

a. The Late Eocene is a period of intense compressive deformation in Cuba and Hispaniola, marked by southwest verging folding and reverse faulting. In the northern Dominican Republic, the Upper Eocene to Lower Miocene Altamira series unconformably overlies the Eocene Los Hidalgos Formation (DeZoeten and Mann, 1991; Calais *et al.*, 1992). In southern Cuba, this event corresponds to the uplift of the Sierra Maestra (Vila, 1984; Calais and Mercier de Lépinay, 1991). In northern Haiti, the Oligocene to Lower Miocene Trois Rivières series unconformably overlies strongly folded and faulted Middle to Upper Eocene marly limestones (Vila *et al.*, 1986).

b. From Late Eocene to Early Miocene, southeastern Cuba and northern Dominican Republic show two series with great facies similarities: the Maquey Formation in Cuba and the Altamira Formation in Dominican Republic (Pindell, 1986; Draper and Barros, 1987; Calais and Mercier de Lépinay, 1990). Both are thick detrital series of sandstones and shales with some conglomerate beds and lignite and gypsum layers. They are Late Eocene to Early Miocene (Aquitanian) in age and end with more carbonated facies (Upper Oligocene to Aquitanian Las Lavas Formation in Dominican Republic, DeZoeten and Mann, 1991; Calais *et al.*, 1992; Lower Miocene (Aquitanian ?) Majimiana Formation in Cuba, Cobiella *et al.*, 1984; Calais and Mercier de Lépinay, 1991). In northern Haiti, the Oligocene to Early Miocene period corresponds to the deposit of the Trois Rivières series (Vila *et al.*, 1986). Throughout the northern Caribbean Domain, this period is characterized by a quiet tectonic regime with basin subsidence. The basin's detrital infilling comes from the erosion of the topography uplifted during the Late Eocene tectonic crisis.

c. The Early Miocene is marked by a new tectonic pulse in the northern Caribbean. This tectonic crisis corresponds to east–west folding throughout northern Hispaniola. In northern Dominican Republic, the Burdigalian to Langhian series unconformably overlies the folded Altamira Formation (DeZoeten and Mann, 1991; Pindell and Draper, 1991; Calais *et al.*, 1992). Along the northern Haitian coast, the tectonic event is marked by the deposit of a significant intra-Lower Miocene olistostrome, the Roches Contrées series (Vila *et al.*, 1986). In the Terre Neuve range (Haiti), the Middle Miocene rocks (NN5 biozone) unconformably overly the lower part of Lower Miocene (NN2 biozone; Vila, pers. comm., 1990). On the southern flank of the Massif du Nord of Haiti, upper Burdigalian to Langhian marls and sandstones unconformably overlys Aquitanian to Burdigalian platform carbonates (Boisson, 1987). In southern Cuba, the Lower Miocene does not correspond to folding; however it is marked by the cartographic unconformity of the Imias Formation (Calais and Mercier de Lépinay, 1991). Besides this major tectonic event in the northern Caribbean, the Early Miocene locally corresponds to strong erosion or tolack of sedimentation. In southern Cuba, no sedimentation seems to occur between the Aquitanian (Majimiana Formation) and the Serravalian (Imias Formation). In northern Haiti, a strong erosional phase is known to take place between the upper part of Early Miocene and the lower part of Middle Miocene (Dubreuilh, 1982; Desreumaux, 1987). These local erosion or non-sedimentation phases can be related to tectonic uplifts due to compressive deformation during the Early Miocene.

d. From Middle Miocene to Late Pliocene, the sedimentation is characterized by clastic deposits, probably as a result of the erosion of areas that were uplifted during the Early Miocene tectonic phase. Clastic facies appear in the Middle Miocene in the Plateau Central of Haiti (Dubreuilh, 1982; Desreumaux, 1987) and in the Presqu'ile du Nord Ouest (Rivière Moustique deltaic series; Vila *et al.*, 1986). In southern Cuba, the clastic carbonate series of Imias starts in Serravalian, overlying the neritic limestones of the Majimiana series. In northern Dominican Republic, the transition occurs between the carbonated Las Lavas/Jicome formations and the detrital Cercado/Villa Vasquez formations. A tectonic unconformity between Langhian and Serravalian has been observed in northern Dominican Republic (Calais *et al.*, 1992) and in northern Haiti (Vila *et al.*, 1986), corresponding to a small folding event within Middle Miocene, around 12 Ma.

e. The Late Pliocene, as the Early Miocene, is a period of revival of tectonic activity in the northern Caribbean. Along southern Cuba, it corresponds to intense normal faulting, determining the present-day morphology of the coastline (Calais and Mercier de Lépinay, 1991). In northern Dominican Republic, the Late Pliocene event is responsible for intense transpressive deformation with folding and reverse strike-slip faulting (DeZoeten and Mann, 1991). It corresponds to the beginning of the Cordillera Septentrional uplift (Redmond, 1982; Eberle *et al.*, 1982; Edgar, 1992; Calais *et al.*, 1992). In Haiti, this tectonic activity is responsible for faulting and uplifting of quaternary reef terraces along the northwestern coast facing the Windward Passage and the Tortue Channel (Sorel *et al.*, 1991; Mann *et al.*, submitted). Since this succession of tectonic and sedimentary events are coeval on both sides of the Windward Passage, we propose to correlate the seismic sequences recognized at sea according to this onland timing, as follows:

1. The last onland tectonic event is Upper Pliocene in age. We correlate it with the last tectonic event observed at sea, i.e. the beginning of strike-slip faulting in the middle of the Windward Passage Sill and along the Imias Basin's northern edge.
2. We correlate the small Middle Miocene tectonic event with the unconformity between A′ and A sequences. In the Windward Passage, as well as in Cuba, this event is not marked by compressive tectonics, but corresponds to a strong transgressive phase. We thus propose the A sequence to be Serravalian to Present in age.
3. We correlate the Lower Miocene tectonic event with the folding event observed between the B and A′ sequences. The erosional phase recognized on land corresponds to the erosion of the B sequence anticlines identified in the Windward Passage Sill area. We thus propose the A′ sequence to be Burdigalian to Langhian in age and the B sequence to be Oligocene to Aquitanian. An alternative solution would be to interpret the top of the B sequence as the mark of the Upper Eocene tectonic event. In this case, A′ would be the Altamira-Maquey equivalent and the base of A would mark the Lower Miocene gap observed in Cuba. However, the Upper Eocene tectonic event is responsible for strong folding and reverse faulting that is not in accordance with the smooth deformation pattern of the B sequence.

Although this proposed correlation is not based on direct sampling, it allows us to assign a coherent tectonic and paleogeographic evolution of the entire northern Caribbean Plate boundary zone from Cuba to Hispaniola for the Neogene. On the northwestern Hispaniola Margin, Dillon *et al.* (1992) also identify three prominent reflective horizons in the Hispaniola Basin (Q, R and T). They separate four seismic sequences that show great facies similarities with the sequences that we defined in the Windward Passage area:

1. The Q-R sequence displays “strong, parallel and continuous reflections”, as the A sequence;
2. The R-T sequence displays “weaker, parallel but discontinuous reflections broken by diffractions”, as the A′ sequence;
3. Below T, the sequence displays “higher amplitudes, lower frequency, coherent reflections”, as the B sequence.

Thus, the T and R horizons could correspond to the B-A′ and A′-A interfaces, respectively. This correlation would assign a 20 Ma age to the T horizon and a 12 Ma to the R horizon. Dillon *et al.* (1992), however, interpret T and R as 40 and 20 Ma in age, respectively.

Conclusion: A Plate Kinematic Reconstruction (Figure 24)

Tectonic and stratigraphic correlations between both sides of the northern Caribbean Transcurrent

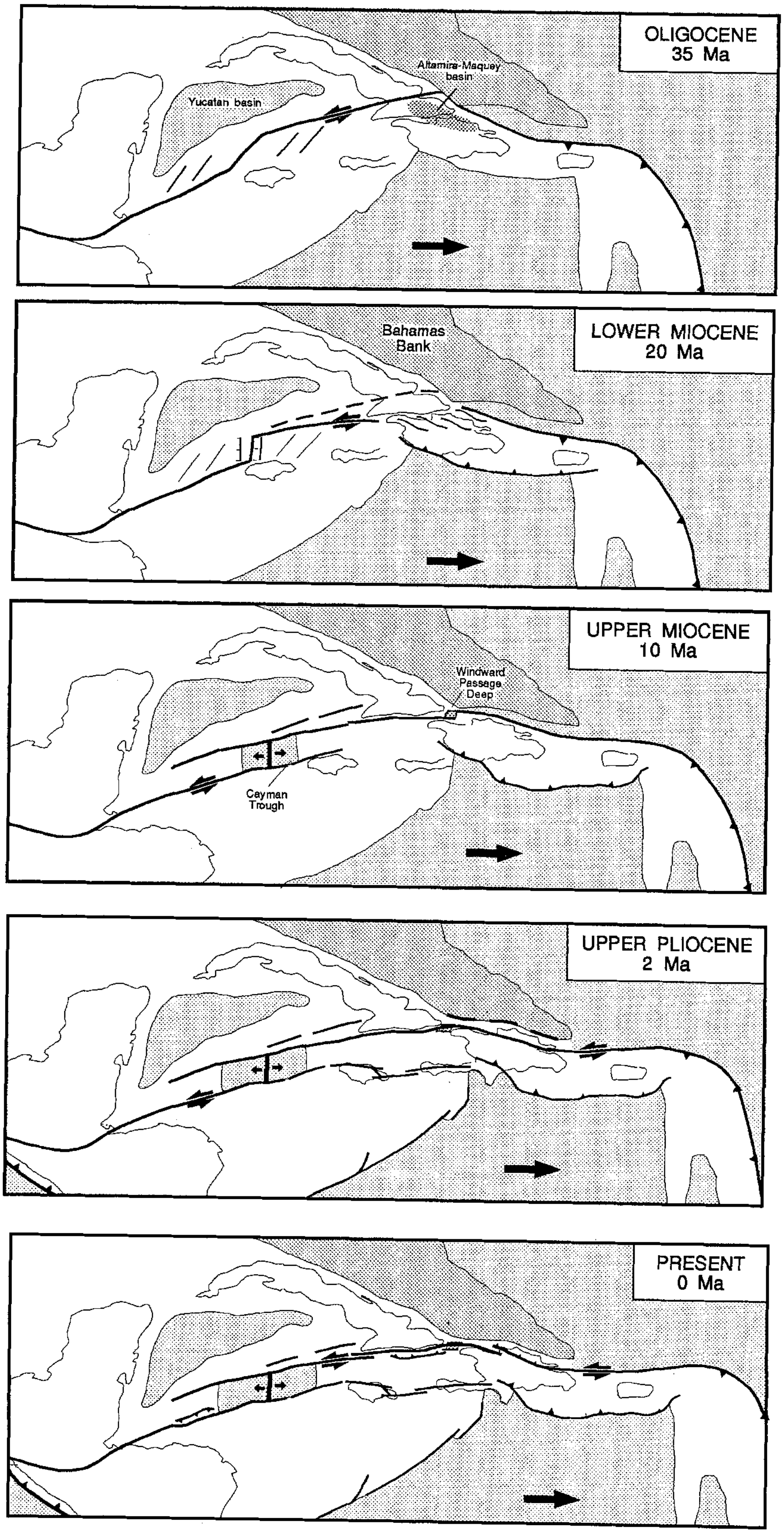


Fig. 24. Kinematic reconstruction for the northern Caribbean during the Cenozoic, based on the data presented in this paper and on Pindell *et al.* (1988), Pindell and Draper (1991), and Mann *et al.* (1992).

Plate boundary in Cuba and in Hispaniola, show that these two blocks follow the same paleogeographic and structural evolution until the Lower Miocene (Pindell, 1986; Draper and Barros, 1988; Calais and Mercier de Lépinay, 1990). The deposit of the Maquey Formation in Cuba and of the Altamira Formation in northern Dominican Republic probably occurred in a single sedimentary basin, isolated from major oceanic circulations. We therefore believe that Cuba and Hispaniola were part of the same tectonic block until around 20 Ma and were not offset by the Oriente Fault before this time, as also proposed by Pindell and Barrett (1990). From 20 Ma to the present this major transcurrent fault is formed and shifts Cuba and Hispaniola apart by 400 km of left-lateral motion. The average motion rate of 2 cm yr^{-1} is in accordance with the rate deduced from the Cayman Trough magnetic anomalies (Rosencrantz *et al.*, 1988). The Late Eocene to Early Miocene period corresponds to the deposit of the B sequence which is the equivalent of the Maquey and Altamira formations. At this time, the Windward Passage Deep does not exist.

The major tectonic event recorded around 20 Ma in the northern Caribbean probably corresponds to the initiation of strike-slip faulting between Cuba and Hispaniola (Pindell and Barett, 1990). We interpret the folding of the B sequence and of the Oligocene rocks of Hispaniola as the expression of a new stress pattern due to the creation of a new strike-slip plate boundary configuration in the northern Caribbean. Since the B sequence is not folded either in the Imias Basin or in the Hispaniola Basin (according to our interpretation of Dillon *et al.*'s (1992) T and R horizons), we propose the deformed area to be a push-up between two strike-slip segments. Once southern Cuba collided with the Bahamas Bank (Early Miocene; Pindell and Barrett, 1990), the northern strike-slip segment was abandoned and the strike-slip motion jumped to the south, between Cuba and Hispaniola. When this new fault was activated, folding stopped in northern Hispaniola and in the Windward Passage. Anticlines were eroded and the erosion products filled up the syncline basins. Some sinistral offsets in the strike-slip plate boundary trace may create a local tensional tectonic regime which is the explanation that we propose for the Windward Passage Deep. This basin was probably an active subsiding pull-apart basin from Early Miocene to Late Pliocene (A and A′ seismic sequences), located on a relay in the Oriente Fault trace during this period. Since northern Hispaniola (the present-day Cordillera Septentrional of Dominican Republic) was formerly close to southern Cuba, the transcurrent plate boundary must have been located north of Hispaniola during the Miocene and Pliocene.

The Late Pliocene (around 2 Ma) marks the shift to the present-day paleogeography and tectonic regime in the whole northern Caribbean Domain. The subsidence of the Windward Passage Deep stops and the strike-slip fault system takes on a new configuration with a single fault running straight through the middle of this basin into the Tortue Channel. At the same time (2 Ma), northern Hispaniola undergoes a dramatic uplift. Transpression along a major strike-slip fault in northern Dominican Republic leads to the uplift of the Cordillera Septentrional. This fault corresponds to the onland continuation of the new transcurrent fault system that crosses the Windward Passage and runs to the east through the Tortue Channel and along the Haitian coast. The previous location of the major strike-slip faults along the southern edge of the Hispaniola Basin is abandoned and strike-slip motion is shifted to the south, along the present-day trace of the plate boundary. This process could be related to the collision of Hispaniola against the Bahamas Bank in the Late Pliocene, that would have locked up the strike-slip motion in the Hispaniola Basin and resulted in the Cordillera Septentrional uplift as a tectonic response to the new plate boundary configuration. During the Quaternary (Dillon *et al.*, 1992), the former strike-slip fault along the Hispaniola Basin is reactivated as a reverse fault and accounts for the small north–south convergence between Caribbean and North America.

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