Modeling Mantle Dynamics in the Banda Sea Triple Junction
Exploring a Possible Link To El Niño Southern Oscillation (Revisited)

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ABSTRACT

The upwelling mantle within the Banda Sea is modeled using computer visualization techniques. The Banda Sea is considered a triple junction of the Pacific, Australian, and Eurasian Plates within the plate tectonic hypothesis. Evaluation of mantle depths from gravity and seismic studies indicates upwelling of mantle from approximately 30-40 km under the continental shelf of Australia to 21 km in the Banda Arc. From here the mantle rises to 14 km within the Weber Deep and finally reaches a depth of 7 km in the North Banda Sea. Seismic epicenter data delineate spatial boundaries of flow regimes and define magmatic migration routes. Epicenter magnitudes are visualized in 3 dimensions by color-coding. Topographic and bathymetric data from in-house sources define geographic position and geomorphology of the model domain, while altimetry data delineate the gravity field associated with a component of mantle dynamics using contour lines or interpolated color fields. Conceptual animation portrays upwelling and divergence of mantle flow structures (geostreams) underlying the tectonic trends of the region and the resulting counterflow within the volcanic arcs based on the surge tectonic hypothesis. This animation uses a series of color-coded arrows and particle systems to represent these flow structures in motion. Induced micro-gravity oscillations in the triple junction may be caused by planetary gravity waves. This phenomenon is explored to determine the coupling effects with the atmospheric pressure flux of the southern oscillation, which modulates El Nino.

Keywords: Banda Sea, Mantle Dynamics, ENSO, Surge Tectonic Vortex, Triple Junction

1. INTRODUCTION

Just north of Darwin, Australia, the Banda Sea region may play an important role in modulating the El Nino Southern Oscillation (ENSO) through mantle dynamics. Teleconnection of the gravitational field to atmospheric pressure was demonstrated [1] with super-conducting gravimeters. Barometric pressure fluctuations were shown to correlate with micro-gravity variations. The inverse is suspected in the Banda Sea triple junction, where micro-gravity fluctuations due to tectonic surges may modulate pressure oscillations of the El Nino/La Nina climatic flux (Fig. 1).

El Niño A Gravity-Driven Process

The World Climate Research Program's initiative on Stratospheric Processes and their Role in Climate (SPARC) currently indicates the importance of parameterizing gravity wave effects in numerical climate simulation models. Using radiosonde data, prominent

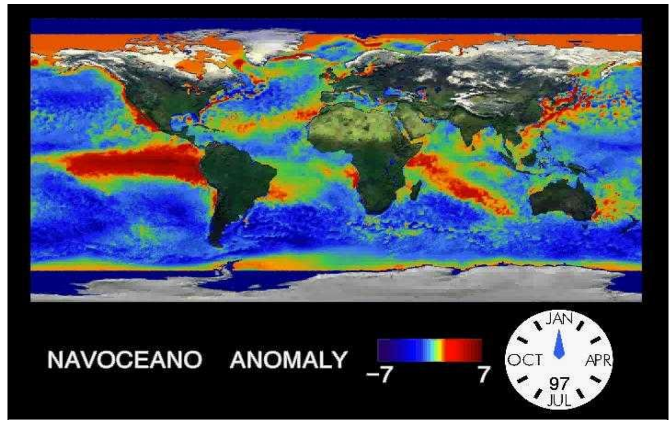

Fig. 1. Typical El Niño Temperature Anomaly.

eastward-propagating stratospheric gravity waves around the equator were first identified by [2] during atomic bomb testing in the Pacific. The dominant source of these stratospheric gravity waves is thought to originate in the upper troposphere from convection processes due to the high heat budgets near the equator. A potentially overlooked source for fluctuations of gravity waves could be attributed to coupling influences of the Earth's interior controlled through tectonic trends [3]. Planetary scale waves associated with El Nino seem to emanate initially within the Indian Ocean Basin during a phenomenon known as Madden-Julian waves, a 40- to 60-day weather oscillation also called the Madden-Julian Oscillation (MJO). These are knots of wind and rain that travel eastward from the Indian Ocean every one to two months. Kelvin Waves bring warm equatorial waters eastward and are the pulse of El Nino in what is considered a gravity-driven process. They originate with the western equatorial Pacific warm pool that normally lies near Indonesia and New Guinea. These waves migrate eastward with interannual time scales in phase with the Southern Oscillation Index. They take 2 to 3 months to cross the Pacific. Convergence of this less-saline warm pool of water with more-saline cold water from the eastern Pacific creates a well-defined salinity front. The zonal displacement of this front, a Kelvin Wave, is associated with El Nino-La Nina wind-driven surface current variations [4]. Another wave with influence on climate is the Rossby Wave, which in the case of El Nino reflects the Kelvin Wave off the American continents. The effects of El Niño's linger for years as discovered by Navy research scientists at Stennis Space Center [5]. From satellite altimetry studies of sea surface height variations, it became apparent that small (5- to 10-cm) anomalies in the sea surface from Japan to the Gulf of Alaska could be traced back in time and were found to originate during the 1982-83 El Nino. These slow-moving masses of warm water originate as Kelvin Waves that bounce off South America, split in two, and travel north and south along the coasts. They become smaller with increasing latitudes and eventually reflect across the Pacific as waves roughly consistent with linear Rossby Wave theory.

Teleconnections

Sir Gilbert Walker pioneered statistical methods revealing the nature of climatic teleconnections, primarily sea level pressure oscillations between Darwin and Tahiti, later known as the Southern Oscillation associated with El Nino. These cross-correlations over great distances between time series of meteorological variables, such as Sea Level Pressure (SLP, Fig. 2 and 3), were realized in the early 1900s [6, 7, 8].

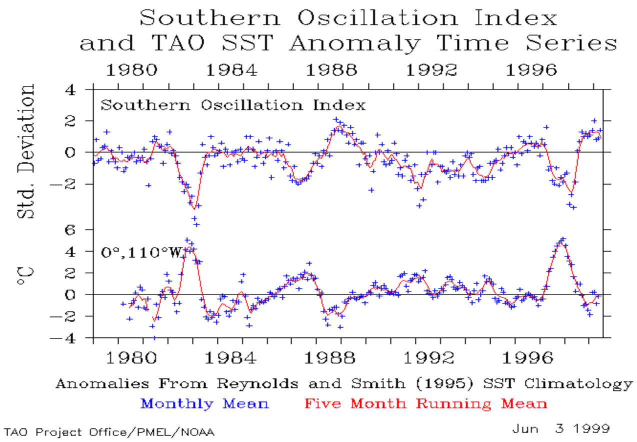

Fig. 2. Southern Oscillation Index (NOAA).

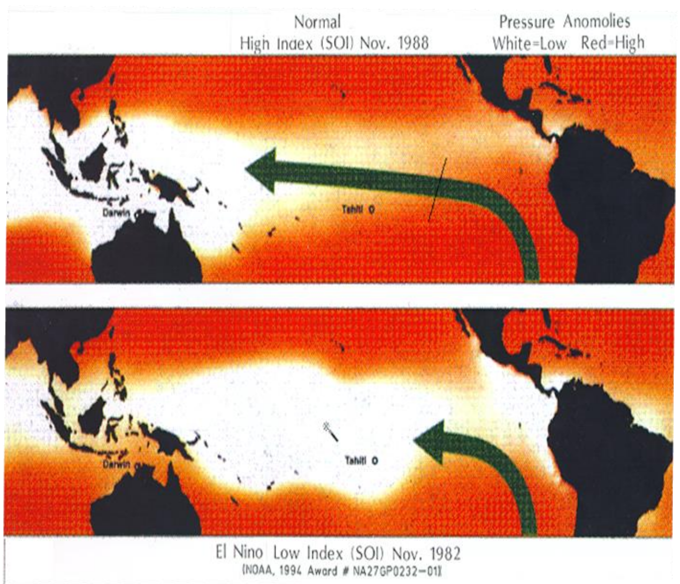

Fig. 3. Normal vs. El Nino SLP Distribution (NOAA).

These linkages between weather anomalies were later called teleconnections. Extensive analysis of SLP (Fig. 3) and Sea Surface Temperature (SST) in Fig. 1 has resulted in the discovery of three major oscillation systems or teleconnections around the globe. The most familiar are the Southern Oscillation (SO) associated with El Nino (ENSO, Fig. 2 and 3), the North Pacific Oscillation (NPO) controlling fronts moving toward North America, and the North Atlantic Oscillation (NAO) exerting control over European weather patterns. An intriguing pattern of tectonic vortexes underlies all these global oscillation systems [9].

Banda Sea

Within the plate tectonic hypothesis, the Banda Sea (Fig. 4) is located at a triple junction between the Australian, Eurasian, and Pacific plates. It is considered an anomalous arc system with Mesozoic crust on the inner side of the arc, and Australian continental crust wrapped around the complete 1800 bend (unique globally) bordering the outer bathymetric trough. Clearly it is difficult to understand how the Australian Plate converges on itself. The outer trough is divided into four segments: from the south counterclockwise they are Timor, Tanimbar, Aru, and Seram Troughs associated with their corresponding islands. The Aru Trough has been interpreted as extensional rather than compressional in origin [10, 11]. Thus, the eastward thrust of the Banda Arc is interpreted as being farther west, bisecting the Kai Island group. These islands portray a metamorphic basement, which is an accretionary complex of Late Miocene to Pliocene age. Tertiary reefs and faulted Eocene to Miocene platform sediments from west to east indicate an uplifted continental basement within a compressive regime of forearc development [10, 12]. Farther west, separating the Kai Islands from the Banda volcanic arc, is the Weber Deep. The Weber Basin is classified as a forearc basin but is unique due to its exceptional depth (>7km) which makes it the deepest point in the world's oceans that is not situated in a subduction trench [13]. Incorporating these factors into a comprehensive framework is key to a correct interpretation of the tectonics of southeast Asia and the Pacific Basin. The Banda Sea triple junction, delineated by earthquake epicenter data (Fig. 5), is considered a tectonic vortex within the surge tectonic hypothesis. This vortex has fragmented the northern Australian continental shelf since the early Tertiary. Large-scale structural features (Fig. 4) fall into place using vortex interpretation with counterclockwise rotation. The Birds' Head configuration of Irian Jaya is a rotated block separated from the end of Papua New Guinea by extension of the Aru Trough. Aru Island will become part of a new outer arc as the vortex propagates east northeast. Thus, accretionary complexes of continental fragments are pulled into the vortex and broken up and consumed in the troughs of the North Banda Sea, which recharge the mantle with lighter elements.

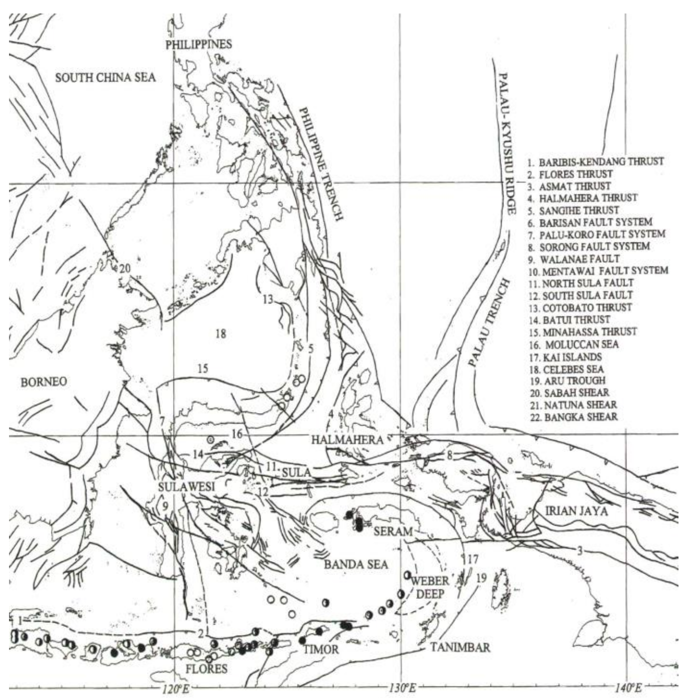

Fig. 4. Banda Sea Structural Trends (Smoot, 1998).

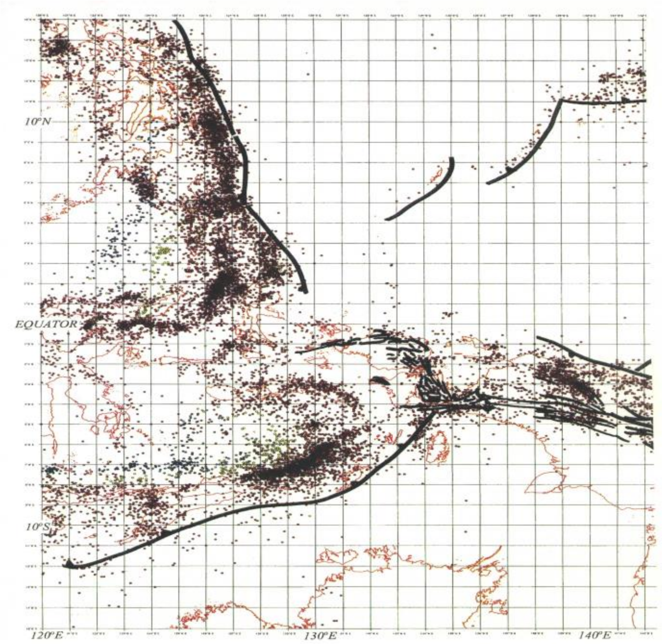

Fig. 5. Banda Sea Earthquake Epicenter Data (from NGDC Seismicity Catalogs). Dark lines mark trench systems and fault zones.

2. DATA SETS

Geophysical data sets evaluated in this study include:

Seismic Earthquake Epicenters (Fig. 5)
Epicenter data delineate spatial boundaries of flow regimes and define magmatic migration routes at depth.

Bathymetry (Figs. 6 and 7)
Bathymetry data exhibit seafloor topography and show geomorphologic structural patterns.

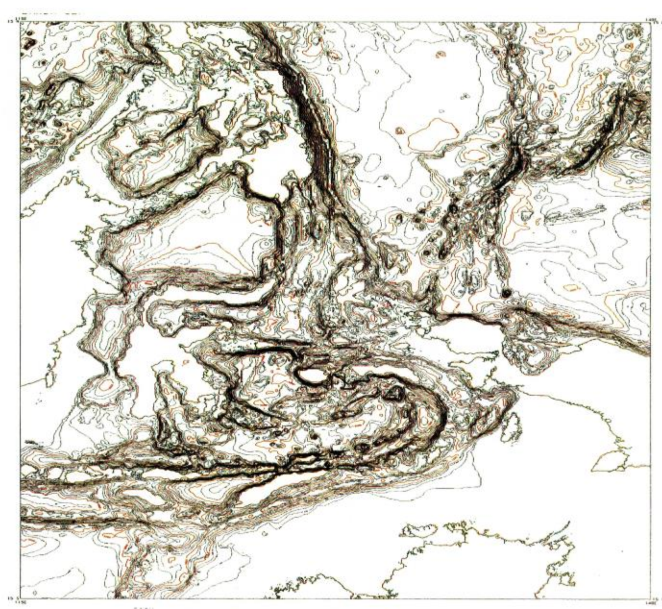

Fig. 6. Banda Sea Bathymetry (5-min. Gridded). Shows depths and ocean basin structure (NAVOCEANO).

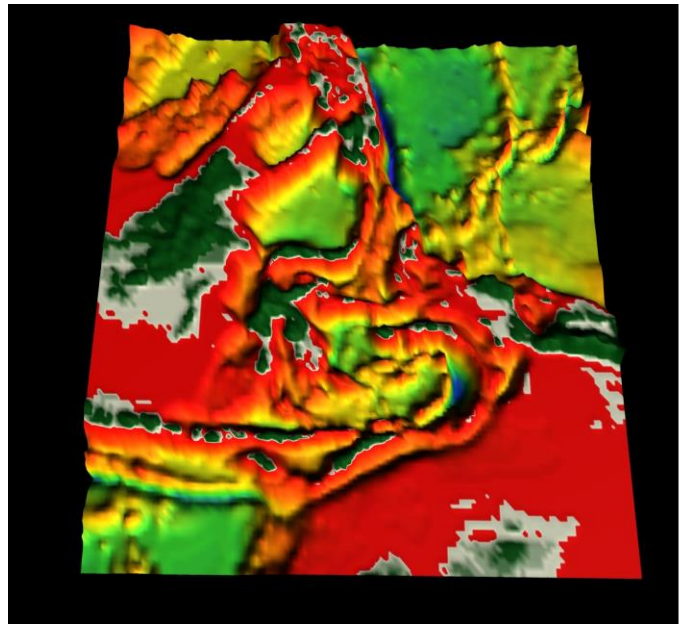

Fig. 7. Banda Sea Tectonic Vortex - South View 3-D Bathymetry (NAVOCEANO). Note Indonesian Volcanic Arc outflow and wings of the vortex much like the hurricane symbol.

Altimetry (Figs. 8 and 9)
Altimetry data delineate the gravity field associated with a component of mantle dynamics; trend maps compiled from high pass filtered GEOSAT data show the regional trends of sea surface topography with wavelengths less than 125 miles. These sea surface trends reflect gravitational variations in the Earth's crust and mantle caused by density variations and tectonic dynamics [9].

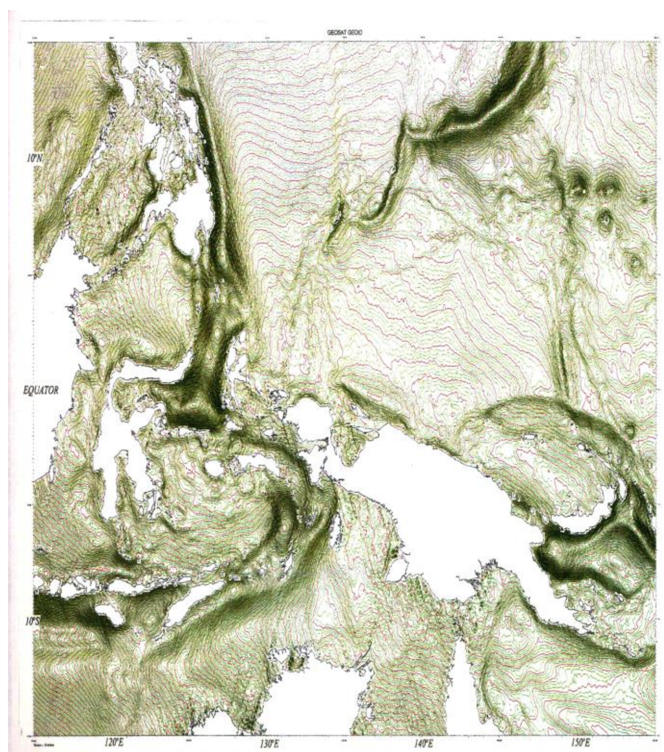

Fig. 8. Banda Sea Geoid Data from GEOSAT Altimetry (NAVOCEANO).

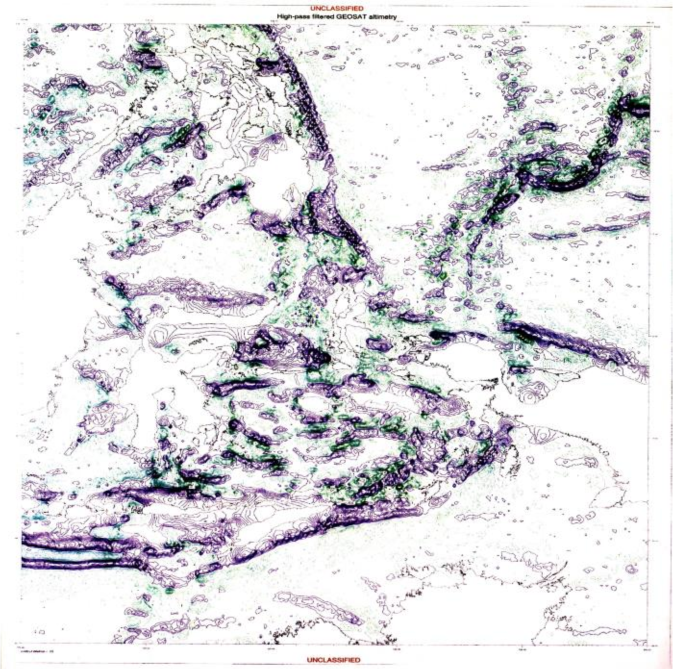

Fig. 9. Banda Sea High-Pass Filtered GEOSAT (NAVOCEANO).

Other Geophysical Datasets

1. Seismic reflection/refraction studies indicate crustal basement, fault zones, velocity/density profiles, differentiation of sedimentary, metamorphic, and igneous rock types and their depths.

2. Magnetic lineation indicate offsets along crustal boundaries and seafloor ages.

3. Gravity anomalies indicate mantle depths and crustal structure.

4. Other, more geological-type information discussed includes dredge samples to differentiate between continental and oceanic crust, studies of benthic foraminiferal assemblages which help determine paleo-bathymetry, and examination of depositional environments along with past sea-level curves to determine tectonic subsidence and uplift histories.

Seismic studies by Scripps Institution of Oceanography Monsoon Expedition in 1960 [10] and gravity modeling [14, 15, 16, 17] portray the mantle dynamics of the region. Refraction lines on the Australian shelf and in the Timor, Tanimbar, and Aru outer arcs and troughs indicate the presence of a continental platform extending over 30 km deep overlain by Plio-Pleistocence sediments. Refraction lines between the Banda Volcanic Arc across the Weber Deep to the outer Banda Arc indicate mantle depths of 10-21 km. Gravity modeling indicates more than 30 km to depth along the outer arc and troughs. Mantle depths of the Banda Sea at 10 km, the volcanic arc at 20 km, and the Weber Deep at 14 km are overlain by oceanic crust as indicated from seismic refraction characteristics. Farther northwest in the North Banda Sea, the mantle shallows to 8-9 km.

Within the Banda Seas, oceanic crust becomes younger northward [18, 19] as inferred from magnetic lineation data, but the nature of the basement of the Banda ridges is incompatible as evidenced from dredge samples [20]. The existence of magnetic lineation suggests oceanic crust where rocks collected from dredge samples indicate continental origin, which indicates a possible fragmentation and mixing of the two crustal elements. Thus, incompatible evidence can be explained by having zones of engulfment vorticity in the Banda Sea Basins, where fragmentation of oceanic and continental crust is mixed by vortex action. Magnetic anomalies in the South Banda Sea, within the vortex area, are compared with similar trending lineation with older ages from the Argo Abyssal Plain. These show possible separation of crustal elements between M14 (131 Ma) and M16 (133 Ma) of up to 12º longitude along strike of the Indonesian Islands Arc. Within the plate tectonic paradigm, this could possibly be explained by a 12º relative rotational component of opposing plates. [10, 21, 22, 23, 24]. Magnetic lineation separation may be used to calculate vortex propagation velocity, which will be shown later.

3. TECTONICS

Previous Interpretations

The present geographic position of the Birds' Head of Irian-Jaya, which is stratigraphically and paleo-magnetically similar to Australia and located to the north of the Banda Sea Vortex, is problematic for the plate tectonic hypothesis. Such geometry [25] requires expansion of the Australian Plate, allowing the arcs to migrate over a single subducting plate [26]. In fact, there should be compression due to northward convergence of the Australian plate unless the Australian plate is actually two or more plates in relative motion [10, 27]. Other fragments within the Banda Basins of eastern Indonesia have lithologic similarities to the continental Birds' Head and Australia [26] and are thought to be trapped lithospheric, "micro-continents" [28]. These fragments were supposedly strike-slip faulted into position during the middle to late Miocene. This assumption is based mainly on low heat flow, depth of basement, and interpretation of magnetic lineation [10, 18, 19, 29]. These fragments are of Pacific origin [30] and of Indian Ocean affinities [27]. A counterclockwise-rotating micro-plate mobilized within the triple junction with an extremely complex set of radiating faults explains some of the anomalies to a degree, with the large exception of the Weber Deep [31]. A re-evaluation using Meyerhoff Surge tectonic hypothesis [32, 33] completes the picture.

Surge Vs. Plate Theory: Geostream Mantle Effects

As a mantle stream (geostream) turns within an arc, compression of lenticular flow and differential heating creates upwelling along the inner arc. This compression and increase in angular momentum create a more vertically exaggerated mantle flow which expands toward the surface and differentiates into magmatic components. These expansion forces magnify the rotational component already induced by the Coriolis force. After emplacement of magmas within the surge channels, the mantle constituents shift laterally by rotation. Thus, cooling at the apex of rotation creates thermal contraction and downwelling along the outer arc, buckling the crust above the geostream along the outer trough. This process is hugely different from the plate tectonic model of a subducting slab of the continental plate considered as a tectonic driving force.

Geostreams merge from sheet flow at depth from under the continents and ocean basins. Sheet flow accelerates and turns into mantle stream flow as it enters the bottom of the rotating stream. Using a hurricane analogy, the western feeder band merges with northward mantle sheet flow at depth from the under the Australian continent. This model portrays a largely decoupled continental block floating on the mantle. Continental edge and bottom erosion by mantle streams may occur, and even underplating accretion by back migrating eddies may be possible. Thus, it is unlikely that large-scale subduction takes place unless the mantle stream migrates laterally. Good examples of laterally migrating north/south-oriented mantle streams do exist around the Pacific Basin, exhibiting large-scale crustal subduction; but in this case, most lithosphere subduction occurs in the back-arc basins and the leading edges of the vortex.

The oldest igneous rocks within the Banda Volcanic Arc are 12 Ma granites near the island of Wetar. According to plate theory, Australia began northward movement during separation from Antarctica in the time frame of magnetic anomaly M34, or 82 Ma. Thus, a gap of 70 million years is unaccounted for in the birth of this supposed convergent margin, the subduction zone of the Banda Arc [20]. Where are the old volcanic rocks created by subduction of older 131-133 Ma crustal rocks? There should be older volcanic rocks within the Banda Arc, since subduction is timed with spreading and does not generally take 70 million years to occur. A clearer picture emerges with vortex analysis.

Tectonic Vortex Analysis and Flow Regimes

Vortex structures are generally not considered in the plate tectonic hypothesis. The Banda Sea triple junction is considered a tectonic vortex within the surge tectonic hypothesis. The vortex propagates along a mantle geostream (lateral rheological mantle flow) upwelling at the southeastern tip of the Indonesian Island Arc. It has been destroying the northern Australian continental shelf since the early Tertiary.

Incoming mantle flows at depths greater than 600 km, but geostream transport occurs primarily in the upper 30-150 km. Deep convergence occurs from three directions, corresponding to the triple junction plate boundaries. They enter the vortex by up-ramping cyclonically within the extension of the Weber Deep. The surface of this upwelling mantle interface would roughly mirror-image the bathymetry. The rise of the mantle and fall of the Weber Deep may be considered as isostatic compensation of vertical motions in the mantle. Below the Weber Deep there are approximately 7 km of mantle upwelling, from 21 to 14 km, corresponding to 7 km of bathymetric fall within the Weber Deep.

A counter-flow is generated within the vortex from anatexis (melting with increased flow rates decreasing viscosity) of the mantle and extruded at the surface as magmas along the volcanic arc. The asthenosphere counter-flow is characterized by lower density, higher elevations, and higher velocities, which oppose upper-mantle stream flow. Within the surge tectonic hypothesis, the upper levels of asthenosphere flow complexes are termed surge channels. This is a simple construction: several layers of opposing flow regimes radiating along triple junction boundaries are evident. The opposing streams are suggested to be density/depth dependent, reaching levels of neutral buoyancy, much like opposing jets found within the inter-tropical convergence zones of the world's oceans and midlevel's of the atmosphere. Seismically these opposing deformation flow regimes are separated by intense earthquake activity (Fig. 5) along the Benioff Zone, where magma melts for intrusions occur.

Vortex inflows may be broadly classified as crustal, shallow-, mid-, and deep-level mantle inflows and may further be divided regionally. Within the Banda Sea vortex northwestern quadrant, surface expression portrays Eurasian crust and shallow-mantle convergence toward the vortex. Pacific mid-level mantle inflow is covered and obscured by shallow-level outflow to the north. This is a region of turbulence and back arc basin crustal subduction and fragmentation. In the northeastern quadrant, deep incoming Pacific mantle converges toward the vortex. Midlevel mantle outflows through Papua New Guinea eastward. As this outflow shallows eastward, it generates an opposing high-velocity counter-flow back toward the Banda Sea Vortex, exemplified by arc building along a vortex street en route to New Zealand. Deep mantle upwelling from under Australia wraps continental crust into the vortex from the southeastern quadrant and merges with the rotational component of the Eurasian Upper Mantle Stream in the southwestern quadrant. Thus, cyclonic mantle inflows from all directions. This generates higher velocity upper-mantle outflows, permeating the Pacific Basin generally around the perimeter, "rim of fire," but also converging along the East Pacific Rise.

Vortex Velocity

The geostream strike-slip components have not yet been quantified, but vortex velocity has been approximated using two different approaches, one using magnetic lineation separation, the other using paleo-bathymetry timing estimates and vortex closest approach approximation. These approaches assume that accretionary complexes of continental and oceanic crust fragments are floating atop the geostream and are left in the wake of the vortex. A magnetic lineation separation of about 12^{o} of longitude in 2 million years yields a strike-slip separation rate of approximately 75 cm/yr. This calculation is based on approximately one nautical mile per minute of arc near the equator. This rate is greater than the fastest plate motions.

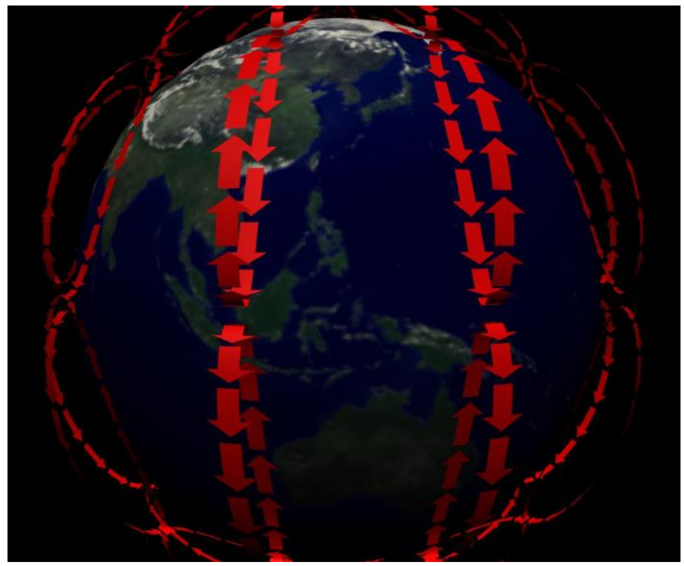

Fig. 10. Generalized Single Cell Hadley Convection Moving Heat from Equator to Poles (MSRC Visualization Lab).

From paleo-bathymetry reconstructions of the Timor Island region based on stratigraphic correlations of benthic foraminiferal assemblages [34], uplift began between 2.4 - 2.2 Ma in the late Pliocene and slowed until uplift ended 1.6 Ma at the end of the Pliocene. After that, it was still some 700-1000 m below sea level. Then, a relatively stable tectonic period existed during which a gradually subsiding basin, filled with marls and turbidites and sedimentation rates, kept pace with subsidence. Rapid uplift began between 750-250 Ka, but neritic sediments were deposited and preserved as late as 120 Ka, since which time they were raised more than 500 m above sea level at minimum uplift rates of 7.8 mm/yr. This puts the vortex time of closest approach to Timor, when it was probably in a position comparable to present-day Aru Island, at approximately 0.5 Ma. Recent uplift is associated with building of the Indonesian Island Arc just north of Timor. The head of the Aru Trough overlies the axial base of the central vortex, where maximum continental destruction and separation occurs. About 9^{o} of separation in longitude exist from the Aru Trough to central Timor. The approximation using one nautical mile per minute arc near the equator yields an average vortex velocity of 180-195 cm/year with relative eastward movement. Even with a large error (50%) in estimates of time or distance, calculations still yield substantial velocities, much faster than the plate paradigm allows for crustal elements. Although large movements of the vortex may be episodic, with violent collapsing stages, satellite studies of the vortex elements may be expected to show exceptional rates of motion.

A Matter of Incomplete Flow Dynamics: Hadley Vs. Walker Circulation

Another oversight and the major misconception of plate tectonics is the use of a secondary flow dynamic as the primary one. The convection heat-driven process of seafloor spreading perpendicular to ridges is indeed occurring, but the expansion/contraction of lenticular magma streams flowing underneath and parallel to ridge strike is the primary driving process as explained by surge tectonics [32, 33]. In an analogy to atmospheric dynamics, this misconception is akin to hypothesizing that Hadley Cell convection (Fig. 10), which transports heat from equator to poles, is the primary process of mass transport in weather patterns along the equator. This, of course, is not true. Walker circulation dominates the mass transport of atmospheric particles along the equator. The dominant mass transport is through pressure cells (vortices), trade winds, and jet streams of the intertropical convergence zone organized along the equator, parallel to the large heat budgets of solar energy. The secondary Hadley Cell convection is more a heat diffusive transport process, much like that proposed as the driving mechanism in the plate tectonic hypothesis (Fig. 11). The same flow processes (Walker and Hadley Cell), occur in tectonics. However, heat budgets are from within the earth and are not necessarily organized along the equator (as in the case of the East Pacific Rise and the Mid-Atlantic Ridge). Walker circulation and Hadley Cell convection orientations of the heat sources within the geodynamo govern internal heat flow.

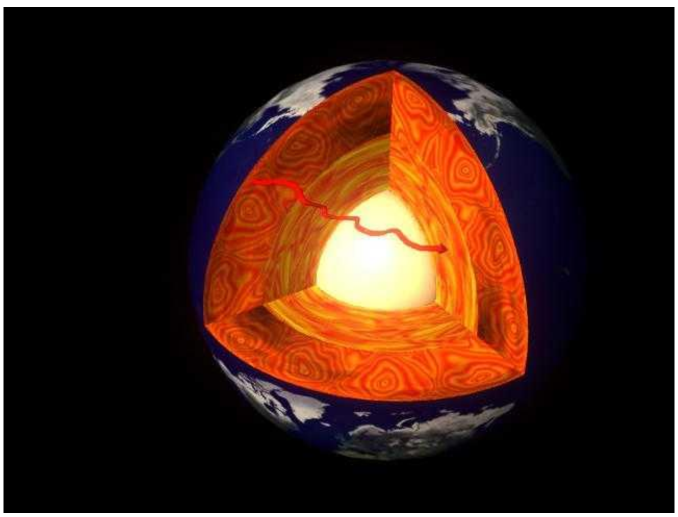

Fig. 11. Idealized Hadley Convection in the Mantle with Geostream Generation (MSRC Visualization Lab).

Similar flow dynamics of the intertropical convergence zone do exist within the tectonic domain due to earth rotation. These tectonic flow dynamics control atmospheric pressure oscillations of El Nino Southern Oscillation (ENSO) through micro-gravity tectonic teleconnections within tectonic vortices across the Pacific Basin. The tectonic flow is directly coupled to and in phase with the ocean/atmospheric Walker circulation patterns observed in the Pacific, although this may not necessarily be the case in the more complex patterns of the northern hemisphere such as the North Atlantic Oscillation (NAO). Flow patterns of the tectonics are more coupled (parallel) to ocean and atmospheric circulation patterns in the Pacific than they are in the Atlantic or Indian Ocean Basins. This hints at insights into earth evolution and ocean basin formation [35].

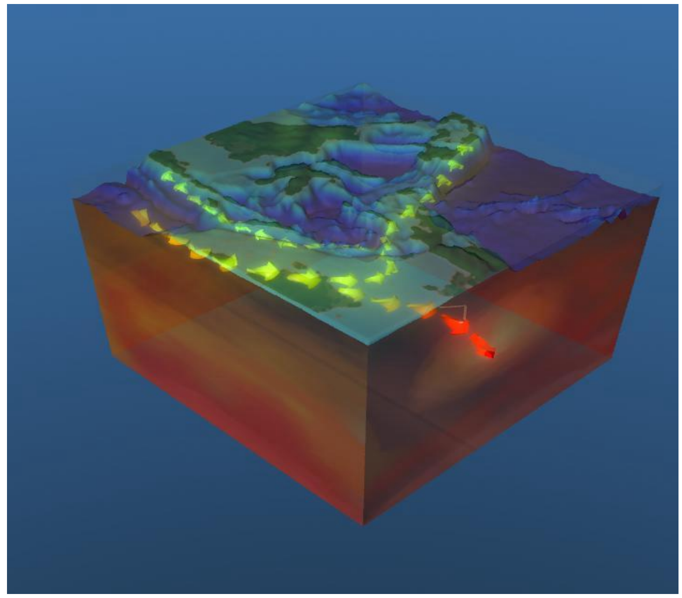

Fig. 12. Early Model Development Portraying Incoming Geostream Under Indonesia, Counterflow within the Volcanic Arc and Divergence of Geostreams around the Pacific Rim (MSRC Visualization Lab).

Model Development: Cutting a Swath in the Continental Crust

The concept of a powerful counterclockwise vortex migrating along a geostream and passing north and east of Timor Island begins this discussion. The small volcanic island group beginning at the head of the volcanic island arc south of Seram Island presently divulges the axial surface expression of the central vortex (Fig. 7). The vortex axis slopes southeastward from the surface, curving differentially with density change at depth toward the opening of the Aru Trough (Fig. 4). At the surface, the axis defining the central vortex currently migrates westward, while geostreams pull eastward, giving it, over geologic time intervals, an unstable oscillatory nature along the volcanic arc. This oscillation process builds the volcanic arc and explains the extent of topographic gaps between islands at the head of the volcanic arc. A working hypothesis maintains these gaps should correspond to minor expansion and contraction phases of the earth's gravitational field, Milankovitch series correlations, and climate change [36]. Thus, a closer study of the complete arc may be warranted to discern past Earth oscillation phases. The present extension in the Weber Deep and the Aru Trough suggests strong westward axis extension, probably during the latest gravitational expansion phase after the last ice age of the Pleistocene. Expansion should increase the vortex dimensions, causing increased axial slopes westward, while a major reversal to a contraction phase collapses structures within the vortex. During collapse the axis should move toward the vertical. This would straighten the volcanic arc eastward, close the Weber Deep, and completely open the Aru Trough. This process will build a new outer forearc, while continuing eastward vortex migration.

The Aru Trough opened because of very deep level geostreams upwelling northwestward from under the edge of the Australian continent. This deep-level flow opposes a midlevel geostream continuing from Indonesia, diving through the Aru Trough, and moving southeast through New Guinea (Fig. 12). The northern incoming flow regime from the midlevel Pacific mantle shows no surface expression because it is obscured by and runs counter to higher level outflow geostreams heading north. They are evident from relative motion of the Sorong Fault into the Seram Trough. Expansion and contraction propagate the vortex, cutting a swath through continental crust, Smirnoff and Wezel discuss theories of earth expansion/contraction phases [37, 38]. This process on a global scale drives the cycles of orogenesis, volcanism, and climate change seen in the geologic record. In short, understanding this process allows the understanding of global cataclysm cycles and much more.

Analysis of the 1972 Banda Sea earthquake suggests seismic sub-events propagated unilaterally along dip and bilaterally along strike, forming a fan-shaped rupture area [39]. A local northward convex plane inferred from the relative strikes of the major seismic sub-events contradicts the overall configuration of contorted, subducting slab of the Australian Plate [40]. The vortex-surge model in this case requires a vortex shear, which has a schematic like the plate model. But the dynamics in 3 dimensions would complement earthquake studies by vortex rotation and upwelling along strike and dip. Vortex dynamics would upwell northwestward in a convex, fan-shaped surface (i.e., vortex wall mass) with a decoupled flow process along the geostream strike after the vortex passes. This model indicates Timor would be rising in rhythm to vortex approach and expansion phase before it was ripped from the Australian continent. The vector strike-slip component of this process may be up to 75 cm/yr. as determined by magnetics or higher, up to 195 cm/yr. as determined by paleo-bathymetry studies. The new tectonic vortex model portrays accretionary complexes of continental and oceanic crustal fragments sheared by the vortex to float above the geostream to the south. To the north, they are further fragmented within the back-arc basins and subducted, or accreted, to new micro-continental masses left in the wake of the vortex.

Visualization Techniques

Epicenter magnitudes are visualized in 3 dimensions by color-coding. Topographic and bathymetric data from in-house sources define geographic position and geomorphology of the model domain, while altimetry data delineate the gravity field associated with a component of mantle dynamics using contoured lines or interpolated color fields. Conceptual animation portrays upwelling and divergence of geostreams underlying the tectonic trends of the region and the resulting counter-flow within the volcanic arcs based on the surge tectonic hypothesis. This animation uses a series of color-coded arrows and particle systems to represent these flow structures in motion.

This process will be visualized, providing an easily understood framework for comprehensively incorporating most geological and geophysical parameters of the Banda Sea region, especially the anomalous characteristics which have caused much controversy about its origins and evolution.

4. TECTONIC TELECONNECTION TO CLIMATE

Curious Evidence

By 1988, a decade of extensive work by Walker [41, 42, 43] at the University of Hawaii on T-phase (tele-seismic signals detected by hydrophone arrays placed in the oceans acoustic wave-guides) seismicity in the Pacific portrayed earthquakes along spreading ridges occurring in swarms along hundreds of kilometers. These earthquakes are associated with hydrothermal venting, magma outpourings, and atmospheric high-index pressure phases (Fig. 2 and 3) of the ENSO. This indicates a swelling of the entire ridge and slippage along a plate boundary. Walker associated these intense episodes of seafloor spreading with reduced atmospheric pressure in the ENSO high-pressure cell over Easter Island [41, 42, 44]. His latest work in 1999 considers gravity as a possible mechanism and states "Leybourne's assessment may be correct."

Gravitational Teleconnection

Studies by Warburton and Goodkind in 1977 [1] at the University of California Department of Physics with superconducting absolute gravity meters indicate strong correlations between the gravity residual (what is left after filtering out tidal affects) and barometric pressure changes at frequencies associated with weather patterns. Six *u*gal changes in the gravitational field are typical with barometric fluctuations in sea level pressure with maximum fluxes of up to 45 micro gals. The gravity response is essentially in phase with the pressure variations throughout the frequency range considered. The gravimeter signal noise is correlated with the random fluctuations of the atmospheric pressure. For the purposes of gravimetric measurements, the results show that gravity can be corrected for pressure effects within 10% by assuming the two are in phase and have admittance of 0.30 *u*gal/mbar below 1 cycle/day, and 0.33 *u*gal/mbar between 4 and 7 cycles/day.

In 1997 researchers [45] stated conclusively that they had found micro-gravity variations "mainly of geophysical origin." This study shows an expansion/contraction phase of a gravity wave or surge moving through Europe in the vicinity of Memback, Belgium in 1996. Micro-gravity increases approximately 17 *u*gals over six months during a contraction phase. These data are corrected for ocean and atmospheric attraction and loading and earth tides. This study shows the first conclusive proof of surges and how they can be quantified and mapped.

Relation to El Niño

A 1996 surge moving through Europe is likely related to the 1997/98 El Nino in the Pacific since surges migrate eastward much like weather patterns. As this surge induces micro-gravity oscillations, they are amplified upon reaching the Banda Sea vortex and produce a coupling effect on the atmospheric pressure flux of the southern oscillation of El Nino. Assuming the validity of the geophysical origins of changes in "g," the Earth would have periodic surges or geoid undulations. This natural frequency of earth oscillation would be modified continually by atmosphere/ocean loading or tides, orbital torque's, planetary alignments, and/or other astrophysical means, most of which can be filtered out, assuming the periods are known. Planetary alignments produce gravity fluctuations in the *u*gal range, as shown by simple calculations. This should perturb the natural oscillation enough to modify the "normal" flux or create larger variations in surge activity. These perturbations are amplified within the larger tectonic flow regimes or tectonic vortices responsible for weather teleconnections around the globe. These teleconnections have been documented by many scientists using pressure and temperature data sets but are not yet resolved in a comprehensive framework.

5. CONCLUSIONS

Surge theory provides a framework for modeling mantle dynamics that incorporates more geophysical data into the model. Surge theory also uncovers the relationship between tectonics and climate patterns. The amplification of small global gravity changes within tectonic vortices has the potential to store and release enormous amounts of energy. The possibility that tectonic phenomena may modulate weather patterns when gravitational potential energy is released at the surface as pressure/temperature changes in the ocean/atmosphere coupled dynamics should be investigated.

The influence of gravitational teleconnection on atmospheric pressure may be factored into current global General Circulation Models (GCM), by coupling geodynamic tectonic flow to ocean/atmosphere models based on principles of surge tectonics [32]. Micro-gravity studies undertaken on the most dominant vortices may provide the data to calculate a regional surge index for modeling longer-range climate patterns such as the ENSO. ENSO is controlled by the largest upwelling tectonic vortex structure on earth, in the Indonesian Island Arc. Across the Pacific Basin the ENSO is controlled by strong downwelling vortices along offsets on the East Pacific Rise near Easter Island.

Application of these concepts in other areas such as the North Pacific and the North Atlantic may provide the answers to questions such as (1) What creates the large-scale changes in pressure (SLP) that cause a vacillation of meteorological patterns between zonal and meridional flow in the northern hemisphere? Or (2) Why is zonal flow predominant in the southern hemisphere? East-West vs. North-South orientation of dominant vortices answers these questions.

The North Pacific Oscillation (NPO) is considered a seesaw of SLP between a belt at high latitudes extending from eastern Siberia (In the Lake Baikal region) to western Canada, and a broad region at lower latitudes including the subtropics. The NPO is controlled by island arcs and deep trench systems in the north and northwest Pacific, which includes the Japan, Kuril, and Aleutian Island arc and trench systems. To the south the NPO pressure is controlled by the Mid-Pacific and Hawaiian volcanic systems. The NAO is controlled by an upwelling tectonic vortex beneath Iceland and a downwelling tectonic vortex along an offset of the Mid-Atlantic Ridge near the Azores.

These teleconnected pressure systems affect weather patterns around the globe. By comparing geodynamic tectonic flow as analogous to ocean and atmosphere flow, which is inferred in surge tectonic theory, we can make the following conclusions. Atmospheric Jetstream flow is analogous to the Gulf Stream or Kuroshio Current flow structures in the ocean, in another word, aqua streams. These in turn are analogous to 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 the earth's crust and mantle. Weather fronts are analogous to Kelvin/Rossby waves in the oceans, or oceanic fronts. These fronts are pressure/temperature waves moving through their corresponding medium and in the earth are called surges, gravity waves, or tectonic fronts [46, 47].

Earth oscillations of various periods generate these surges and affect the vortex structures and geostreams in ways that may be predictable, provided micro-gravity studies of tectonic vortices are undertaken. A strategically placed global array of super-conducting gravimeters, networked with seismic and other environmental monitoring stations, may increase the ocean/atmospheric modelers' ability for climate prediction. Satellite geoid data may be ground truth for micro-gravity oscillations. A pilot study in the Banda Sea is recommended to test the validity of these proposals.

B. A. Leybourne is an employee of the Naval Oceanographic Office. However, the opinions and assertions contained herein are those of the author and are not to be considered as official statements of the U.S. Department of the Navy.

6. REFERENCES

[1] Warburton, R.J., and Goodkind, J.M., 1977. The influence of barometric-pressure variations on gravity. *Geophys. J.R. Astr. Soc*. 48:281-292.

[2] Yanai, M., Maruyama, T., Nitta, T., and Hayashi, Y., 1968. Power spectra of large-scale disturbances over the tropical Pacific, *J. Meterorol. Soc. Jpn., 46, 308, 1968.*

[3] Leybourne, B.A., 1996. A tectonic forcing function for climate modeling. *Proceedings of 1996 Western Pacific Geophysics Meeting, Brisbane, Au., EOS Trans. AGU,* Paper # A42A-10. 77 (22): W8.

[4] Picaut, J., Ioualalen, M., Menkes, C., Delcroix, T., and McPhaden, M.J., 1996. Mechanism of the zonal displacements of the Pacific warm pool: implications for ENSO. *Science,* 274:1486-1490.

[5] Jacobs, G.A., W.J. Teague, J.L. Mitchell, and H.E. Hurlburt, 1996. An examination of the North Pacific Ocean in the spectral domain using Geosat altimeter data. *J. Geophys. Res.* 101(C1):1025-1044.

[6] Walker, G., Correlation and seasonal variation of weather, *Memoirs of Indian Meteorol. Dept.,* 24, 275-332. 1924.

[7] Walker, G., and Bliss, E.W., World Weather, V, *Roy. Meteorol. Soc.,* 4, 53-84, 1932.

[8] Wise, V., Correlation between meteorological conditions and distinct areas on the globe, *Met. Bull.* (Russian), 11, 229-239, 1927.

[9] Smoot, N.C., and Leybourne, B.A., 1997. Vortex structures on the world-encircling vortex street: case study of the Adriatic Basin. *Marine. Tech. Soc. Jour*. 31(2):21-35.

[10] Bowin, C., Purdy, G.M., Johnston, C., Shor G., Lawver, L., Hartono, H.M.S., and Jezek, P., 1980. Arc Continent collision in the Banda Sea region. *Am. Assoc. Petrol. Geol. Bull.* 64, 868-915.

[11] Jongsma, D., Husson, W., Woodside, J. M., Suparka, S., Sumantri, T., and Barber, A.J., 1989. Bathymetry and geophysics of the Snellius II Triple Junction and tentative seismic stratigraphy and neotectonics of the northern Aru Trough. *Neth. J. Sea Res.* 24, 231-250.

[12] Achdan, A. and Turkandi, T., 1982. *Preliminary geologic map of the Kai (Tayandu and Tual) Quadrangles, Maluku*, 1:250,000, and accompanying GRDC File Report.

[13] Charlton, T.R., Kaye, S.J., Samodra, H., and Sardjojo, 1991. Geology of the Kai Islands: implications for the evolution of the Aru Trough and Weber Basin, Banda Arc, Indonesia. *Marine and Petrol. Geol. 8, 62-69.*

[14] Chamalaun, F.H., Lockwook, K., and White, A., 1976. The Bouguer gravity field and crustal structure of eastern Timor. *Tectonophysics* 30, 241-259.

[15] Chamalaun, F.H., Grady, A.E., Von der Borch, C.C., and Hartono, H.M.S., 1981. Banda Arc tectonics: the tectonic significance of the Sumba Island, In: J.S. Watkins and C.L. Drake

(Eds.), *Studies in Continental Margin Geology.* Am. Assoc. Pet. Geol. Mem. 30, 361-376.

[16] Dwiyanto, B., 1985. *Marine geology and geophysics of the northern Banda Sea*. M.S. Thesis, University College London, 94 pp. (unpublished).

[17] Schluter, H.V., and Fritsch, J., 1985. Geology and tectonics of the Banda Arc between Tanimbar island and Aru island. *Geol. Jahrb., Reihe E*, 30, 3-41.

[18] Lapouille, A., Haryono, H., Laure, M., Pramumijoyo, S., and Lardy, M., 1985. Age and origin of seafloor of the Banda Sea (Eastern Indonesia). *Oceanologica Acta* 8, 379-389.

[19] Lee, C.S., and McCabe, R., 1986. The Banda-Celebes-Sulu basin: a trapped piece of the Cretaceous-Eocene oceanic crust? *Nature, Lond.* 322, 51-54.

[20] Hartono, H.M.S., 1990. Late Cenozoic tectonic development of the Southeast Asian continental margin in the Banda Sea area. *Tectonophysics* 181, 267-276.

[21] Heirtzler, J.R., Cameron, P., Cook, P.J., Powell, T., Roeser, H.E., Sudardi, S., and Vevers, J.J., 1978. The Argo Abyssal Plain. *Earth Planet Sci. Lett.*, 41: 21-31.

[22] Haile, N.S., 1978. Paleomagnetic evidence for the rotation of Seram, Indonesia. *J. Phys. Earth*, 26 (Suppl.): S191-S198.

[23] Otofuji, Y.I., Sasajima, S., Nishimura, Yokoyama, I., Hadiwisastra, S., and Hehuwat, F., 1981. Paleomagnetic evidence for the paleoposition of Sumba island, Indonesia. *Earth Planet Sci. Lett.*, 52: 97-100.

[24] Wensink, H., Hartosukorahardjo, S., and Kool, K., 1987. Paleomagnetism of the Nakfunu Formation of Cretaceous age, western Timor, Indonesia. *Geol. Mijnbouw*, 66: 89-99.

[25] Audley-Charles, M.G., 1981. Geometrical problems and implications of large-scale over-thrusting in the Banda arc-Australian margin collision, McClay, K., and Price, N. eds., *Thrust and nappe tectonics*: Geological Society of London Special Publication 9, 407-416.

[26] Hamilton, W., 1979. Tectonics of the Indonesian Region. *Geol. Surv. Prof. Paper 1078*, U.S. Govt. Printing Office.

[27] Cardwell, R.K. and Isacks, B.L., 1978. Geometry of subducted lithosphere beneath the Banda Sea in eastern Indonesia from seismicity and fault plane solutions. *J. Geophys. Res.* 83, 2825-2838.

[28] Rehault, J.P., Malod, J.A., Larue, M., Burhanuddinn, S., and Sarmili, L.,1991. A new sketch of the central North Banda Sea, Eastern Indonesia. *J. of Southeast Asian Earth Sciences*, 6: 329-334.

[29] Karta, K., 1985. Etude geodynamique de la mer de Banda (Indonesie) par interpretation des donnees magnetiques et gravimetriques. *These de Docteur-Ingenieur*, Universite de Bretagne Occidentale, Brest.

[30] Silver, E.A., Gill, J.B., Schwartz, D., Prasetyo, H., and Duncan, R.A., 1985. Evidence for a submerged and displaced continental borderland, North Banda Sea, Indonesia. *Geology* 13, 687-691.

[31] Charlton, T.R., 1991. Postcollision extension in arc-continent collision zones, eastern Indonesia. *Geol. 19, 28-31*.

[32] Meyerhoff, A.A., Taner, I., Morris, A.E.L., Martin, B.D., Agocs, W.B., and Meyerhoff, H.A., 1992. Surge tectonics: a new hypothesis of Earth dynamics, In: *New Concepts in Global Tectonics*. eds. S. Chatterjee and N. Hotton III. pp. 309-409. Lubbock. Texas Tech University Press.

[33] Meyerhoff, A.A., Taner, I., Morris, A.E.L., Agocs, W.B., Kamen-Kaye, M., Bhat, M.I., Smoot, N.C., and Choi, D.R. 1996. *Surge Tectonics: A New Hypothesis of Global Geodynamics.* ed. D. Meyerhoff Hull, Kluwer Academic Publishers. 317 pp.

[34] van Marle, L.J., 1991. Late Cenozoic paleobathymetry and geohistory analysis of Central West Timor, eastern Indonesia. *Marine Petrol. Geol*. 8, 22-34.

[35] Leybourne, B.A., 1998. Surge Theory vs. Plate Theory: El Nino has The Last Word - A Theoretical Discussion of the Driving Force Behind El Nino. New Concepts in Global Tectonics conference proceedings at Tuskba Research Center, Japan, Nov. 1998.

[36] Leybourne, B.A., 1998. Implications of Surge Tectonics, Gravitational Teleconnection, and Milankovitch Series Correlations. New Concepts in Global Tectonics Newsletter, June, No. 7, p. 8.

[37] Smirnoff, L.S., 1992. The contracting-expanding Earth and the binary system of megacyclicity. In: *New Concepts in Global Tectonics*. eds. S. Chatterjee and N. Hotton, III. pp. 441-449. Lubbock. Texas Tech University Press.

[38] Wezel, F.C., 1992. Global change: shear-dominated geotectonics modulated by rhythmic Earth pulsations. In: *New Concepts in Global Tectonics*. eds. S. Chatterjee and N. Hotton, III. pp. 421-439. Lubbock: Texas Tech University Press.

[39] Fukao, Y. and Kiluchi, M., 1987. Source retrieval for mantle earthquakes by iterative deconvolution of long-period P-waves. *Tectonophysics*, 144: 249-269.

[40] Hirata, K. and Kawasaki, I., 1995. Spatio-temporal moment-tensor inversion for multiple shock: an application to the deep 1972 Banda Sea earthquake. *Physics of the Earth and Planetary Interiors*, 91: 229-244.

[41] Walker, Daniel A., 1988. Seismicity of the East Pacific: correlations with the Southern Oscillation Index? *EOS Trans. AGU.* 69:857.

[42] Walker, Daniel A., 1995. More evidence indicates link between El Niños and seismicity. *EOS Trans. AGU. 76 (33).*

[43] Walker, Daniel A., and Hammond, S.R., 1990. Spatial and temporal distributions of T-phase source locations on the Juan de Fuca and Gorda Ridges. *EOS Trans. AGU.* 71:1601.

[44] Walker, Daniel A., 1999. Seismic Predictors of El Nino Revisited. *EOS Trans. AGU, 80 (*25).

[45] Francis, O., Ducarme, B., and Van Ruymbeke, M., 1997. One year of registration with the C021 cryogenic gravimeter at station Membach (Belgium). In: *Gravity, Geoid and Marine Geodesy* eds.

Segawa et al. v. 117, pp. 336-342. International Association of Geodesy Symposia, Berlin Heidelburg: Springer-Verlag.

[46] Leybourne, B.A., and N.C. Smoot, 1997. Ocean basin structural trends based on GEOSAT data. *Proceedings of Gulf Coast Section of Marine Technology Society*. Stennis Space Center Conference, April 23-24, 1997. Pp. 135-140.

[47] Leybourne, B.A., 1997. Earth-Ocean-Atmosphere coupled model based on gravitational teleconnection. *Proc. Ann. Meet. NOAA Climate Monitoring Diag. Lab.* Boulder, CO. March 5-6, p. 23. Also: *Proc. 1997 Joint Assemb. IAMAS-IAPSO.* Melbourne, Au. July 1-9. JPM9-1.