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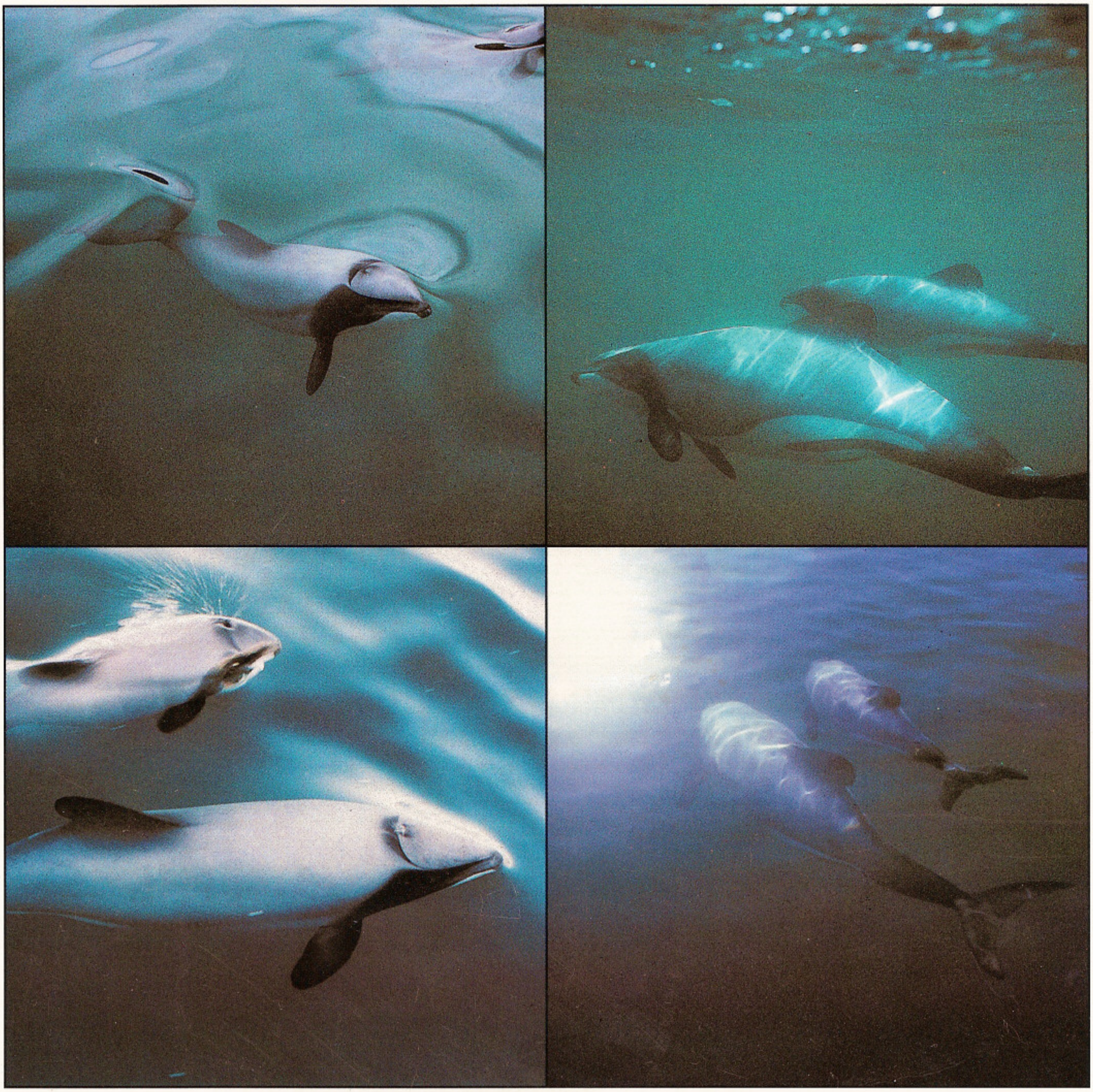

Vortex Structures and the World-Encircling Vortex Street: Case Study of the South Adriatic Basin

PAPER

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ABSTRACT

Based on the newer surge tectonic hypothesis, the vortex feature is immediately recognizable. Defining the present evolution of a vortex structure by analyzing the GEOSAT data base, 3.5 kHz reflection profiles, and available bathymetry shows the South Adriatic Basin to be in a state of rotation and subsidence. Acoustic characters define fault trends and compression zones, with faults trending ESE across the basin. A time-sequence analysis of the regional earthquake data around the vortex structure also shows clockwise rotation. The Adriatic vortex is an integral part of the currently active, equatorial world-encircling vortex street, a geostream of vortex and eddy structures interconnected by active surge channels.

INTRODUCTION TO THE THEORY OF THE EVOLUTION OF A VORTEX STRUCTURE

A 1988 symposium at Texas Tech. University (Chatterjee and Hotton, 1992) addressed the current hypotheses of earth dynamics. The gist was that the plate-tectonic hypothesis could not address many problems. To begin with, spurious to nonexistent bathymetry were used to prove the plate-tectonic hypothesis. Much better data sets were available from at least 1974, but were ignored (Smoot and Meyerhoff, 1995; Meyerhoff *et al.*, 1996a). Detailed mapping of the structural trends in the ocean basins verify this. Another example is that mid-ocean ridge magma flow is along-strike, not perpendicular to the ridge. Other problems pertaining to the plate-tectonic hypothesis include: (1) mantle diapirs, (2) distorted tectonic lines such as orthogonally intersecting and braided, anastomosing fractures, (3) aseismic oceanic ridges, (4) vortex structures, (5) dike swarms, (6) low-velocity zones in the lithosphere, (7) the fluctuating gravity field, (8) the failure of the magnetics measurement in many magnetic quiet zones, and (9) anomalous rock ages all over the ocean floor (based in part on Meyerhoff *et al.*, 1992).

One geodynamics hypothesis uses a cyclic contraction and expansion, a pulsating Earth which goes through four evolutionary stages (Wezel, 1988): (1) krikogenesis (expansion) spin-minimum time is characterized by crustal swelling and rifting, (2) oceanization when the continental crust is undergoing remobilization and destruction, (3) tectogenesis, done at the contraction spin-maximum, is characterized by orogenic compression and root formation, and (4) epirogenesis, or emergence, is characterized by reintegration of the continental crust.

The changing radius of Earth is shown by the weakening universal gravitation gradient (Smirnoff, 1992). During times of contraction, orogenies follow the Mega-Omega extinctions and magnetic reversals with low magnetic fields between occur. (Mega extinctions coincide with major orogenies, such as the Taconian, Uralian, etc. They are all in the past. The Omega extinction is reserved for us in the future.) This concept is connected to high levels of heat radiation with unusually strong mafic volcanism. All things being equal in the conservation of angular momentum, as Earth's radius decreases the acceleration is increased during the contraction cycle and days become shorter. Conversely, as Earth's radius increases deceleration occurs during the expansion cycle and days get longer. Not only does that reinforce Wezel's theory above but it also lends verisimilitude to the following surge tectonic hypothesis.

Now evidence exists in the lithosphere and upper mantle of pipe-like, tubular, or lens-like hot bodies that are interconnected (Meyerhoff *et al.*, 1992). The hot, lenticular bodies are called surge channels, occurring at depths of between 50 km and the asthenosphere. The surge channels underlie foldbelts, rift zones, and strike-slip zones. The surge channels are alternately filled and emptied in a sequence called the geotectonic cycle. During a period of quiescence, or taphrogenesis (Wezel's krikogenesis), the surge channels are completely filled and ocean basins are formed, similar to seafloor spreading. This phase is the cause of Earth's expansion. During a period of activity, or tectogenesis, contraction and compression occur and the ocean basins are partly destroyed, similar to subduction.

The entire system still needs a driving force. Seismotomography has shown that organized convection, one of the assumed driving forces of the plate tectonic hypothesis, does not exist in the mantle (Anderson et al., 1992). Many others have already shown us that the subducting slab cannot pull plate tectonics because the slab is segmented at the lithosphere-asthenosphere interface (Benioff, 1954). In fact, the subducting slabs at depth bend landward (Hasegawa *et al.*, 1991). Removing the driving forces theorized to drive the plate-tectonic hypothesis leaves a major void in that explanation. However, a combination of the above hypotheses gives the driving forces as expansion/contraction, rotation, and gravity.

Using those forces, the geotectonic cycle of the surge tectonic hypothesis is described (see Meyerhoff *et al.*, 1996a for a more robust discussion) whereby: (1) Contraction of the mantle (strictosphere) is always occurring because Earth is always cooling. (2) The already cool, overlying lithosphere adjusts its basal circumference in discrete pulses by large-scale thrusting, or subduction, along lithosphere Benioff zones and normal-type faulting along the mantle Benioff zones. (3) Thrusting of the lithosphere is not continuous, occurring only when the underlying support fails. When the weight of the lithosphere overcomes both the Benioff zone friction and the pressure applied from below by the asthenosphere, the lithosphere collapses. (4) During periods of lithospheric stability, or anorogenic intervals, the asthenosphere volume increases slowly as the strictosphere radius decreases and decompression of the asthenosphere begins. (5) Decompression is accompanied by rising temperature, increased magma generation, and lowered viscocity in the asthenosphere. (6) During lithosphere collapse into the asthenosphere, the landward sides of the Benioff zone obduct the ocean floor. Lithosphere at the Benioff zone buckles, fractures, and founders. Enormous compressive stresses are produced by this action in the lithosphere. (7) When the lithosphere collapses into the asthenosphere, the asthenosphere-derived magma begins to surge in the overlying surge channels intensely. Where that volume exceeds the normal carrying capacity, and when the compression in the lithosphere exceeds the strength of that lithosphere directly overlying the surge channel, the surge channel roofs rupture bivergently along-strike in cracks that comprise the fault-fracture-fissure system generated before the rupture. (8) Once tectogenesis is complete, another geotectonic cycle sets in, usually within the same belt.

Obeying the physical laws of fluid dynamics, the result of surge channel flow is a series of eddies caused by disturbances in the flow pattern or rate. When the eddies become larger in size, they are called vortex structures. The avenue for the growth of a vortex structure is the intersection of two or more surge channels, an analog of which is the highway roundabout. If the channels are actively carrying magma, and if they intersect at a discrete point, there is only a finite amount of space for which this abundance of magma can collect. The surge channels are deflected, either clockwise or counterclockwise, until the excess magma finds an outlet. This is either in two forms. In regions of positive gravity geoid where the stress is released either upward or horizontally, the vortices appear as seamounts, rises, or plateaus (Smoot, in review). In regions of negative gravity geoid where the stress is relieved either downward or horizontally, the vortices appear as basins with whorl-pattern features surrounding them. The entire sequence, the vortices and the interconnecting surge channels, is interchangeably called a vortex street or geostream. Earth pulsations of various periods generate these surges and affect the vortex structures and geostreams in predictable ways (Leybourne, 1996).

Geodynamic tectonic flow obeys the laws of fluid dynamics, so a comparison can be made relating this flow to ocean and atmosphere flow. Atmospheric jetstream flow is analogous to the Gulf Stream or Kuroshio Current flow structure in oceans, in another word, aquastreams. These are in turn analogous to horizontal upper asthenosphere tectonic flow or geostreams, which create surface trends in the crust. The high/low pressure cells in the atmosphere are analogous to cold/warm core eddies in the oceans and downwelling/upwelling vortex structures in Earth's crust and mantle. Weather fronts are analogous to Kelvin/ Rossby waves in the oceans, or oceanic fronts. These fronts are simply pressure/temperature waves moving through their corresponding medium and in the upper mantle are called surges, gravity waves, or tectonic fronts (Leybourne, 1997).

An immediate plate-tectonics problem is presented. While vortex structures had been previously discovered (Kober, 1921), they did not fit into the plate-tectonics hypothesis because no mechanism exists that will produce a vortex structure. Nevertheless, vortex structures are ubiquitous. Many terrestrial vortices were known: the Pannonian Basin, Lake Victoria, the Dasht-e-Lut depression in Iran, the Deccan Traps, and the Columbia River flood basalts. Topography shows them to be large, ovate oval-to-circular regions up to 1000 km in diameter (Meyerhoff *et al.*, 1992).

Multibeam bathymetry and satellite altimetry data now allow a closer look at the seafloor. As an example, the North Pacific Vortex resides in the region of the Hess Rise/Emperor Fracture Zone/Emperor Seamounts (Smoot, 1997). Bathymetry and gravity data show at least three eddies. In a surge tectonic framework, vortex structures are variously called fracture zone offsets, channel offsets, and vortex structures themselves, the difference being one of size (Meyerhoff *et al.*, 1992). Fracture zone offsets, or transform faults on ridges, are related to constrictions in the surge channel. Channel overlaps are eddy structures, or overlapping spreading centers, which form during channelparallel movement. Eddies are represented by the three sub-vortices, or eddies, in the North Pacific Vortex, the San Clemente fault zone (Legg *et al.*, 1989), the San Francisco Bay, and many others. Vortex structures occur where one surge channel intersects another at a large enough angle to cause an eddy. They also form at continental margins where the roots are too deep to permit passage and at Benioff zones.

Multibeam bathymetry describing vortices in the literature includes the North Fiji Basin (Auzende *et al.*, 1988), the Easter Island "microplate" (Searle *et al.*, 1989), the Aegean Sea (Meyerhoff *et al.*, 1996a), the North Pacific Vortex, and the Horseshoe Seamount vortex structure off the coast of Portugal (Smoot, 1997).

In general, the downwelling vortex usually displays bathymetry leading to a whorl pattern or across-basin fractures dominated by a major depression. From a geophysics standpoint, vortices are also recognizable by excessive microearthquakes, volcanic and hydrothermal activity, high heat flow, and jumbled gravity and magnetics lineations. Most of the vortices of the world's ocean basins are shown in figure 1.

MATERIALS AND METHODS

The Naval Oceanographic Office (NAVOCEANO) has extensive survey data of much of the world's ocean basins. Multibeam sonar data of the South Adriatic basin has been combined with 3.5 kHz seismic data (Leybourne *et al.*, 1995). This combination has given a surface view of a rotational basin or vortex structure.

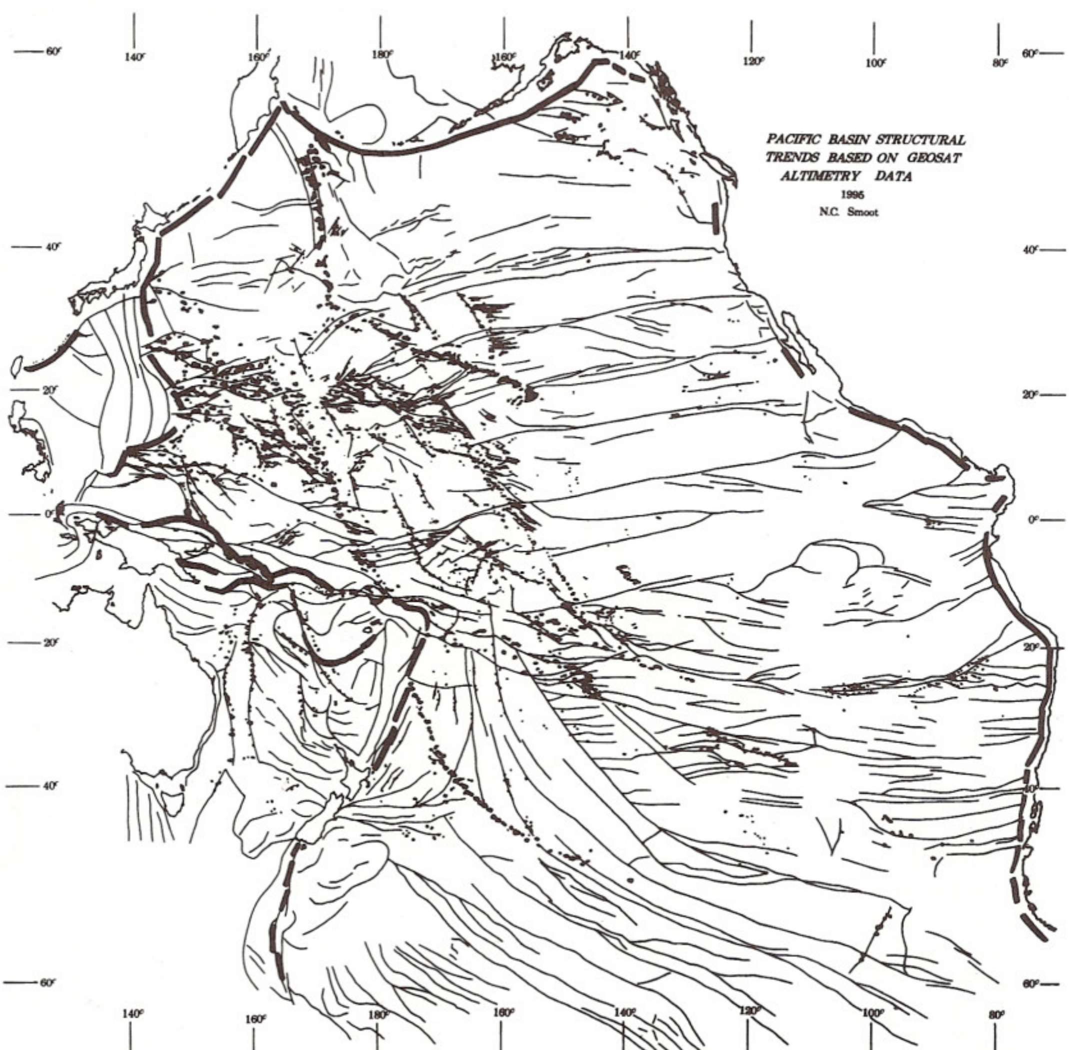
The determination of that rotational direction is made by a time-sequence analysis of earthquake data from the Italian Telemetered Seismological Network (ITSN) collected between 1985 and 1990. A regional overview of the Mediterrenean basin shows several more vortex structures based on the earthquake information from the National Geophysical Data Center (NGDC) of events between 1964 and 1990.

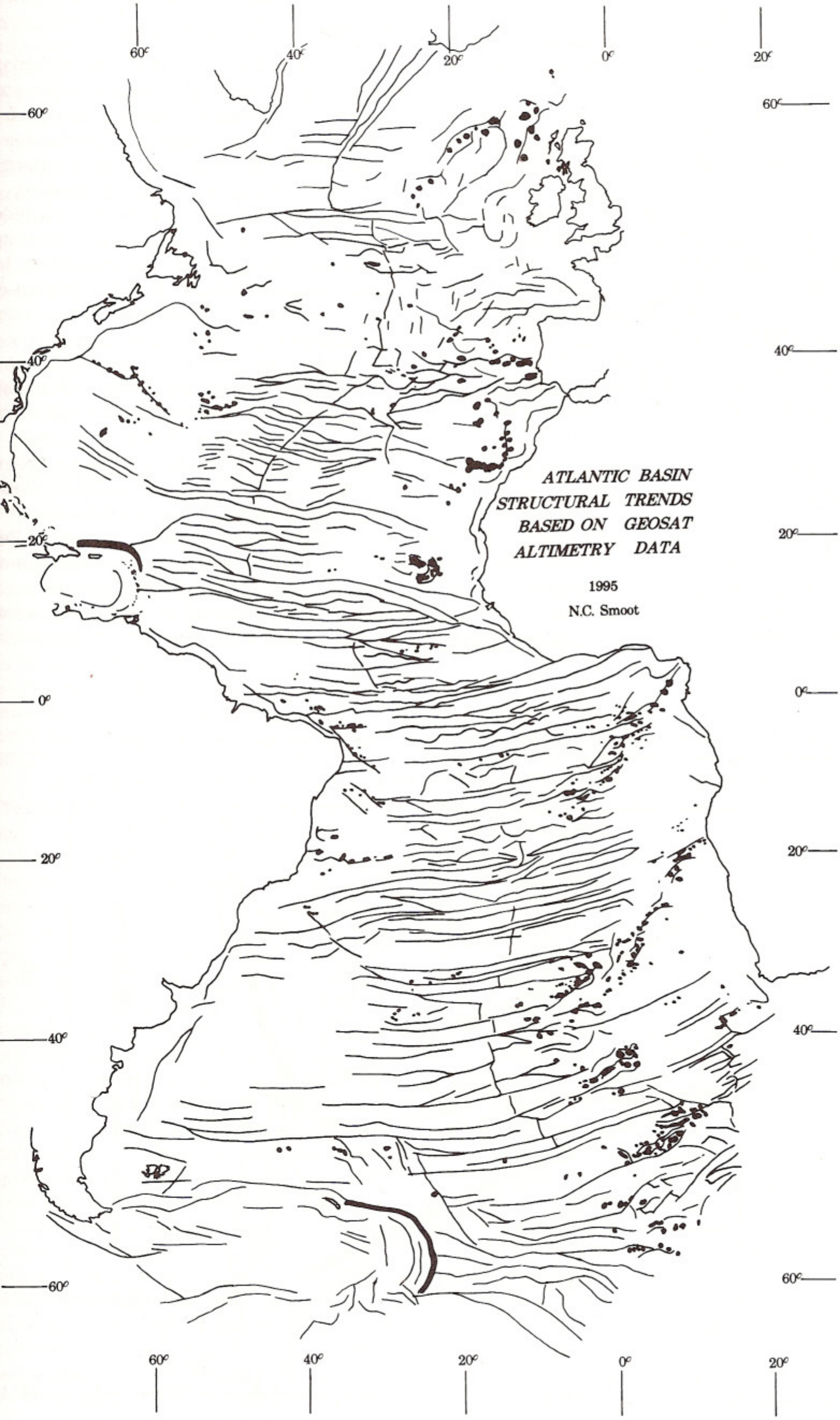
A recent development has led to a breakthrough in regional interpretation; indeed, worldwide interpretation. The Navy's classified GEOSAT satellite altimetry data has been made public (figure 1). The geodetic mission extended over an 18 month period from

Figure 1. GEOSAT total field showing the positive and negative geoid. Vortex structures exist at all of the enclosed anomalies.

April 1985 to October 1986 (Cheney *et al.*, 1989). The ground tracks lie within three km of each other. In 1989, NAVOCEANO produced a worldwide, 5-minute gridded GEOSAT data base using approximately 8000 of the world-orbiting satellite revolutions. The data were manually edited to remove obvious spikes and noise, misadjusted tracks, and segments over polar ice. This collector measured the marine geoid height to determine the gravity geoid, since undulations in the geoid are caused by changes in the local gravity field (Christou *et al.*, 1989). NAVOCEANO geophysicists produced an algorithm that applied a two-dimensional high-pass filter to the gridded GEOSAT data file, creating a filtered data set (Sramek, 1992). The filter extremes were set to pass data at wavelengths over 125 nmi and less than 70 nmi. An along-track filtered data set provided a less noisy presentation for NAVOCEANO's purposes. With certain exceptions the changes correlate well with bathymetry (Vogt and Jung, 1991), and that is the value of the GEOSAT data. As a result, many new uncharted features have been found. At NAVOCEANO, these trends are used to help drive the contours where needed, especially on long, linear features such as ridges and valleys. Essentially, the GEOSAT data have twice the accuracy of the initial SEASAT information originally compiled in 1986 (Haxby, 1987). While bathymetry cannot be deduced from satellite altimetry data at this time, the structural trends on the ocean basins can (figures 2 and 3). The high-pass filtered 5-cm GEOSAT yields the basin-wide fracture trends. These have been ground-truthed for the North Atlantic basin by comparison with the

Figure 2. Pacific basin structural trends based on the high-pass filtered 5-cm GEOSAT data base. The presence of these negates the plate-tectonic hypothesis alone.




ATLANTIC BASIN
STRUCTURAL TRENDS
BASED ON GEOSAT
ALTIMETRY DATA
1995
N.C. Smoot
60°
40°
20°
0°
20°
60°
40°
20°
0°
20°
40°
60°

Navy's SASS multibeam sonar data (Smoot and Meyerhoff, 1995), so we extrapolate this to the regions of little or no bathymetry data.

The 5-minute grid, contoured at a 1-meter interval, gives the total gravity field of all the seafloors (figure 1). Not only does this figure show the positive and negative geoid regions, it also shows large and small vortical structures, which are the basis for the vortex street.

The combination of bathymetry, 3.5 kHz reflection profiles, earthquake data, and satellite altimetry is now presented to show the evolution of an actual vortex structure, the South Adriatic Basin. Once the guidelines have been established for vortex identification, other vortex features are easily located worldwide and connected by the active surge channels to define the world-encircling vortex street.

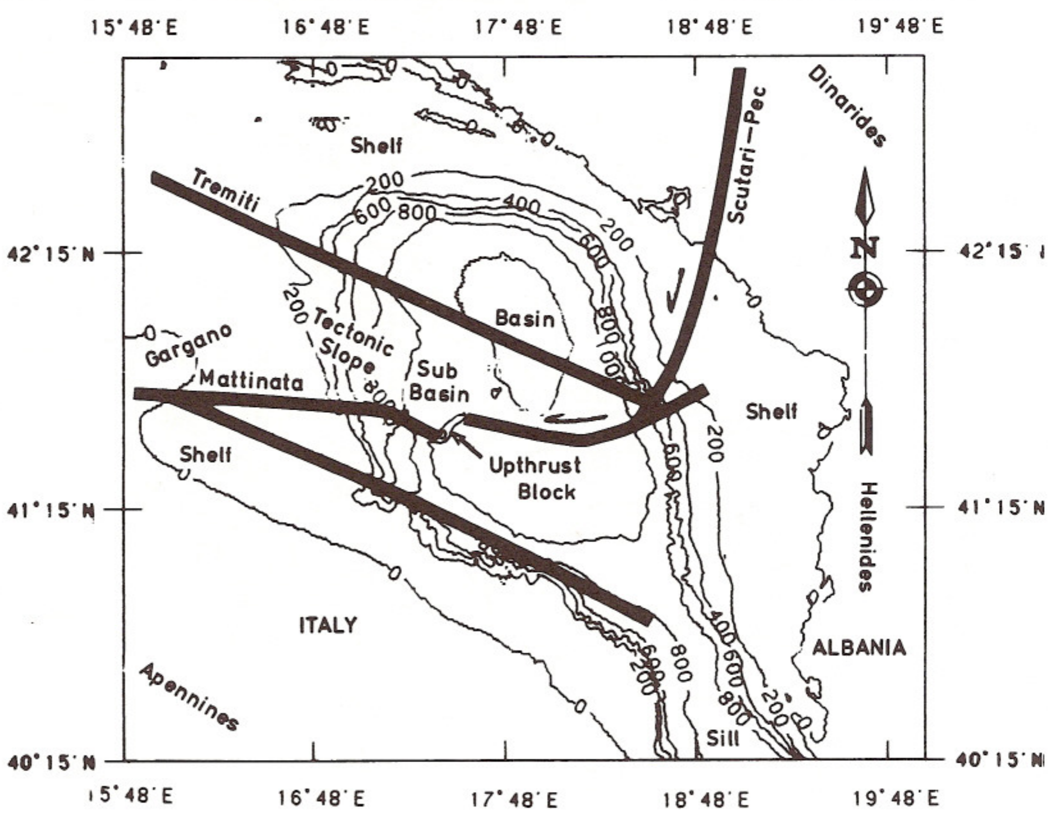
THE SOUTH ADRIATIC BASIN VORTEX STRUCTURE

A new vortex is introduced. Multibeam sonar bathymetric data covering the South Adriatic Basin were gridded and contoured (figure 4). Seismic data show the basin to be very active tectonically, and the acoustic data lend supporting evidence for clockwise rotation and subsidence in this region.

1. Physiographic Province

Geomorphology of the South Adriatic Basin (1200m depth) is dominated to the north and east by escarpments plunging steeply from about 450m to 800m (figure 4). This has been considered by other authors to be a surface expression of overthrust faulting, from the Dinardines to the NE and from the Hellenides to the SE. Several authors, who base their interpretation on the plate-tectonic hypothesis, have presented the Adriatic Region as a portion of continental lithosphere located between two facing subduction systems (Jackson and McKenzie, 1986; Anderson, 1987; Royden *et al.*, 1987; Moretti and Royden, 1988). The Apennine thrust belt to the SW, trending through central Italy, is the subduction system facing the Dinardines and Hellenides subduction systems. Furthermore, the Dinardines and Hellenides systems are segmented by several zones of strike-slip faults. One system, the Scutari-Pec fault zone (figure 4), dissects the eastern escarpment at approximately 41°35′N latitude (Finetti, 1982; Finetti *et al.*, 1987). This location is a fault system juncture between the Scutari-

Figure 4. Bathymetry of the South Adriatic basin at a 200-m contour interval (Leybourne et al., 1995).



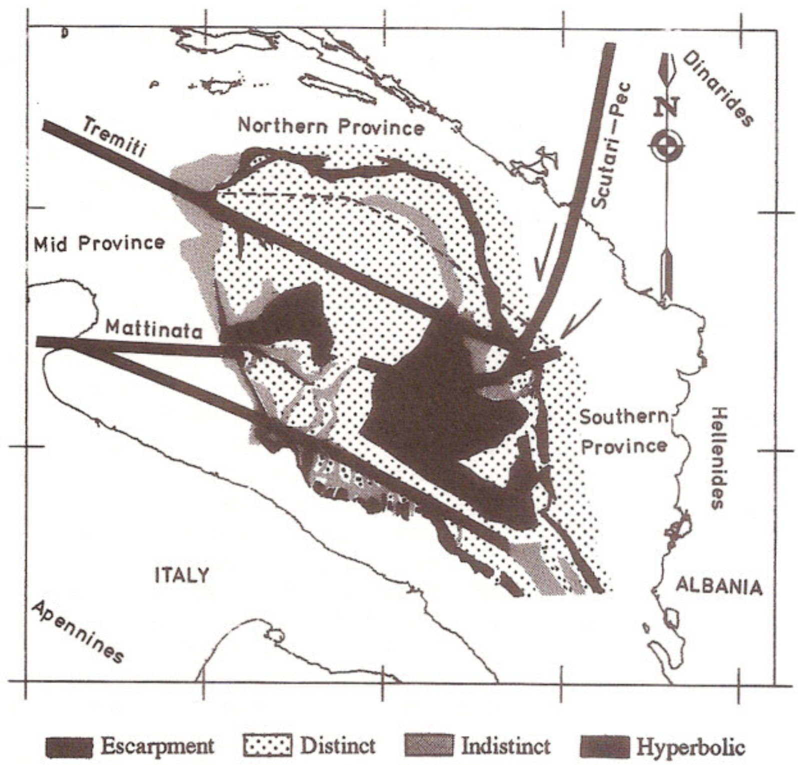
Pec, Tremiti, and Mattinata fault systems. From the west side of the basin, extensions from the Gargano headlands seaward of the Tremiti and Mattinata fault systems (Finetti, 1982; Finetti et al., 1987), dominate the fault-controlled geomorphology and surface acoustic characteristics of the basin (figures 4 and 5). Beginning in the Tertiary, these fault systems have been strike-slip, as learned from micro- and macrostructural investigations (Montone and Funiciello, 1989), and from recent offshore well data and seismic profile interpretation (Ricchetti, 1980; DeDominicis and Mazzoldi, 1987; De Alteriis and Aiello, 1993). Structural evidence, with analysis of surface acoustic data, suggests that these fault systems are still active, cutting all stratigraphic series (DeDominicis and Mazzoldi, 1987).

2. Evidence of Bathymetric Change Through Acoustic Analysis

Fault zones trending ESE from the western shelf break (200m) subdivide the basin into three general acoustic provinces based on tectonic stability. The Tremiti fault divides the northern province from the mid province, while the Mattinata Fault divides the mid province from the southern province. The tectonic division of these provinces is very significant because they exhibit varying degrees of tectonic stability which is reflected in the surficial acoustic data.

In the northern province, extension of the Tremiti Fault from the shelf break at 42°15′N latitude causes the northern escarpment to turn SE along the fault trend in the NW corner of the basin (figure 5). The Tremiti Fault shows no recent signs of disturbance to the northwest in surface acoustic signatures. Farther to the SE it merges into the Scutari-Pec Fault system (Finetti, 1982; Finetti *et al.*, 1987). The Tremiti Fault system is the southern boundary for the northern surface acoustic province. Currently this province is the most tectonically stable region in the basin. This interpretation is based predominantly on the distinct acoustic character (or lack of disturbed sediments along the Tremiti Fault) of the province. Although there was no data north of the dashed line (figure 5), acoustic character was inferred from bathymetric trends. In the SE corner of this northern province, a wedge of acoustically complex hyperbolic sediments, generally covered with fine silts in the deep basin, pinches out northward along an acoustically indistinct slope. This is interpreted to be a region of deep basin compression against disturbed sediments on the lower slope due to clockwise rotational and subsidence forces acting near the juncture of the Tremiti and Scutari-Pec Fault systems.

Figure 5. Surface sediment general acoustic characteristics of the South Adriatic basin (Leybourne et al., 1995).



The mid province of this basin, separated by the Tremiti Fault to the north and the Mattinata Fault to the south, is the most complex and tectonically unstable region. These fault boundaries tectonically control the slope in the NW sector of the province where the slope is actively subsiding clockwise along the Mattinata Fault. The Mattinata Fault strikes SE from the western shelf break at 41°40′N latitude and creates an active escarpment that terminates as the fault is offset by an upthrust block. This block is characterized by a very distinct hard acoustic reflection. The Mattinata Fault then crosses the basin southeastward in a sinuous path as it also merges with the Scutari-Pec Fault zone. It is characterized by offsets in map view of surface sediments (figure 5). This lends evidence for very recent strike-slip clockwise movement of the mid province relative to the southern province. Indistinct acoustic zones which trend along the base of the fault-sheared escarpment follow the fault trend as it curves between the subbasin at 1100m and the upthrust block. This suggests a recent zone of subsidence along the southern edge of this tectonically controlled slope, a slope that is characterized by a fairly stable area to the north and west as indicated by distinct surface acoustics. Moving SE and down the slope, an indistinct zone indicates sediment transport downslope by gravity sliding and slumping. The net result of mass wasting is to compress sediments on the lower slopes, causing a wedge of hyperbolic sediments to be pinched between these downslope-moving sediments and the escarpment. An anomalous zone of distinct sediments lies below the active escarpment and just above (to the east) the subbasin which is probably the result of active current transport of sediments from the upper escarpment. The subbasin itself exhibits a complex echo (fine silts covering hyperbolic and distinct acoustic reflections) similar to the ones found due east across the basin and just under the lower slope. The offset upper thrust block is interpreted as a resistant zone of Mesozoic carbonate platform limestones (DeAlteriis and Aiello, 1993) that have rotated upward and counterclockwise due to an offset along the fault trend. The zone of distinct sediments in the deep midsection of this province is an extension of sedimentation from the northern province and is due to low slope gradients and possibly higher depositional rates. Moving SE, a zone of acoustically complex hyperbolics is encountered, suggesting a zone of compression. As the Mattinata Fault begins its twist toward the Scutari-Pec Fault system, indistinct zones and offsets dominate the fault region juncture with interspersed distinct zones immediately downslope of the escarpment. The mid province is at an early stage of development and is evolving in a similar pattern to the more mature northern province.

The southern province is bounded to the north by the Mattinata Fault and to the south by a dissected escarpment trending SE. The escarpment is controlled by a main subvertical regional fault with a predominant dip-slip component which bifurcates from the Mattinata Fault system in the Gargano promontory (Favali et al., 1993). This main fault trends SE, breaking the western escarpment at 41°20′N latitude. Normal faults radiate and curve S-to-SE from the main SE-trending fault, dissecting the southern escarpment in many places as shown by indistinct zones of surface acoustic signature. Again, interspersed zones of distinct sediments underlie this escarpment. Just to the NE of this main fault region lies a NW-SE-trending zone of distinct sediments. This zone is broken by normal faults upslope to the NW as it nears the western escarpment. To the SE it merges with other zones of distinct patterns under the eastern escarpment. Two zones of distinct patterns lie in the deep basin. The one to the west of the upthrust block is an extension of distinct patterns from the northern, deepest basin. The other zone to the east is interpreted as a stable zone surrounded by shifting compressional forces, as exemplified by the surrounding complex hyperbolics. The most intense areas of recent hyperbolics occur just south of the Mattinata Fault, as it dips and turns eastward before merging with the Scutari-Pec Fault, and in zones trending along and below the eastern escarpment north and south of the Scutari-Pec Fault line. Most other complex hyperbolic areas are either completely or partially covered with silts or are interspersed with small indistinct areas and occasional acoustically distinct zones. Finally, the southernmost portion of this province, known as a sill, is the entrance/exit for all Adriatic waters. Surface acoustic characteristics of alternating distinct-in-distinct patterns probably reflect intense current scouring with low depositional rates along indistinct zones on the lower slopes. Slight deposition occurs under escarpments on both sides and along the central channel. Some tectonic shear component may exist in the indistinct zones, especially in the wide indistinct zone to the west, which may be an extension of the southern boundary faults.

Summarizing, a thorough analysis of detailed bathymetric and surface acoustic data show the geomorphology of the South Adriatic Basin to be tectonically dominated by a downwelling vortex. Surface expression of major fault systems subdivides the basin into three tectonically controlled provinces: (1) a mature and stabilized province exists to the north with recent tectonic activity occurring in the SE corner near a fault system juncture, (2) a mid province that is the most tectonically active, with surface expression of subsidence and clockwise rotation relative to the southern province along its southern boundary, and (3) a southernmost province that is characterized by active normal faulting with predominantly dip-slip components. It exhibits surface acoustic patterns of fault segmentation due to active subsidence along its northern boundary and other fault systems to the south. This evidence supports conclusions about recent clockwise rotation and subsidence mainly along the Mattinata and Scutari-Pec Fault systems.

3. Mechanism for Rotation of the South Adriatic Vortex

The surges through the Adriatic region are intermittent. The assumption implied is that a lack of seismic activity indicates a dormant period, while an increase of seismic activity indicates surge activity. A directly proportional relationship exists with increasing seismic activity directly related to increasing surge strength. The Adriatic vortex is a relatively small vortex along the vortex street and the breakout channel controlling its movements may not be reactivated during every small regional surge, but there is reason to believe the surge between 1985-1990 was a very strong event which may be correlated to strong Pacific surges between 1982-1983. Historically, the Adriatic has been known to have strong earthquake activity since the beginning of written records. The fact that Mesozoic carbonates within the basin (DeAlteriis and Aiello, 1993) are currently being subducted by the vortex, infers this vortex began sometime after the Mesozoic. Vortex structures discreet beginnings and endings by nature are difficult to define as they tend to be intermittent within most fluid flow dynamics, but a tectonic vortex as mature as the Adriatic basin with at least 1200m of subsidence would have taken geologic time frames with an order of magnitude of tens of millions of years to evolve.

Earthquake data collected between 1985 and 1990 by the ITSN (Console et al., 1993) have been analyzed by time sequence (Table 1). A vector diagram (figure 6) of these earthquakes plots a clockwise rotation pattern. Historically, a period of quiessence existed before the first seismic swarm in July-August 1985. The initial flow is shown by event 1. It moved NW along the Appenines, where a breakout occurred along vector 2, from 1986 through 1987. (A breakout channel occurs in gaps in the Benioff zone behind features called cusps. The trunk channel, ever seeking to flow in the direction of rotation, will follow the path of least resistance in that direction. An analog is the hole in the toothpaste tube. The trunk channel is the tube itself, and the breakout channel is a hole in the side. Frequently, features along the axis of the breakout channel will show an age progression. As an example, a prominant cusp exists where the Emperor Seamounts intersect the North Pacific Benioff zone.- authors). Between October and December 1986, the next seismic swarm occurred along vector 3, passing beneath the eastern Appenines. On July 3, 1987, a breakout occurred off that trend to the NE along vector 4a. This was the strongest event to date. Two days later surge forces produced event 4b. In general, most breakout channels flow preferentially eastward, so it was only a matter of time before a breakout was successful. On September 4 and 10, 1987, two more events opened an incipient breakout channel near events 5a and 5b. A 5.3 Richter scale event, number 6, opened the breakout channel finally in April 1988. This breakout moves across the South Adriatic Basin and merges with a SE-trending surge channel through the former Yugoslavia. By event 7 the breakout channel had completely opened surge channel circulation across the entire basin to the accompaniment of near-constant microseismicity. Since 1990 that has ceased, giving all indication of a temporary end to surge channel activity (Leybourne *et al.*, 1995).

The South Adriatic Basin vortex, by providing a framework to delineate vortex structures, is located in a region of negative gravity anomaly. Many of these anomalous regions exist so much so that locating the vortex street is now possible.

Table 1. Earthquake Epicenter Positions And Magnitude From 1985 to 1990 (Console et al., 1992 and 1993; Favali et al., 1993)

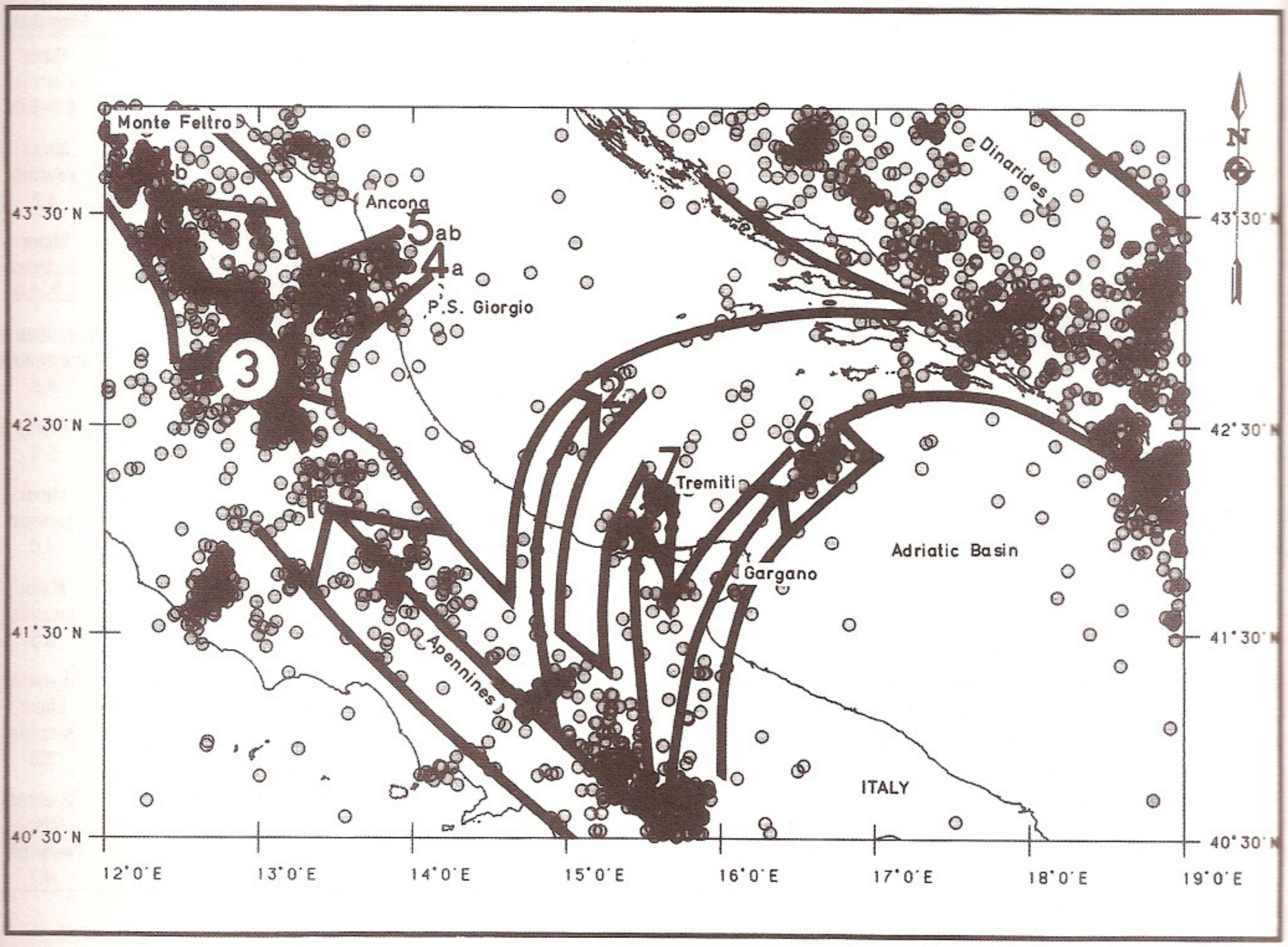
Event	Date	Position	Magnitude
1	July-August 1985	South of Ancona, Italy	Minor swarms 2.2–3.9
2	January 1986–January 1987	50 km north of Tremiti Islands	Minor swarms 4.2
3	October–December, 1986	South of Ancona, Italy	Minor swarms 2.2–3.9
4a	July 3, 1987	Off the coast of P.S. Giorgio, Italy	More than 80 aftershocks 4.9
4b	July 5, 1987	Monte Feltro, Italy	33 events > 2.3
5a	September 4, 1987	Off the coast of P.S. Giorgio, Italy	Minor swarms 4.0
5b	September 10, 1987	Off the coast of P.S. Giorgio, Italy	Minor swarms 3.8
6	April 1988	East-northeast of Gargano Promontory	81 events Minor swarms 5.3
7	October 1989–October 1990	Tremiti	33 events Minor swarms 4.7

THE WORLD-ENCIRCLING VORTEX STREET

The tools for mapping the asthenosphere flow structures or vortex streets are: (1) GEOSAT data, (2) concentrations of epicenters, (3) belts of microseismicity, (4) seismic reflection studies show cross-sectional depth, size, and location of flow structures, (5) seismic refraction studies map the velocity and activity of flow structures, (6) linear-trending surface basalts yield the ages of flow structures, and (7) perturbations of the magnetic and gravitational fields may indicate movement of subterranean fronts or movements in large scale flows.

These phenomena were collectively mapped in the 1980s (figure 7) to show the hot and cold regions in the surge channel depth range, from 50 to 150 km, which have been

Figure 6. Regional pulse map of the South Adriatic basin (Leybourne et al., 1995).

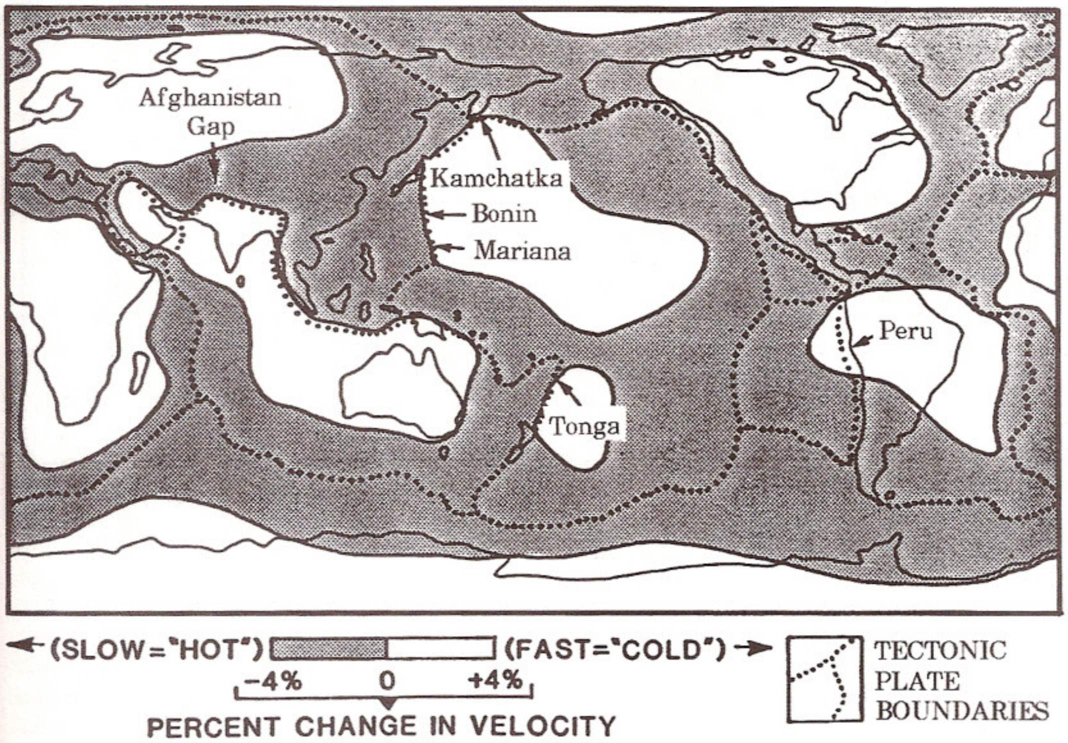


determined from seismic refraction velocities (Woodhouse and Dziewonski, 1984). In the interest of clarifying the surge tectonic hypothesis this figure is explained. First, the proposed driving force of plate-tectonics, convection cells, cannot exist as illustrated by the cold regions under the oceanic plates, especially in the central Pacific. The presence of fracture zones precludes the contiguous plate concept. Without a contiguous plate, no contiguous convection cell exists. In relation to figure 7, a heated convection cell cannot exist under the colder central Pacific basin. The fact that the central Pacific basin is cold is directly related to the presence of the Benioff zones, which act as a barrier to the eastward flow of the surge channels. This phenomenon is nowhere more evident than in the western Pacific, where the trench system from Kamchatka south through the Mariana trenches and the southern Tonga/Kermadec trenches are major dams. The older, deep-cratonal roots on most continents also act as dams. The street being discussed generally follows the hot, slow, equatorial dark zone.

The vortex street for our particular purpose has been delineated by the use of heat flow maps based on seismotomography (figure 7), the earthquake activity, and the GEOSAT data (figure 1). The surge channel/vortex street/geostream is continuous so this discussion begins with the South Adriatic Basin (figure 8a). For the purposes of this discussion, the particular vortices are consecutively labelled alphabetically.

As described, the South Adriatic basin is a clockwise, down-welling vortex. Earthquake data show the breakout channel flows off the northern portion of the vortex, intersecting the Dinardines and Hellenides surge channels. The geostream then flows southeast-ward until it intersects the primary surge channels at the Aegean Sea to create another vortex. The

Figure 7. Generalized seismotomographic map of the surge channel depth range from 50-150 km (Meyerhoff et al., 1992). The grey area is the hot region where the current surge channels may reside. The white areas show areas of inactivity.



Aegean, with flow going counterclockwise, is a region of upwelling, or a plateau-vortex (figure 8b). The surge channel then flows eastward, in part along the Anatolia Fault and in part along the Zagros Crush Zone and the Makran convergent margin. From there it is deflected to the north by either the Ornach-Chaman Fault or the western pinch in the Afghanistan Gap (figure 7) and forms a counterclockwise vortex at the Dasht-e-Lut, a huge depression surrounded by mountain ranges (Iran; figures 8c and 9). The Dasht-e-Lut is characterized by high heat flow, active volcanism, high seismicity, ophiolite belts, kobergens, and other surge channel features (Meyerhoff *et al.*, 1992).

The surge channel bifurcates again to the south of the Caspian and Aral Seas. There the channel intersects the Ornach-Chaman Fault and the Chagos-Laccadive channel, and the channels continue to the NE to the Afghanistan Gap in a pinch-and-swell situation (figure 7), where the Himalayan Mountains rose in an orogenic phase (Meyerhoff *et al.*, 1996b).

Continuing, the active surge channel passes through the Himalayas, where it is deflected to the south to intersect the Indonesian archipelago upwelling vortex (figures 1, 7, and 8e). During the Silurian-Devonian periods, the site of the Indonesian archipelago seems to have consisted primarily of deep-water troughs that surrounded shallow-water, small continental platforms. Widespread germanotypic tectogenesis and epirogenic movements took place (Meyerhoff, 1995). The trench system stretching from the Andaman-Nicobar Islands to Papau New Guinea was also in place. The surge channel came SE out of the Indian downwelling vortex (figure 8d) in a series of five splayed channels, also indicating that India was in—or nearly in—place by the Permian at the very latest (Gupta, 1993; Meyerhoff *et al.*, 1996b).

Carboniferous shallow-water carbonates are known from Sumatra, Sarawak, Kalimantan, the Philippines, Timor, and several localities between Sulawesi and Papau New Guinea (Meyerhoff, 1995). This shows the possibility that the islands were in place by the Devonian for Carboniferous carbonates to have been deposited on them. The broken-up fragments are proposed to have been moved by the invasion of the surge channel from India. The SE-flowing surge channel phase of epeirogenesis has evolved into the krikogenesis stage by flowing SE along the Shan Boundary to create the island arc behind the Andaman-Nicobar convergent margin, which has been in place and

Figure 8. The vortex street across the Pacific Ocean basin as determined by the GEOSAT structural trends and the mid-plate earthquake epicenters.

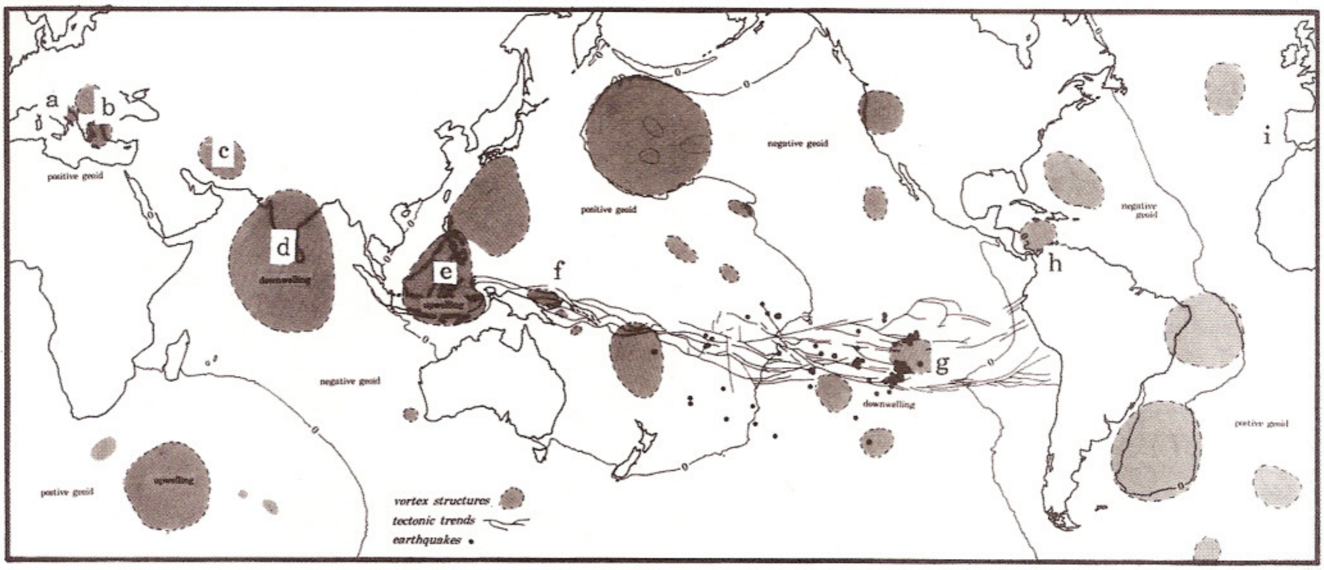
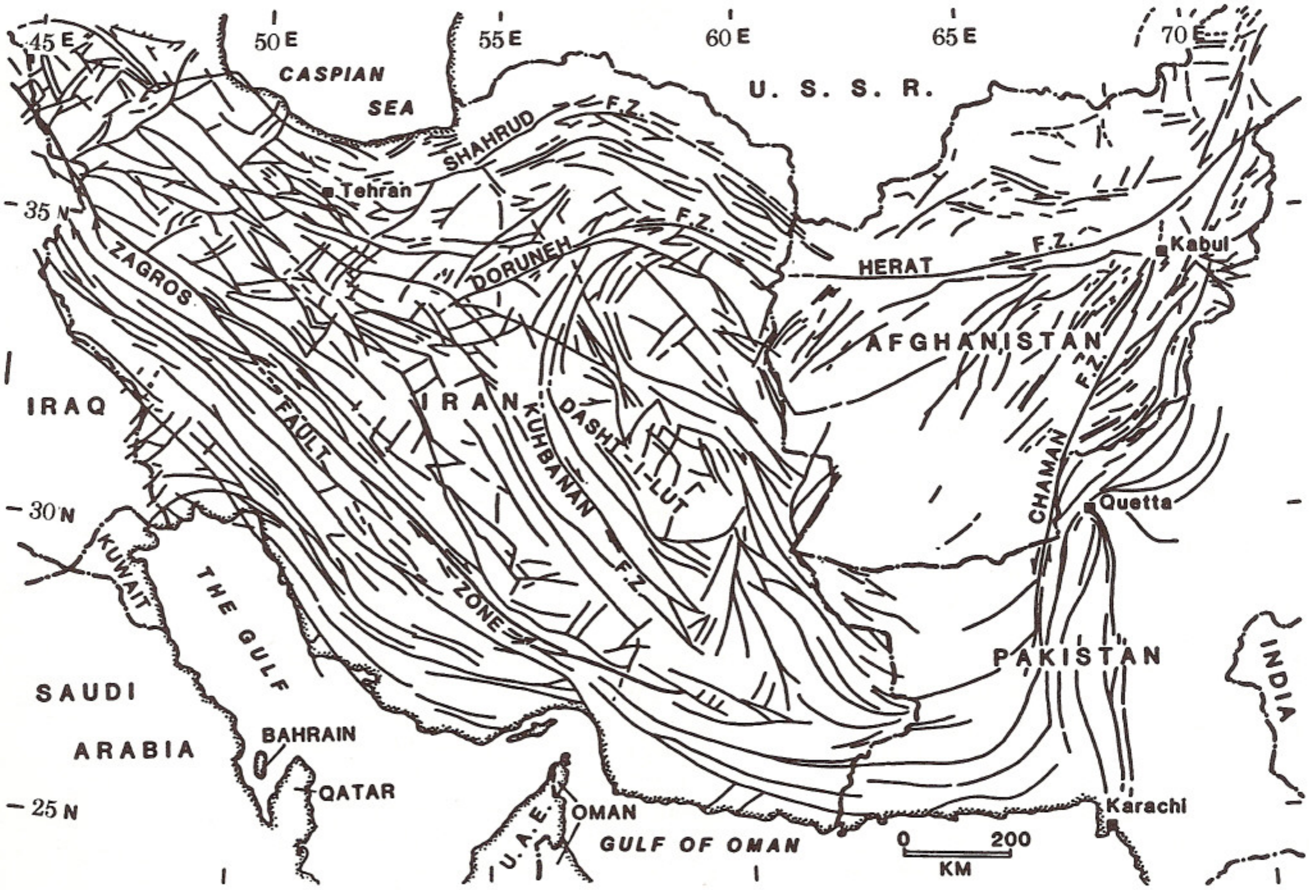


Figure 9. The tectonic trends of the Dasht-e Lut vortex (Meyerhoff et al., 1992).



working since the Silurian and Devonian, from there through New Guinea (Meyerhoff *et al.*, 1996a).

Marine conditions spread in this region during the Triassic-Middle Jurassic. The Hyrcinian orogeny in SE Asia caused the collapse of many surge channels and the creation of new routes so during the Late Jurassic the surge channel began the period as inactive. The Himalayan orogeny blocked the access route of the magma rising from the asthenosphere. New splayed channels formed, one of them from Myanmar which extended southeasterly through the Andaman-Nicobar islands (Meyerhoff *et al.*, 1996a).

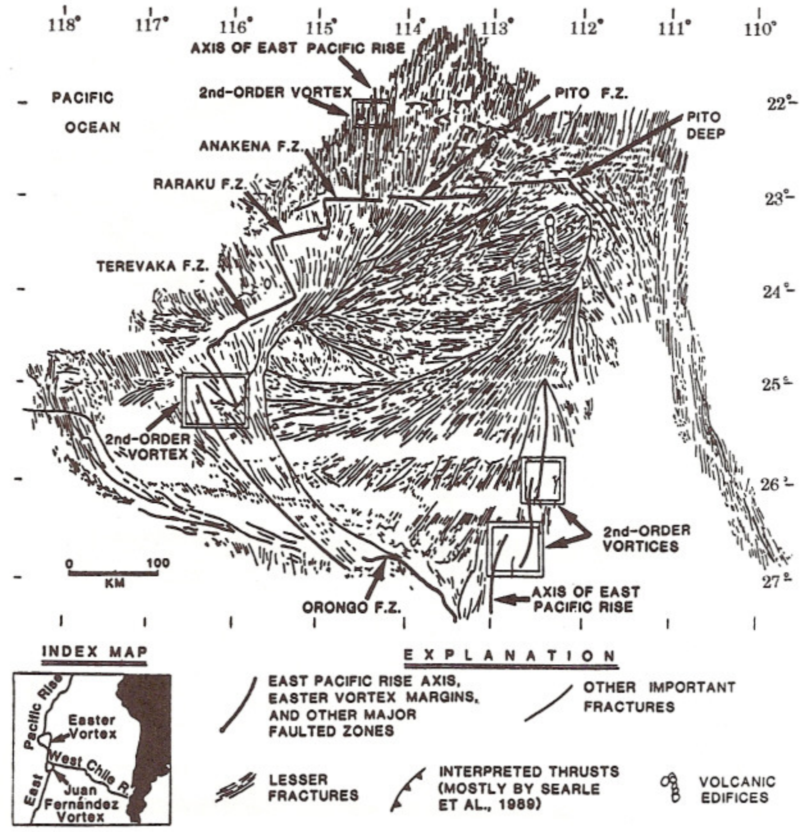
In the Indonesian archipelago, the Banda Trench seems to have worked its way eastward into the Arafura platform. Some of the underlying surge channels seem to have been active for about 200-300 Ma as shown by the multiple-aged rocks associated with them. This indicates stability over a long period of time. From Sulawesi the surge channel bifurcates. The northern and eastward flowing branch first formed an upwelling vortex at Sulawesi and then a breakout channel. This breakout passes out to the east between its legs, and has been there since the Carboniferous-Permian time (Meyerhoff, 1995).

All of the surge channels being discussed converge on the Caroline Basin and continue beneath the Ontong-Java Plateau (figure 8f), which is the site of the largest cusp in the world (figure 1). Made up of the Yap and Palau trenches on the north, Sulawesi on the west, and Irian Jaya and Papau New Guinea, and the New Britain, South Solomon, and Vityaz trenches on the south, this is the type of feature where one would necessarily go to look for a surge channel. Because the splayed surge channels were in existence for the 411 Ma preceding the end of the Ordovician, the western Pacific Benioff zones must have necessarily already been in place. In fact, sampling has given at least a Paleozoic-aged basement to the Philippine Islands (Easton and Melendres, 1963), Proterozoic granitic clasts in western New Guinea (1,250 Ma; Pieters *et al.*, 1983) and NW Irian Jaya, 1,700-1,500 Ma on western Malay Peninsula. The Ontong-Java Plateau is dated at 129-83 Ma (Mahoney et al., 1993). Flow is still taking place beneath this region as witnessed by the earthquake and volcanic activity. As the flow increases, the surge channel revolves counterclockwise and upwells. The GEOSAT diagram (figure 2) indicates a massive surge channel pouring out to the east from that region.

From there, any of the channels could be the primary route across the Pacific, the route through the Easter Island downwelling vortex (figure 8g and 10) giving the strongest indication (based on figures 7, 8, and 10). On the other side of the world, from the Adriatic Sea the geostream splays at the East Pacific Rise, a trunk channel (figures 8 and 10). Part of the geostream continues eastward as the Nazca and Cocos ridges, trending ENE to South America. A portion travels along the East Pacific Rise until it veers off to the east as the Tehuantepec Ridge, a feeder channel. That route is forced out to the east between South America and Mexico to form the Caribbean vortex (figure 8h). The channel does this because the craton's roots are too deep to admit a sub-passage as determined by the earthquake data from NGDC (Russo and Silver, 1995). The Caribbean vortex has been determined to be a large igneous extrusion rather than a plate (Morris *et al.*, 1990; Coffin and Eldholm, 1993) so it is the surface expression of this surge channel.

After a whirl around the Caribbean, the geostream continues ever eastward beneath the Vema and Barracuda Fracture Zones in the Atlantic (figure 3). It forks once again at the Mid-Atlantic Ridge trunk surge channel to go northward and southward. The northern fork splays eastward as a feeder channel in the form of the

Figure 10. The Easter Island counterclockwise vortex on the East Pacific Rise. The trends are taken from GLORIA and SeaMARC II survey data (Meyerhoff et al., 1996a). Secondary eddy structures are also present.



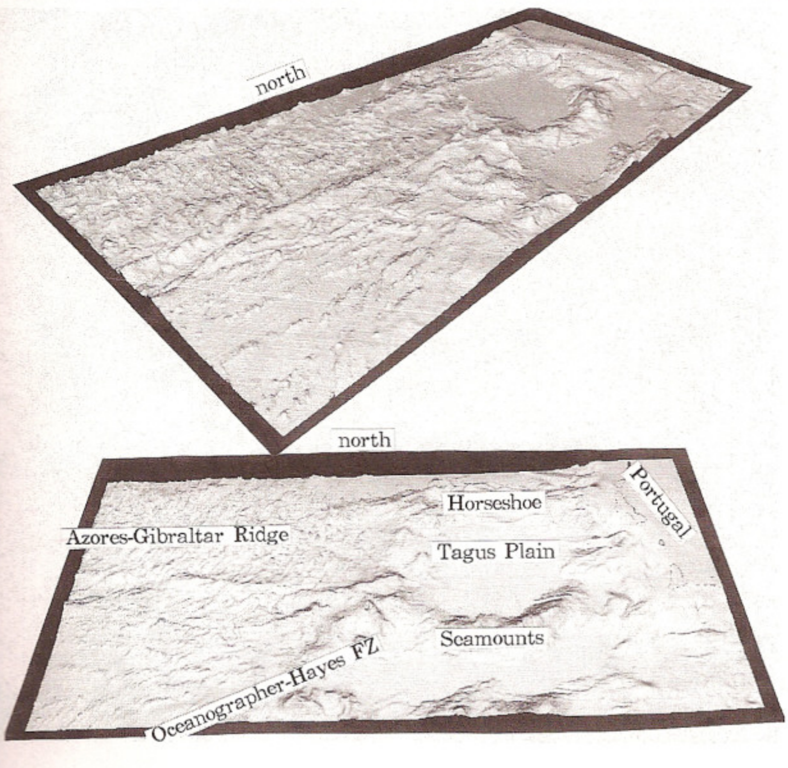
Azores-Gibraltar Ridge. Oceanward of Portugal, this surge channel intersects the southerly passing active surge channel paralleling the coast of Europe and the NNE-trending Hayes/ Oceanographer fracture swarm to create the large vortex surrounding the Tagus Plain, commonly called the Horseshoe Seamounts (figures 8i and 11). From that point the surge channel/vortex street, or geostream, passes into the Mediterranean Sea and returns to the South Adriatic vortex (figures 4 and 8a), thus interconnecting all the vortices by surge channels.

Vortex structures explain many events in seafloor tectonics, while removing the need for features such as microplates.

CONCLUSION

Using surge tectonic hypothesis, a rotation mechanism is explored. This analysis produces a vector model which, at the time of its publication, incorporated the most recently published earthquake epicenter data for the region. Deformation of sediments occur in the South Adriatic Basin as recently as 1990 along the Mattinata and Scutari-Pec Fault systems, cutting all stratigraphic series and creating new zones of hyperbolic and indistinct acoustical signatures in surficial sediments. This model portrays a very simple yet plausible relationship between magmatic movement through surge channels, earthquake epicenters, surficial acoustic data, and previously documented rotational and subsidence forces at work in the South Adriatic Basin. The bathymetry is easily explained when one realizes the causal agents for the geomorphology of such a feature. Eventually this same exercise will be applied to all of the rest of the vortex structures in the world and the model will be refined. For now, this is a first-order-approximation of how to apply the newer survey technique of the GEOSAT to already established systems such as the multibeam sonars, 3.5 kHz acoustic analysis, and the NGDC earthquake data to solve tectonic problems.

Figure 11. The Horseshoe Seamount vortex lying to the west of Portugal (Smoot, 1997).



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