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PLATE TECTONIC ACCELERATIONS HIDDEN IN THE NOISE

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ABSTRACT

Iterative filtering of the quaternion history for the Euler poles that define absolute plate motion history for the past 68 million years has revealed an unprecedented precision for plate angular rotation variations with time at 2-million year intervals. These consistent velocity variations yield, in turn, consistent estimates of plate accelerations, and therefore. indicate that conservation of plate angular momentums' must be globally conserved. Accordingly, if a plate decelerates, other plates must increase their angular momentums to compensate. Plate accelerations support the contention that Plate Tectonics is a product of forces that most likely are sustained by the sinking of positive density anomalies due to phase changes in subducted gabbroic lithosphere at depth in the upper lower mantle. The tectonic plates are pulled along by the sinking positive mass anomalies, rather that moving at near constant velocity on the crests of convection cells driven by rising heat. In this interpretation, spreading centers become passive reactive features, and fracture zones (and wedge-shaped sites of seafloor spreading) are adjustment zones that relieve strains in the lithosphere.

This report summarizes processing results for 12 of the 14 major tectonic plates of the Earth (except for the Juan de Fuca and Philippine Plates) and presents estimates of the changes in magnitude and location of the Earth's axis of total plate tectonic angular momentum for the past 62 million years.

INTRODUCTION

The author had the pleasure of being a graduate student of Harry H. Hess, and being the first Princeton University graduate student, as part of Harry's Caribbean Research Project, to conduct geologic mapping in the Dominican Republic. When Harry gave me a copy of his December 1960 preprint "Evolution Ocean Basins", I was initially skeptical of his broad conclusions on the internal workings of the Earth, but pleased for his sole acknowledgement. His conclusion 14) "The continents are carried passively on the mantle with convection and do not plow through oceanic crust" was the heart of his new vision. And, his conclusion 13) " Rising limbs coming up under continental areas move the fragmenting parts away from one another AT A UNIFORM RATE so a truly median ridge forms as in the Atlantic Ocean [Emphasis added]". Hess's Preprint (1990) was eventually published in Hess (1962). After Hess's passing, Bowin (1987) tried to reconstruct why that acknowledgement was there.

With the introduction of the Vine and Matthews (1963) explanation for the magnetic stripes over oceanic crust being revealed by ship and airborne magnetometers, as resulting from alternately polarized crust that recorded time variations in the polarity of the Earth's north magnetic pole; Dietz's (1961a, 1961b) proposing the name 'seafloor spreading'; and then came the hypothesis of hot-spot plumes (Wilson, 1963, 1965) creating volcanic edifices on the ocean floor, but presumed to originate from depths in the lower mantle, perhaps from close to the core-mantle boundary (CMB), because the trends of such chains of prior extinct older, and more submerged, volcanic seamounts show no relation to the relative motions between the tectonic plates which they puncture. Morgan (1971, 1972, 1973) used Euler poles to elucidate mathematically the spreading history of plates away from 'mid-ocean spreading centers', and to estimate plate absolute motions. Forsyth and Uyeda (1975) concluded that "…all the oceanic plates attached to substantial amounts of downgoing slabs move with a 'terminal velocity'. Thus in a little more than a decade, Plate Tectonics became the dominant hypothesis for understanding the tectonics of the Earth. Many investigators concentrated on analyzing possible internal convection models that might produce the observed surface pate tectonics by using theoretical and computer simulation approaches (eg. Richard, et al. 1993; Bercovici, et al., 2000). Gripp and Gordon (2002) noted that the current rotation rate of the HS3-NUVEL1A solution is approximately 50 percent faster than the average rotation rates since 0-47 Ma of Watts et al. (1988) or of Petronotis and Gordon (1999). Now, as Plate Tectonics approaches its 50th anniversary, details of its very low plate accelerations are being revealed.

Initially the hotspot traces were considered to provide a means of determining absolute motions of the plates with respect to fixed source sites near the base of the mantle just above the CMB. There was then debate as to whether or not the Atlantic and Indian Ocean hotspot plumes are, or not, fixed in regard to each other and to the Pacific Ocean hotspots. Then further considerations of varying mantle viscosities with depth in the mantle, suggested to some investigators, that a plume's vertical trajectory may shift laterally with respect to its deeper mantle source site as it rises, and thereby explain why the bend in the Pacific Ocean's Emperor-Hawaiian seamount chain is only noted in the Pacific Plate (Cande et al., 1995; Steinberger and O'Connell, 2000). Douglioni, et al., 2005, offer the suggestion that the Hawaiian hotspot may originate within the asthenosphere If either of these hypotheses is the case, then hotspot tracks would not provide a link to absolute plate motions without secure knowledge of convective motions in the Earth's mantle. Torsvik, et al., 2008 develop a "hybrid" model from analyses of four different reference frames (paleomagnetic, African fixed hot spot, African moving hot spot, and global moving hot spot), and conclude that "….there is still no generally accepted mechanism that consistently explains plate tectonics in the framework of mantle convection".

Norton (1995, 2000, Fig. 10) superimposed transposed past locations on Asia, Africa, Antarctica, India, Australia plates, North America, and South America, relative to the Indo-Atlantic hotspot reference frame, as if they had converged upon Hawaii. Only the North America and South America transposed traces show bends in their traces near 47 Million years, but the bend locations are not coincident with the bend location in the Emperor-Hawaii seamount chain

Although my principal research activities at the Woods Hole Oceanographic Institution (WHOI) were involved in developing and managing a real-time marine gravity program, and using gravity observations to elucidate Earth structures. Marginal forays were made into plate tectonics (Bowin, 1973, 1974, 1976, 1991); the structure of the Moon (Bowin,1975; Bowin, Simon, and Wollenhaupt, 1975); Venus (Bowin, 1975, 1983; Bowin, Abers, and Shure, 1985); or Mars (Bowin, 1976, 1997). My unconventional geologic approach to gravity geophysical analyses led me to a decomposition of the Earth's gravity field (Bowin, 1983, 1986, 2000; Bowin et al 1982; Bowin, Scheer, and Smith, 1986) utilizing ratios of gravity to geoid at the centers of the Earth's major geoid anomalies. These studies provided a decomposition of the planet's potential field into three main component packets of spherical harmonic degrees. The greatest contribution to the Earth's geoid comprises degrees and orders 2-3 (which have equivalent point mass depths deeper than the CMB at 2,900 Km, and have the Earth's greatest mass anomalies [2-4x10^{22} grams]). The second greatest geoid contribution arises from degrees 4-10, which reveal bands of positive geoid anomalies beneath the sites of plate subduction that have the Earth's second greatest mass anomalies [3-7x10^{21} grams]; and thirdly, the geoid packet of degrees 11-infinity (which have the smallest mass anomalies [10^{19} – 7x10^{20} grams}, but being near the Earth's surface, they dominate the contributions to the Earth's surface gravity anomalies.. These interpretations were convincing to me, but contrary to the prevailing hypothesis of dynamic viscous mantle flow, which explained the lack of correspondence between the Earth's geoid anomalies and surface plate tectonics because of an inferred triplet of mass anomalies associated with subducting plates (Hager and O'Connell, 1981; Hager, 1984; Ricard, et al, 1993). The triplet comprises two negative mass anomalies (one at the seafloor where the lithosphere is depressed downward – displacing ocean crust by water – from the downward motion of the subducted sinking slab; and the other at the core-mantle boundary (CMB), where the nickel-iron of the core is depressed toward the center of the Earth by the subducting silicate slab pressing downward on the CMB. The positive mass anomaly, that drives the two negative viscous flow interface deformations, is the positive mass anomaly within the subducted slab due to mineral phase changes in the gabbroic crust when taken to depth in the peridotitic mantle. This hypothesis was very compelling until the gravity to geoid anomaly ratio of the South American Andes subduction zone was analyzed (Bowin, 2000, Fig. 13 (SA)), and all geoid derivatives have a common equivalent single positive point mass source at about 1,200 km depth was indicated for all harmonic degrees 2 to 30. This is contrary to the triplet mass anomaly distribution expected from the dynamic viscous mantle flow models. Note, also, that the South American Andes geoid high is the only subduction geoid high of the 4-10 degree geoid field that is evident in the global geoid field. Although viscous mantle flow should produce surface and deep boundary deflections, for the Earth, I infer such deflections must be minimal. Slab densities identified in forward modeling (Bowin, 2000) are about 200 times smaller than those used in the dynamic topography modeling, yet yield driving force estimates that agree with prior force estimates based on thermal modeling, further suggesting that the dynamic topography solutions had to overestimate subduction densities in order to effect sufficient deflections on the surface and CMB to produce their great degree 2-3 contributions of the Earth's gravity field. Hence, I turned to examining plate tectonic motions in an attempt to find a relationship with the distribution of positive lower mantle density anomalies that appear in the spherical harmonic geoid degree 4-10 packet cited above. And, that relation is now herein revealed.

IMPROVED RESOLUTION OF ABSOLUTE PACIFIC PLATE MOTIONS

Harada and Harmano (2000) provided a new way for geometrically estimating past Euler pole positions; evenly distribute in time (at 2 or 4 Ma) intervals. Their method assumed a fixed hot-spot reference frame, and depended upon the existence of three hot-spot tracks (Emperor-Hawaiian, Easter-Line, and Louisville) delineated on satellite gravity maps (Sandwell and Smith, 1992).on the same Pacific plate. Using the spherical triangle defined by the present day locations for those three hot-spots as a fixed template for identifying, which past points, along each plume trace congruently link together. Then by using the conjugate points along the Emperor-Hawaiian and Louisville seamount chains, they could, one at a time, bisect the arc between such point and its' zero age location. Each arc separation distance represents an accumulation rotation angle from the present day location back to a prior time. Using the two great circle arcs, normal's to each of the two arcs at their bisect locations, their point of intersection were then calculated. The sites of intersection of the Emperor-Hawaiian with the Louisville bisect great circle arcs, then provide an estimate of the location for the accumulative plate rotation axis (an Euler pole) for each conjugate point along the plume traces. For the more recent ages, the arc lines to be bisected become shorter and shorter, leading to less precise estimates of the accumulation rotation pole axes. Harada and Harmano (2000) then used those calculated Pacific Plate rotation poles to estimate plume tracks for Bowie, Cobb, Carolina, Guadalupe, Socorro, Marquesas, Pitcairn, Macdonald, Phoenix, foundation, Gilbert-Marshall, Tahiti, and Samoa seamount chains with rather compelling success (their Plate 1) without using age data. Such results support the assumption of a fixed hot-spot reference frame for the entire Pacific plate. To assign ages to the geometrically established plume-trace points, they then plotted the accumulation angle verses radiometrically established ages from rocks along the plume traces to calibrate the ages of the total rotation points along each plumes trace (Their Fig. 4). For this study, a digital file of the 2 Ma accumulation pole data of their Table 3 was prepared (see Appendix A).. Latitude and longitude had to be time shifted to be associated with the end of each time interval (rather than the beginning as published, so as to be compatible with Jason Morgan's Fortran code 'mpfin.f' received from Gary Acton, which was modified to accommodate the author's data file needs, and renamed mpfinf3.f

A Quicktime movie of Harada and Harmono (2000) Pacific plate absolute motions from 68 Ma at 4Ma intervals (Bowin . 2004; Bowin and Kuiper, 2005) can be viewed at www.whoi.edu/scc No. 12.. The changing velocity colors in that movie was the first clear demonstration of Pacific Plate acceleration. The somewhat erratic location movements of the Pacific plate at 4 Ma intervals in that movie, as well as the small irregularities in the positions and spacing's of the Pacific plate Euler Poles, although much smoother and consistent than previously published results, suggested that, most likely, the Pacific plate history would, in reality, have had a much smoother and coherent motion history.. A manuscript submitted to Science in 2005 following Bowin (2004) stated "… Now with clear evidence that plates do accelerate, perhaps other new insightful ways will be able to glean acceleration rates of other plates, and lead to refined estimates of the Earth's total angular momentum for controlling plate tectonics", but was rejected without comment. The present paper now provides such estimates.

FILTERING OF EULER POLES

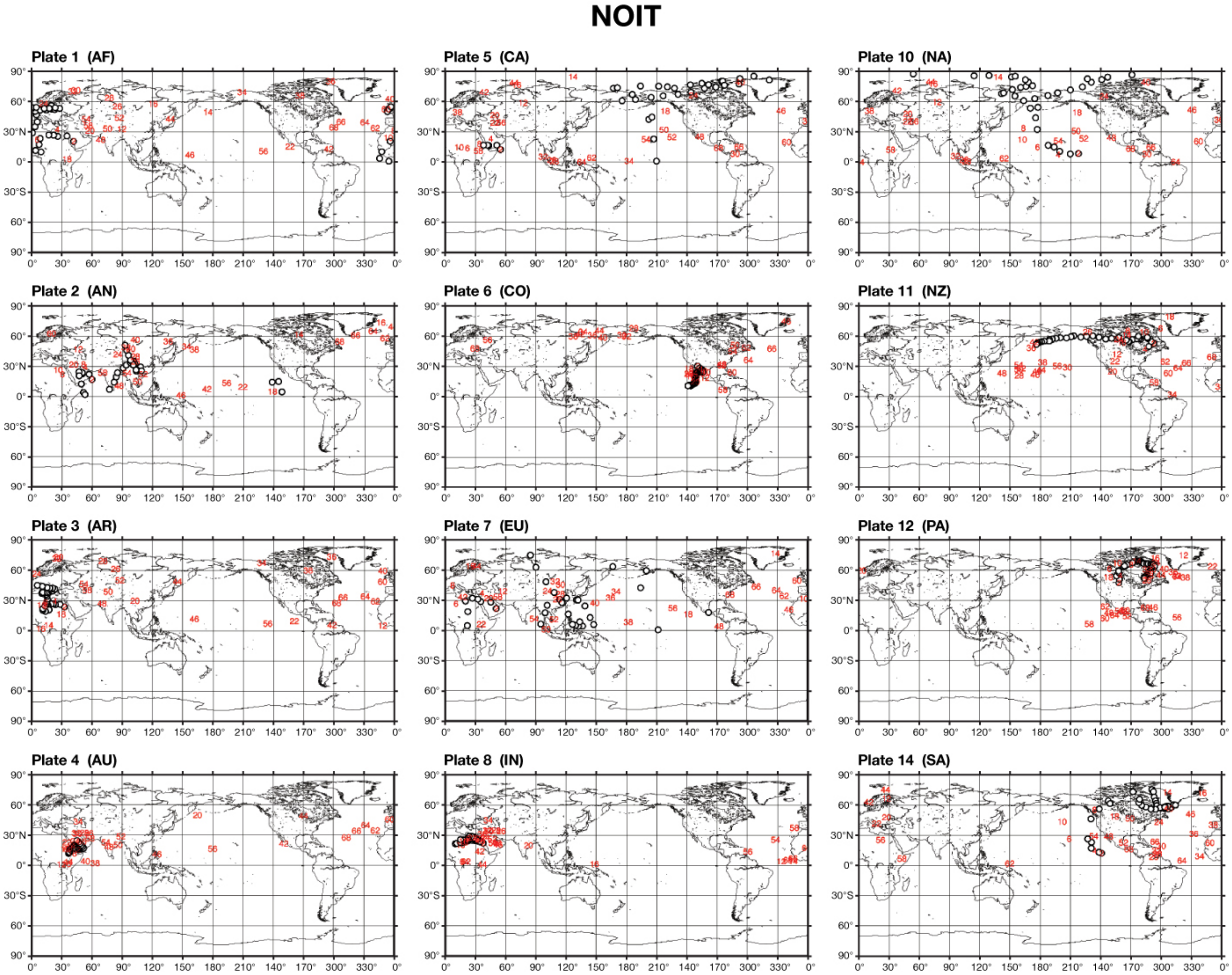
The Pacific Plate was originally documented (Bowin, 2004) to have had two periods of acceleration during the past 68 million years. That conclusion was obvious from a plot of maximum velocities for the Pacific plate attained using the 4 Ma spaced stage poles of Harada and Harmano (2000)., and is also clear in the color velocity changes shown by the Pacific Plate in the QuickTime movie viewable at www.whoi.edu/scc. No. 12. Furthermore, the maximum velocity vectors for the 66 to 48 Ma period point toward Sakalin (the easternmost edge of the North American Plate) for the stage poles from the Emperor seamount chain, but towards the Philippine arc for the stage poles along the Hawaiian trend (see appropriate figure in Bowin and Kuiper, (2005) poster, viewable at ftp://ftp.whoi.edu/pub/users/cbowin named poster_agu_2005.pdf). My interpretation then, and now, is that deep positive mass anomalies (from phase changes, such as pyroxene to spinel, in subducted lithosphere) provides the mass anomalies observed in the degree 4-10 packet of geoid anomalies, and provides the driving force for plate tectonics (Bowin, 2000). The change in direction of the Pacific plate maximum velocity vector between 48 Ma and 44 Ma resulted in a shift from underthrusting the westernmost edge of the North American plate to underthrusting the Philippine and Eurasian plates at about 46 Ma. Conrad and Lithgow-Bertelloni (2002) concluded previously that subductiion is the primary driver for plate tectonics.

Because the Earth assuredly did not move the Pacific Plate along the somewhat erratic stage pole pattern of Harada and Harmano (2000), some method for filtering (smoothing) a series of Euler pole quaternions was sought to obtain a more realistic progression for the motions that the Pacific Plate may have actually followed.

How to filter (smooth) a series of Euler poles became the next objective, which the author likens to that of applying a spline function with adjustable tension across a series of Euler poles? A web search did not provide an answer, but did indicate the existence of the" CwMtx library for matrix, vector and quaternion math" written in C++ by Harry Kuiper. Following an exchange of emails, Kuiper prepared a quaternion filter routine that has been used for iterative smooth filtering of the Pacific, and other plate, Euler poles, for this study.

The quaternion filtering routine provides for selecting the number of iterations to be used, and for subdividing a sequence of quaternions (from Euler or stage poles) into separate segments if desired. Our first use was to filter the 68 Ma to 0 Ma set of Pacific plate Eluer poles (identified by "NOIT", for no iterations), as two segments divided at 46 Ma (68-46 Ma and 46-0 Ma), identified by "4448", and later a second test used three segments divided at 46Ma and at 20Ma (68-48 Ma, 46-22 Ma, and 20-0 Ma) identified by "2046". The use of an iteration number of 1, makes very little change to the original Euler pole locations, whereas an iteration number of 1,000,000 reduces the original Euler pole series to essentially a single Euler pole near the original's mid-point. The first results (Bowin and Kuiper, 2005) were presented at a Poster Session during the 2005 Spring AGU Meeting in Montreal, Canada used 1000 iterations [Poster viewable at ftp://ftp.whoi.edu/pub/users/cbowin as "poster_agu_2005.pdf"]. For this present paper, however, an iteration number of 2^{10} (= 1024) is used. As noted above, the youngest Pacific Euler pole locations had very short arc distances to be bisected, and thus those poles had the largest uncertainties. For this study the 6, 4, 2 Ma Pacific Euler pole data were replaced with interpolated values between the filtered 8 Ma Euler pole and the 0 Ma absolute Euler pole data from Gordon and Jurdy (1986) and Gripp and Gordon (1990).

Various tests using the Euler pole histories of Gordon and Jurdy (1986). Gripp and Gordon (1990). Engebreton, Cox, and Gordon (1986), and Jin and Zhu (2004) were initially conducted, but I concentrated on using the Harada and Harmano (2000) data which provided absolute Pacific Plate Euler pole estimates at 2 Ma intervals. These estimates provided a primary hot-spot reference for converting relative poles between two plates into estimates of each plates' absolute Euler poles, also at 2Ma intervals, via the program modified from Morgan's original Fortran program. Morgan's code allowed positive or negative rotations depending upon the order in which the two input Euler poles were processed. That is why the Pacific plate Euler poles before filtering plot in the northern hemisphere (Figure 1), whereas later, after quaternion filtering, using the normal convention (right-hand-rule) that Euler rotations are always positive, the filtered Pacific plate Euler poles plot in the southern hemisphere (Figure 2 for 4448 data, and Figure 3 for 2046 data).



NOIT

Plate 1 (AF)

Plate 5 (CA)

Plate 10 (NA)

Plate 2 (AN)

Plate 6 (CO)

Plate 11 (NZ)

Plate 3 (AR)

Plate 7 (EU)

Plate 12 (PA)

Plate 4 (AU)

Plate 8 (IN)

Plate 14 (SA)

Figure 1. Plots of NOIT Euler and stage pole locations (red numbers for million years).

The most striking filter result shown in the 2005 AGU poster was the mirroring of the bend in the Emperor-Hawaiian seamount chain in the locations of the 4448 filtered stage pole locations for the absolute motions of the Nazca plate (plate No. 11, Fig. 2). Pulling this striking result out the noise of the quasi random stage pole locations before filtering (Fig. 1), indeed, gave credence to this quaternion filtering methodology. Interestingly, and probably profound, for understanding the tectonics of Plate Tectonics, is that, of the 14 plates analyzed, the Nazca plate is the only one that has a pattern revealing such a bend in stage pole trend at 46 Ma. The Nazca plate data 2046 filtered stage poles (Fig. 3, Plate No. 11) is more curved, and dose not have a sharp change of trend at 46 Ma, suggesting that a lower number of iterations would here produce better resolution of plate motion details for the three-segment analyses. However, it is interesting to note that in Norton (2000, Fig. 10) that both North America and South America motions relative to the Pacific show sharp changes in linear trend near 47 Ma when translocated to start at Hawaii. The North America-Pacific boundary is a subduction/transcurrent fault (San Andreas) zone; and the South America-Nazca boundary is one of subduction of the Nazca Plate. In the same figure, the Australian Plate also shows a sharp change of trend at 47 Ma, but only of about 40 degrees, rather than the near 60 degree change of the North and South America plates, and the Emperor-Hawaiian seamount bend. However, the Euler poles used by Norton had not been filtered.

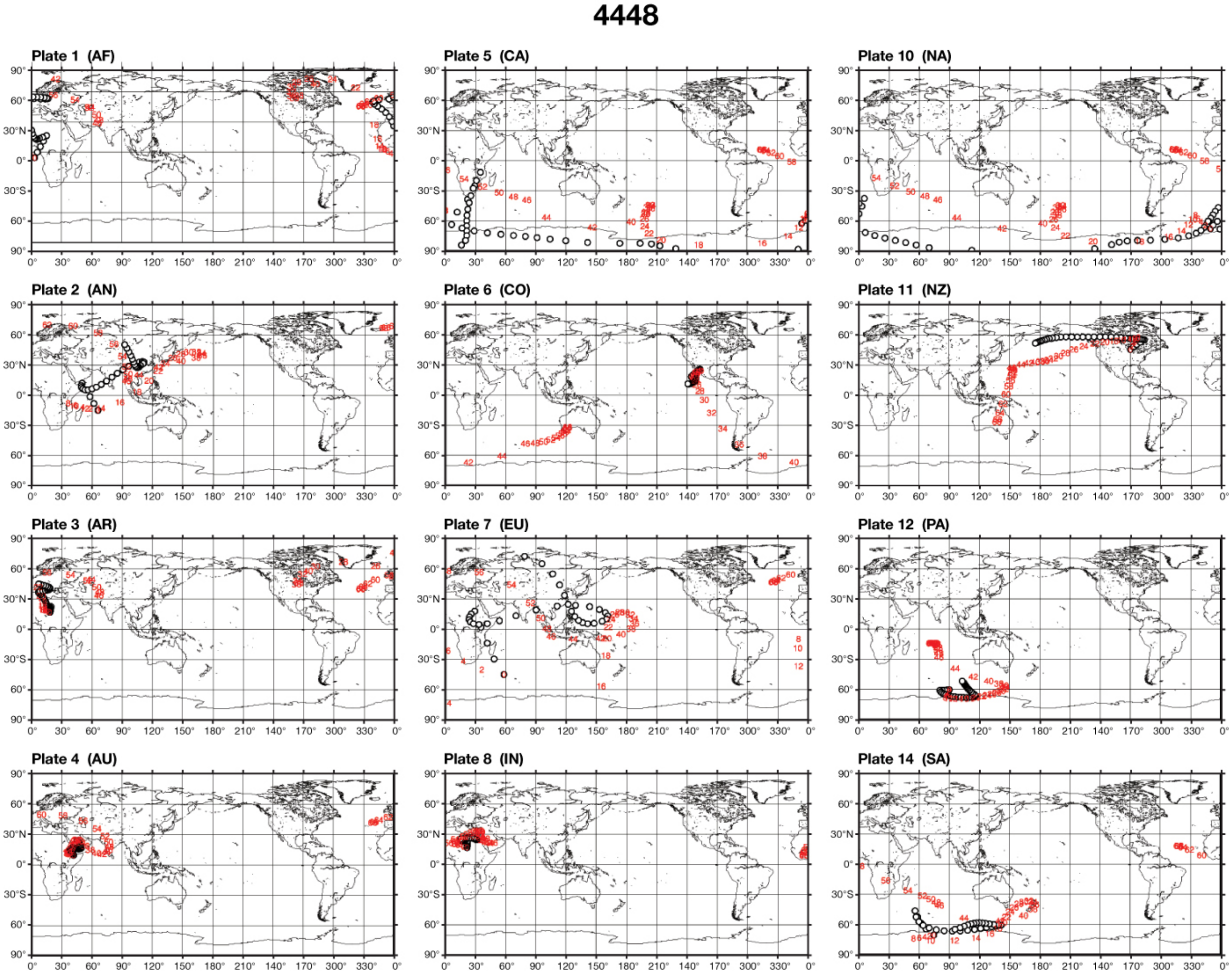


Figure 2. Plots of 4448 Euler and stage pole locations (red numbers for million years).

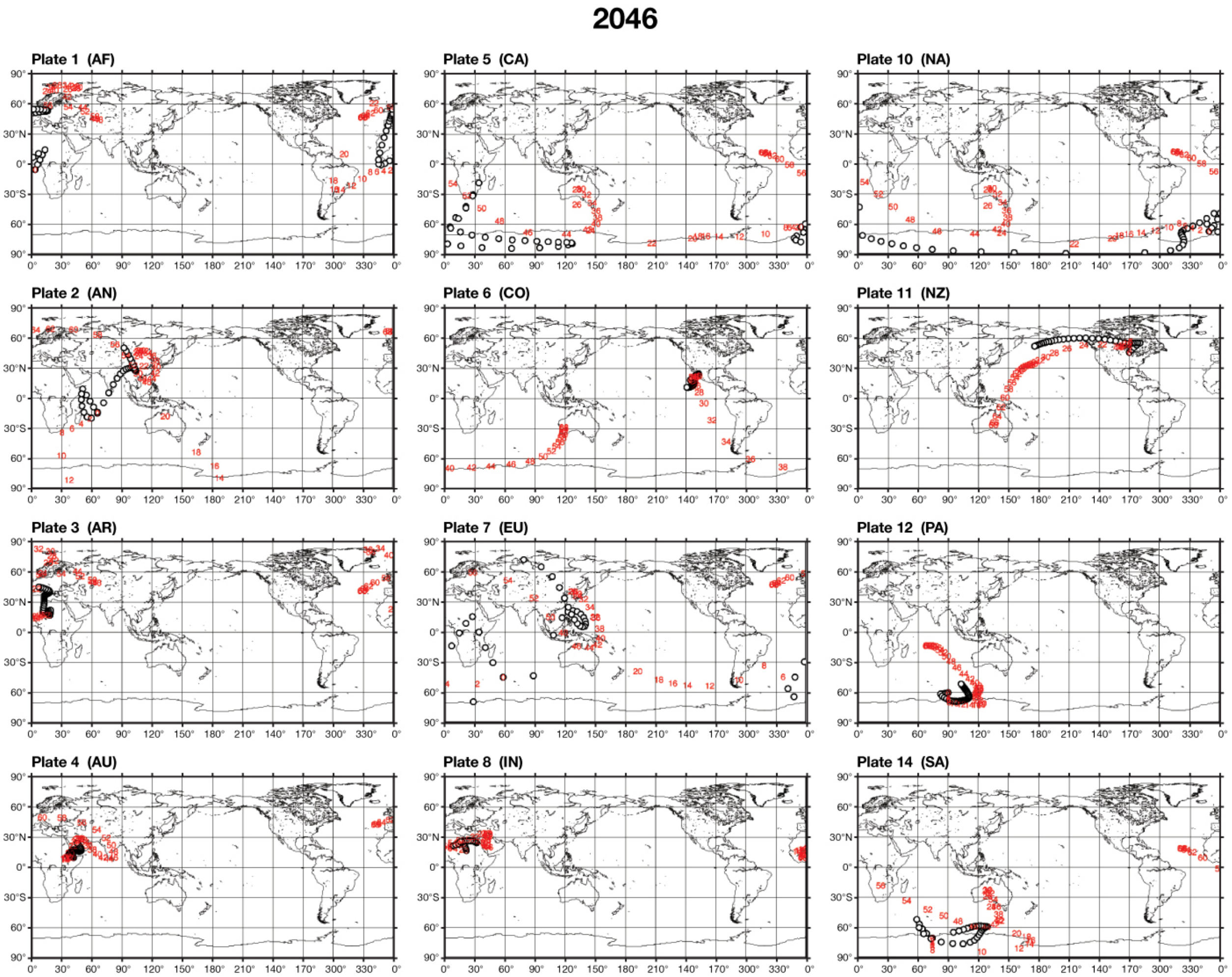


Figure 3. Plots of 2046 Euler and stage pole locations (red numbers for million years).

Maximum plate velocity data for the NOIT, 4448, and 2046 quaternion filtering verses time are displayed in Figure 4, for PA Plate [12], NZ Plate [11], AU Plate [4], and AF Plate [1], along with the velocity vector's azimuth, and acceleration (in mm/yr/Ma). Plots for all filtered plates are given in Appendix B. These plots demonstrate smoothly varying plate velocities, and, in turn, provide the first comprehensive estimates of the plates' low acceleration values (mm/yr/Ma). Fig. 4 shows both similarities and differences between these initial 4448 two-segment, and the 2046 three segment quaternion filtering results. Future quaternion filterin tests are continuing.

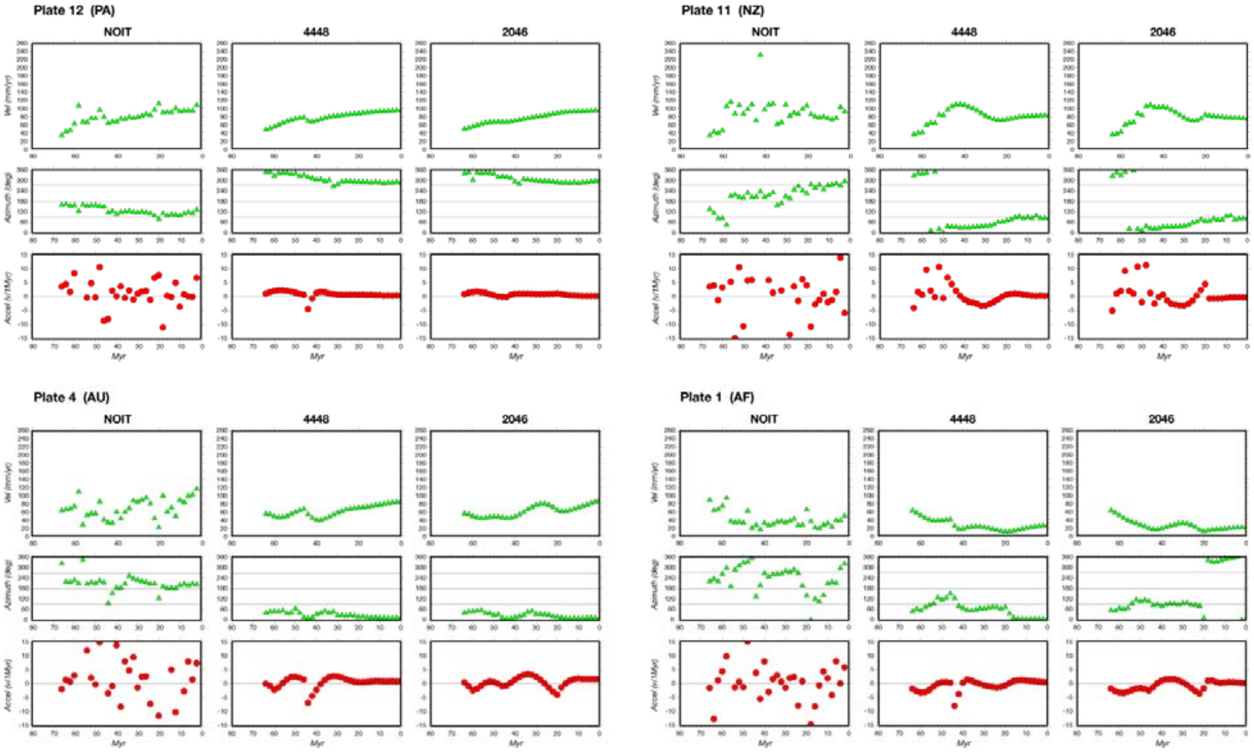


Figure 4. Maximum velocity (mm/yr), azimuth (degrees), acceleration (mm/yr/Myr) for NOIT, 4448, 2046 for plates 12 (PA), 11 (NZ), 4 (AU), 1 (AF) for 68-0 Myr.

PLATE TECTONICS AND CONSERVATION OF ANGULAR MOMENTUM

The exceedingly low acceleration rates for the Earths tectonic plates clarifies why the early ‘no net torque’ or ‘dynamical equilibrium’ assumptions for global plate reconstructions provided reasonable assessments of the relative magnitudes for possible driving forces (Morgan, 1973; Tullis and Chapplle, 1993; Soloman and Sleep, 1974; Forsyth ane Uyeda, 1975). And, also why the concept of large-scale mantle convection cells transporting the overriding plates at constant velocities over extended time periods seemed so reasonable. However, the velocity and acceleration data shown in Figure 4 (4448 and 2046), and those in appendix B, demonstrate that the plates do accelerate and decelerate. Therefore, plate tectonics is governed by conservation of angular momentum. Thus, if the angular momentum of one plate decreases, the angular momentum of some other plates must increase to conserve a constant global angular momentum.

To test how well our quaternion filtered plate data for 14 plates, at 2 Ma intervals, might demonstrate such a global conservation of angular momentum, the following steps were taken.

(1) A 1-degree global latitude (-90 to +90) and longitude (0 to 259) grid was generated (area of each cell varies as a function of latitude), and files of 1-degree spaced data were produced for each plate at zero Ma (the present time).

(2) A Perl script was written (which eventually grew to 50+ pages) to aid consistent processing of 14 plates through steps at 2 Ma intervals, from 68 to 0 Ma, for processing, listing, graphic plotting, display, and printing of intermediate and combined final results. The

processing was done initially on an SGI Indigo computer with IRIX operating system, and later on a PC computer running Cygwin under Microsoft Windows 2000Pro or XP operating systems. Each plate grid point normally comprised 15 binary values, but for some steps, ASCII files with fewer variables sufficed. The Perl script aided in combining operations utilizing Fortran 77, C, C++, GMT scripts, awk, sed, cc, cp, ls –l, and Enscript commands.

(3) Global gravity data (Bowin, 2000, Sandwell and Smith, 1992) demonstrate that most of the Earth's surface is within 40 milligals of zero, and hence is in isostatic equilibrium. Following Hess (1960, Fig. 2) I adopted 11,775 Kgm as the mass of a 40 km thick column, 1 cm^2 of lithosphere for a mean isostatic Earth column.

(4) Calculation of each plates's 1 deg cell moment of Inertia assuming lithospheric mass (11,775 Kgm/cm^2) lies at 75 km depth, the mid point of a 150 km thick lithosphere.

(5) Summing 1-deg cell moment of inertia contributions to obtain a plate's angular momentum at 2 Ma intervals. Results for different mass and lithosphere thickness assumptions can be estimated by multiplying these estimated angular momentum values by a scaling factor to account for differing assumptions.

(6) Sum estimates of plate angular momentums for all plates at each 2 Ma interval. For these initial estimates, plates 9 (Juan de Fuca) and plate 13 (Philippine), and the Scotia plate were left unprocessed because of limited age rotation data.

(7) The angular momentum history for the 4448 quaternion filtered data (1024 iterations) is shown in Figure 5.

(8) The angular momentum history for the 2046 quaternion filtered data (1024 iterations) is shown in Figure 6.

GLOBAL PLATE VELOCITY MAP IMAGES

The computations of plate angular momentums referred to above utilized 1-deg grid files (for each plate, at each 2 Ma time) of stage pole velocity and azimuth at each grid point For each 2 Ma age, the individual plate velocity grid point values were added to an empty 1-deg data grid in the following plate order: 1,2,3,10,14,7,12,4,8,11,6. If a plate velocity value had previously been assigned to that grid cell, then the new velocity value would not displace the prior one. This procedure reduced the number of 'black spots' that result from contour lines around errant velocity values. White numbers are plotted at the location of each plates stage pole for that Ma plot. A red star plotted at the location of the Total Angular Momentum pole is also plotted for the 62 to 0 Ma plots. Again, data for plates 5 (Caribbean), 9 (Juan de Fuca), and 13 (Philippine), as well as the Scotia Sea, were not included Plate 6 (Cocos) was included, but since its data range is only 0 to 26 Ma, the older results are not reliable.

These stage pole velocity maps were assembled into two QuickTime movies: one for the 4448 quaternion filtering [4448_y3map_1.mov], and the other for the 2046 quaternion filtering [2046_y4map_1.mov]. Both were computed using 1024 iterations for the smoothing process, and can be downloaded from ftp:/ftp.whoi.edu/pub/users/cbowin.

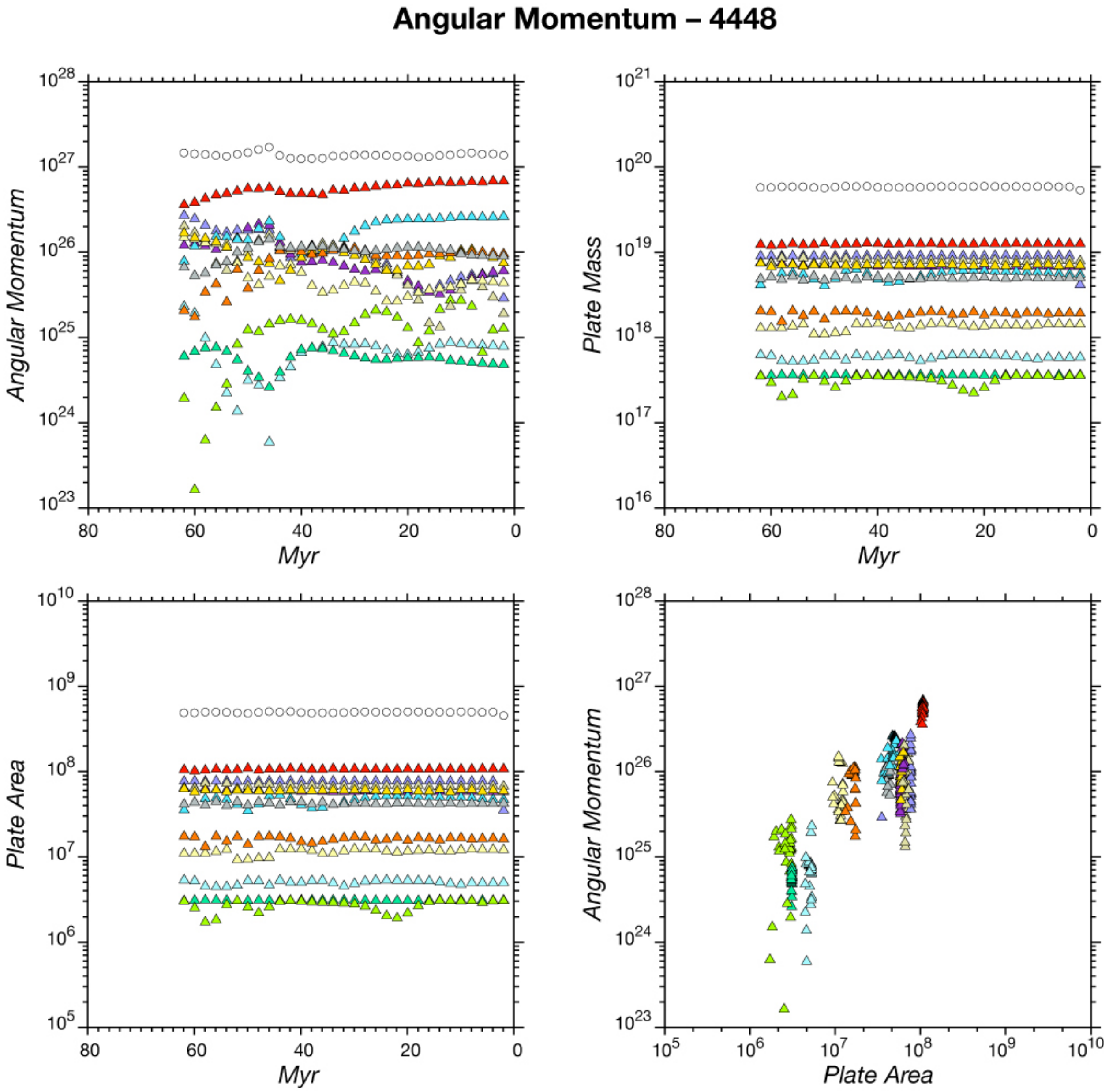


Figure 5. Angular momentum, plate mass, plate area and angular momentum vs. plate area for the 4448 filtered data for 62 - 0 Myr.

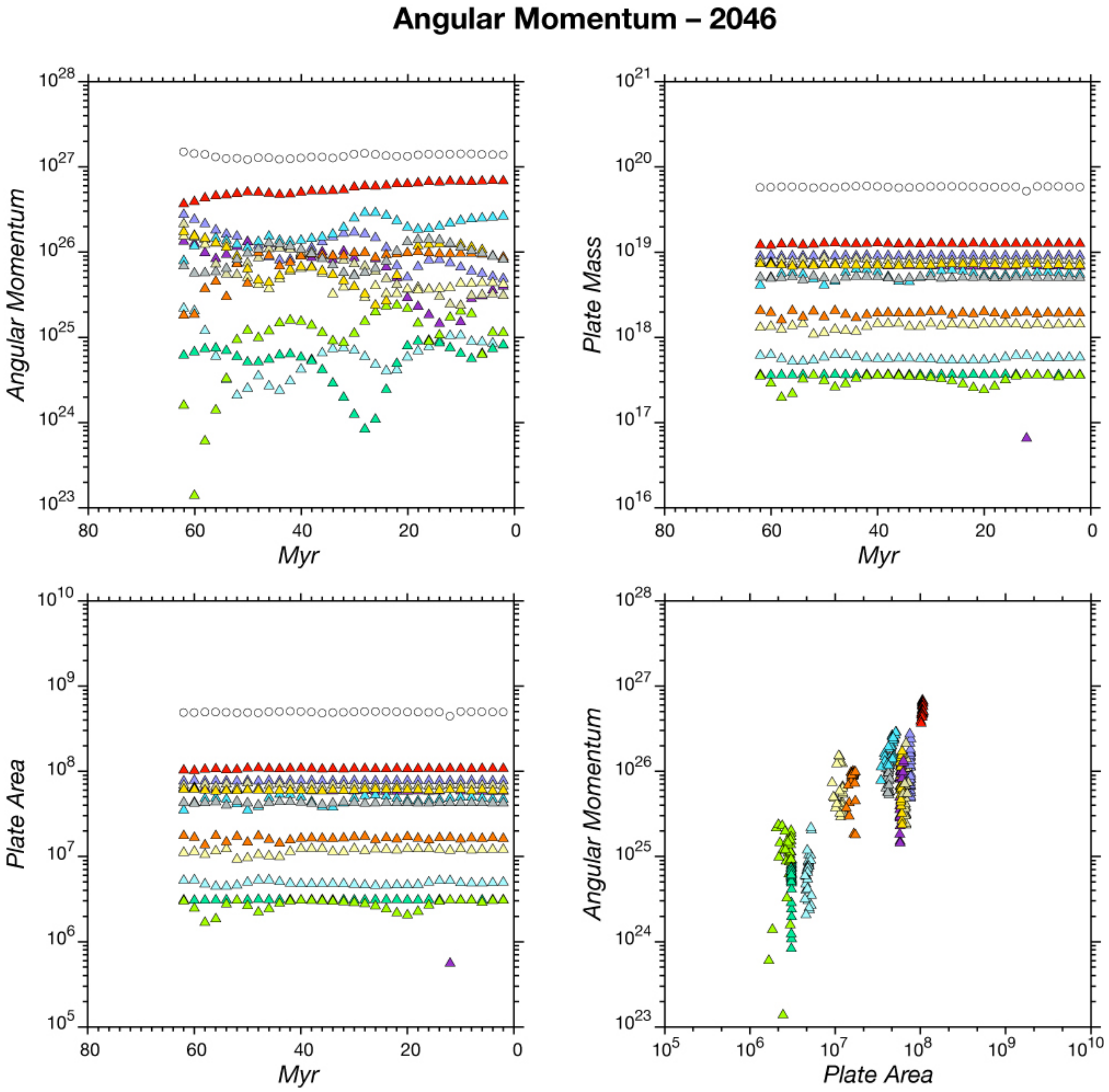


Figure 6. Angular momentum, plate mass, plate area and angular momentum vs. plate area for the 2046 filtered data for 62 - 0 Myr.

RESULTS AND CONCLUSIONS

1) This paper documents that the Earth's tectonic plates have undergone acceleration and deceleration during the past 62 million years. Further our estimates of the Earth's total plate tectonic angular momentum support its' conservation during this time interval, as expected from the physical Law of Conservation of Angular Momentum. The very slow accelerations (mm/yr/Ma) of Plate Tectonics has only recently become definitive because of the geometric

solution for the Euler pole history of the Pacific Plate developed by Harada and Harmano (2000), and the development of an iterative ability to smooth filter a time series of Euler poles by Bowin and Kuiper (2005). It is tempting to speculate that if new techniques for resolving and integrating slow acceleration histories of ocean currents (such as the Gulf Stream) were to come available, then physical oceanography for the world's oceans would also reveal a conservation of angular momentum.

2) A particularly striking change in angular momentum for the Pacific Plate occurred near 46 Ma when its northward acceleration towards the the Aleutian Arc subductioon zone (along the direction of the Emperor Seamount chain) slowed, and changed to a slower and more westerly motion toward the Philippine and Japanese subduction zones (along the direction of the Hawaiian Seamount chain). Concomitantly, the wedge-shaped spreading in the Tasman Sea ceased, and the Australian Plate renewed its subduction beneath the Indonesian Island Arc which continues to the present day. Thus the migration of a pattern of opening in the Indian Ocean noted in Bowin (1974) has been a consequence of plate tectonic conservation of angular momentum. The geometrically interlocked pattern of the pacific plate moving westward (subducting at the Tonga-Kermadec trench), with the Australian plate moving northward (subducting at the Indonesian Arc) is explained: it simply grew that way.

3) Another filtering experiment at including another change in angular momentum near 20 Ma was also tried, dividing the 46 - 0 Ma interval into two segments. Future attempts will explore how to best process shorter time interval segments.

4) Wedge-shaped spreading segments are like propagating cracks, and result from adjustments to conserve plate tectonic angular momentum.

5) Spreading rige axes are passive (responsive) features, not drivers.

6) Gakkel Rige, SW Indian Ridge, and the Mid-Atlantic ridge, where undeformed peridotite (non-volcanic crust) is exposed on the seafloor are taken as further evidence of the passive (reactive) nature of spreading sites.

7) Extrapolating from the Pacific Plate velocity curve (Fig. 4, plate 12), the Pacific Plate might have had a zero velocity about 90-120 Ma ago. Engebreton, Cox, and Gordon (1986, p.9) suggested evidence that the Pacific Plate had little or no absolute motion prior to the mid-Early Cretaceous time. Their maps (their Fig. 3) do not depict Pacific subduction zones until 80 Ma when a Kula Plate is shown.

8) If the Pacific Plate (or any other plate) did have zero angular momentum in the 80-120 Ma range, or any other time range, that would not indicate that plate tectonics started then, but that other plates were in motion.

9) How, when, or why plate tectonics may have started, or how plate subuction is initiated, is not being answered here. I infer that 'conservation of Angular Momentum' must also have applied during the Mesozoic and Paleozoic periods. Hence I cannot concur with the arguments of Silver and Behn (2008) that Plate Tectonics may have stopped during past times because continent-continent collision might eliminate most of Earth's subduction zones.

10) Very large massive asteroid or planetismal impacts upon the Earth could be a mechanism for altering the total magnitude of Plate Tectonic angular momentum.

11) The estimated acceleration values found in this study, are about 10^{-8} times smaller in magnitude than typical plate velocities. No wonder that the fact that plates accelerate has been so difficult to discern. Prior Euler and stage poles have been too coarse to resolve such low acceleration rates. This is why prior 'no-net-torque' solutions have been very good first approximations for analyzing plate tectonics. Although the plate acceleration values are very

low, in geologic history it is Impulse (Force times time) that produces subsidence of basins and mountain building. Impulse equals change of momentum, and the same change of momentum can be brought about by a violent massive blow of short duration, or by a small force acting over millions of years.

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APPENDIX A: Input data set of relative plate Euler poles.

```
Pacific rots (all) 2my Harada and Hamano 2000, p.335 + Acton+others
hs-   999
hs-pa    2    0      47.400   258.000    -1.925     Harada and Hamano, 00
hs-pa    4    0      50.800   258.500    -3.603       lt & lg values shifted
hs-pa    6    0      54.200   255.700    -5.268       to end of each 2 my
hs-pa    8    0      57.100   258.100    -6.919       period for mpfinf3.f
hs-pa   10    0      59.000   257.600    -8.556
hs-pa   12    0      63.100   262.300   -10.174      14jan2005 NOW with hs-pa
hs-pa   14    0      64.000   263.600   -11.774       ver hs5a w/ pa -rots
hs-pa   16    0      65.300   265.900   -13.353
hs-pa   18    0      64.000   263.500   -14.909    03feb2006 edit 2my epole
hs-pa   20    0      67.400   271.500   -16.441      to 47.400 258.000 -1.925
hs-pa   22    0      69.100   277.600   -17.946         to be like 2jan2006
hs-pa   24    0      69.100   279.000   -19.424   '12_acton91b_a6c_noit.asc'
hs-pa   26    0      67.800   280.400   -20.871
hs-pa   28    0      67.000   281.500   -22.287
hs-pa   30    0      66.700   282.300   -23.669
hs-pa   32    0      66.400   282.700   -25.016
hs-pa   34    0      66.200   285.300   -26.326
hs-pa   36    0      66.100   287.000   -27.597
hs-pa   38    0      66.000   289.500   -28.828
hs-pa   40    0      65.900   290.200   -30.016
hs-pa   42    0      65.700   291.700   -31.160
hs-pa   44    0      65.400   292.300   -32.257
hs-pa   46    0      63.800   293.300   -33.307
hs-pa   48    0      61.900   290.100   -34.307
hs-pa   50    0      60.400   289.100   -35.255
hs-pa   52    0      58.800   288.400   -36.151
hs-pa   54    0      57.600   287.400   -36.991
hs-pa   56    0      56.800   289.500   -37.775
hs-pa   58    0      55.000   285.900   -38.499
hs-pa   60    0      53.900   284.600   -39.164
hs-pa   62    0      53.300   283.700   -39.765
hs-pa   64    0      52.600   283.200   -40.303
hs-pa   66    0      52.100   283.000   -40.775
hs-pa   68    0      51.800   283.200   -41.179
hs-pa  200   68
pa-an   11    0       72.00    -70.00      9.75     Stock & Molnar, 87
pa-an   20    0       71.25    -73.19     15.41      Stock & Molnar, 87
pa-an   35    0       74.83    -56.86     28.01      Stock & Molnar, 87
pa-an   41    0       75.08    -51.25     32.56      Stock & Molnar, 87
pa-an   58   41      -47.87    107.21     -6.58       Stock & Molnar, 87
pa-an   68   58      -47.87    107.21     -8.42       Stock & Molnar, 87
pa-an   83    0       64.94    -62.49     53.09      Mayes et al. 90
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pa-an	90	0	64.03	-56.96	57.65	Mayes et al. 90
pa-an	200	90				
pa-co	2	0	37.70	-107.10	4.50	Schilt et al., 1982
pa-co	12	0	35.50	253.80	33.20	D.C. Demets [pc > gaj]
pa-co	15	12	40.00	-121.00	8.80	D.C. Demets [pc > gaj]
pa-co	26	15	40.00	-121.00	32.40	D.C. Demets [pc > gaj]
pa-co	200	26	40.00	-121.00	32.40	D.C. Demets [pc > gaj]
nz-pa	4	0	50.90	-87.00	-7.00	Chase [1978a] in gaj86
nz-pa	26	0	63.00	-90.60	-39.60	Pilger [1978]
nz-pa	28	0	64.50	-93.00	-41.30	Pilger [1978]
nz-pa	29	0	64.80	-95.60	-42.70	Pilger [1978]
nz-pa	30	0	64.80	-96.90	-43.90	Pilger [1978]
nz-pa	32	0	65.20	-99.60	-45.10	Pilger [1978]
nz-pa	34	0	67.10	-99.90	-45.90	Pilger [1978]
nz-pa	37	0	69.40	-102.50	-49.80	Pilger [1978]
nz-pa	40	0	70.80	-107.80	-52.70	Pilger [1978]
nz-pa	42	0	72.80	-112.50	-57.10	Pilger [1983]
nz-pa	56	0	75.10	-125.50	-68.80	Pilger [1983]
nz-pa	200	56				
pa-fa	8	0	-59.25	-165.76	-4.85	Nishimura et al.[1984]
pa-fa	28	0	81.00	65.00	19.00	Engebretson et al. 84
pa-fa	37	28	80.00	212.00	13.10	Engebretson et al. 84
pa-fa	43	37	80.00	212.00	11.00	Engebretson et al. 84
pa-fa	48	43	80.00	212.00	8.00	Engebretson et al. 84
pa-fa	56	48	77.00	178.00	10.50	Engebretson et al. 84
pa-fa	85	56	66.00	64.00	20.70	Engebretson et al. 84
pa-fa	200	85				
pa-ku	48	0	0.00	0.00	0.00	Engebretson et al. 84
pa-ku	56	48	18.00	111.00	2.60	Engebretson et al. 84#
pa-ku	61	56	18.00	111.00	1.70	Engebretson et al. 84
pa-ku	67	61	18.00	111.00	3.80	Engebretson et al. 84
pa-ku	200	67				
an-po	4	0	0.00	0.00	0.00	Engebretson et al. 84
an-po	6	4	33.00	338.00	0.50	D.C. DeMets [gaj PC],85
an-po	16	6	33.00	338.00	5.30	D.C. DeMets [gaj PC],85
an-po	23	16	33.00	338.00	2.80	D.C. DeMets [gaj PC],85
an-po	45	23	33.00	338.00	8.10	D.C. DeMets [gaj PC],85
an-po	51	45	-3.80	315.30	4.10	D.C. DeMets [gaj PC],85
an-po	64	51	-14.90	309.00	15.70	D.C. DeMets [gaj PC],85
an-po	200	64				
au-an	11	0	13.10	36.10	-6.61	Royer and Chang, 91
au-an	20	0	15.40	32.70	-11.97	Royer and Chang, 91
au-an	35	0	13.80	33.40	-20.41	Royer and Chang, 91
au-an	41	0	8.68	34.52	-22.80	Stock & Molnar, 87
au-an	58	0	4.45	35.99	-25.55	Stock & Molnar, 87
au-an	68	0	3.76	36.23	-26.08	Stock & Molnar, 87

au-an	79	0	6.20	35.10	-26.37	Royer and Sandwell, 89
au-an	83	0	4.90	35.80	-26.81	Royer and Sandwell, 89
au-an	200	83				
af-an	11	0	8.20	-49.40	-1.53	Royer and Chang, 91
af-an	20	0	10.70	-47.90	-2.78	Royer and Chang, 91
af-an	35	0	12.00	-48.40	-5.46	Royer and Chang, 91
af-an	59	0	8.80	-42.60	-10.83	Royer and Chang, 91
af-an	64	0	2.76	-40.26	-11.63	Molnar et al., 88
af-an	67	0	2.22	-40.74	-12.50	Molnar et al., 88
af-an	79	0	0.75	-42.06	-15.71	Molnar et al., 88
af-an	83	0	-5.03	-36.12	-18.24	Molnar et al., 88
af-an	200	83				
sa-af	11	0	59.99	321.11	3.13	Shaw and Cande, 90
sa-af	20	0	58.07	322.58	7.04	Shaw and Cande, 90
sa-af	27	0	57.16	324.66	9.98	Shaw and Cande, 90
sa-af	35	0	56.63	326.09	13.38	Shaw and Cande, 90
sa-af	44	0	57.62	327.93	17.58	Shaw and Cande, 90
sa-af	50	0	59.30	328.41	20.08	Shaw and Cande, 90
sa-af	58	0	61.07	328.51	22.30	Shaw and Cande, 90
sa-af	66	0	63.30	326.55	24.77	Shaw and Cande, 90
sa-af	73	0	63.11	326.19	27.93	Shaw and Cande, 90
sa-af	79	0	62.91	325.81	30.97	Shaw and Cande, 90
sa-af	83	0	61.59	325.85	33.50	Shaw and Cande, 90
sa-af	200	83				
na-af	11	0	79.08	77.95	2.41	Klitgord & Schouten '86
na-af	20	0	79.57	37.84	5.29	Klitgord & Schouten '86
na-af	35	0	76.41	7.12	9.81	Klitgord & Schouten '86
na-af	48	0	74.51	-4.83	15.32	Klitgord & Schouten '86
na-af	58	0	80.60	-0.50	18.07	Klitgord & Schouten '86
na-af	66	0	82.51	-0.63	20.96	Klitgord & Schouten '86
na-af	71	0	81.35	-9.15	22.87	Klitgord & Schouten '86
na-af	73	0	80.76	-11.76	23.91	Klitgord & Schouten '86
na-af	79	0	78.30	-18.35	27.06	Klitgord & Schouten '86
na-af	83	0	76.55	-20.73	29.60	Klitgord & Schouten '86
na-af	200	83				Klitgord & Schouten, 86
in-af	11	0	23.70	33.30	-4.61	Royer and Chang, 91
in-af	20	0	30.90	17.50	-6.32	Royer and Chang, 91
in-af	35	0	21.80	35.00	-14.39	Royer and Chang, 91
in-af	52	0	17.60	38.90	-29.54	Royer and Chang, 91
in-af	59	0	23.10	26.70	-31.71	Royer and Chang, 91
in-af	64	0	18.29	26.56	-39.88	Molnar et al, 88
in-af	67	0	18.45	23.47	-44.14	Molnar et al, 88
in-af	79	0	20.32	21.39	-51.30	Molnar et al, 88
in-af	83	0	23.36	19.57	-51.54	Molnar et al, 88
in-af	200	83				
af-ar	20	0	26.50	21.50	7.60	KcKensie etal.[1976]gaj

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af-ar  300   20
na-ca   10    0        50.00    116.00      2.00    Morgan [1983] gaj'86
na-ca  200   10
eu-na   11    0        68.00    137.00     -2.50    Srivastava & Tapscott, 86
eu-na   20    0        68.00    138.20     -4.75    Srivastava & Tapscott, 86
eu-na   35    0        68.00    129.90     -7.78    Srivastava & Tapscott, 86
eu-na   48    0        67.12    137.28    -10.94    Srivastava & Tapscott, 86
eu-na   54    0        62.28    140.37    -12.68    Srivastava & Tapscott, 86
eu-na   58    0        63.25    143.89    -14.15    Srivastava & Tapscott, 86
eu-na   66    0        69.82    145.61    -17.10    Srivastava & Tapscott, 86
eu-na   68    0        70.66    147.91    -17.59    Srivastava & Tapscott, 86
eu-na   79    0        74.52    147.69    -20.30    Srivastava & Tapscott, 86
eu-na   83    0        76.23    148.80    -21.83    Srivastava & Tapscott, 86
eu-na  200   83
zz
   36   34   32   30   28   26   24   22   20   18   16   14   12   10    8    4    2
```

APPENDIX B: Maximum velocity (mm/yr), azimuth (degrees), acceleration (mm/yr/Myr) for NOIT, 4448, 2046 for plates 1-8, 10-12, 14.

Plate 1 (AF)

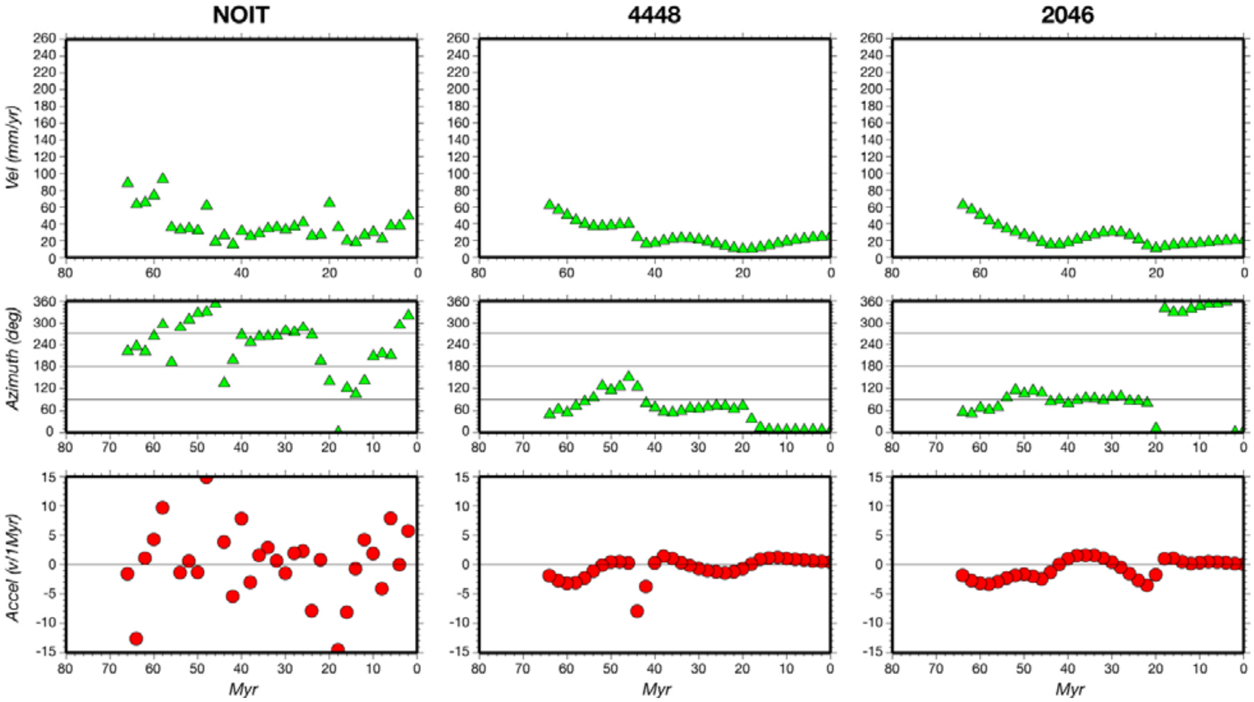

Plate 2 (AN)

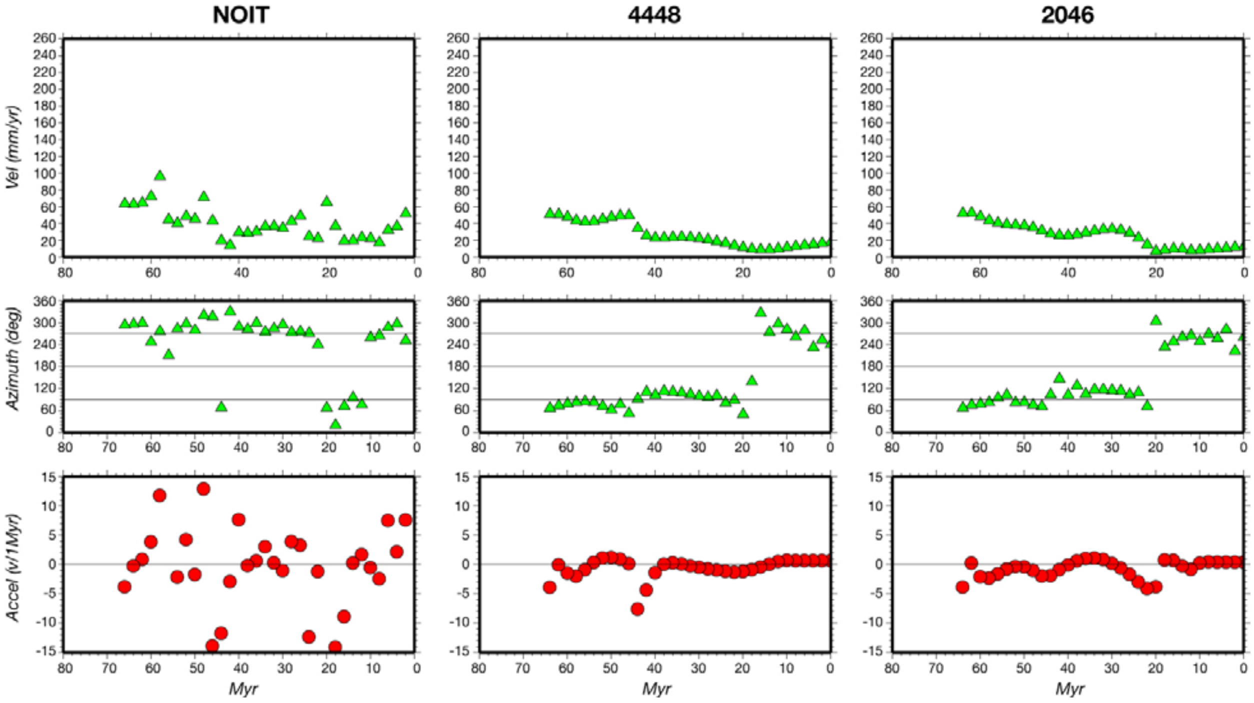

Plate 3 (AR)

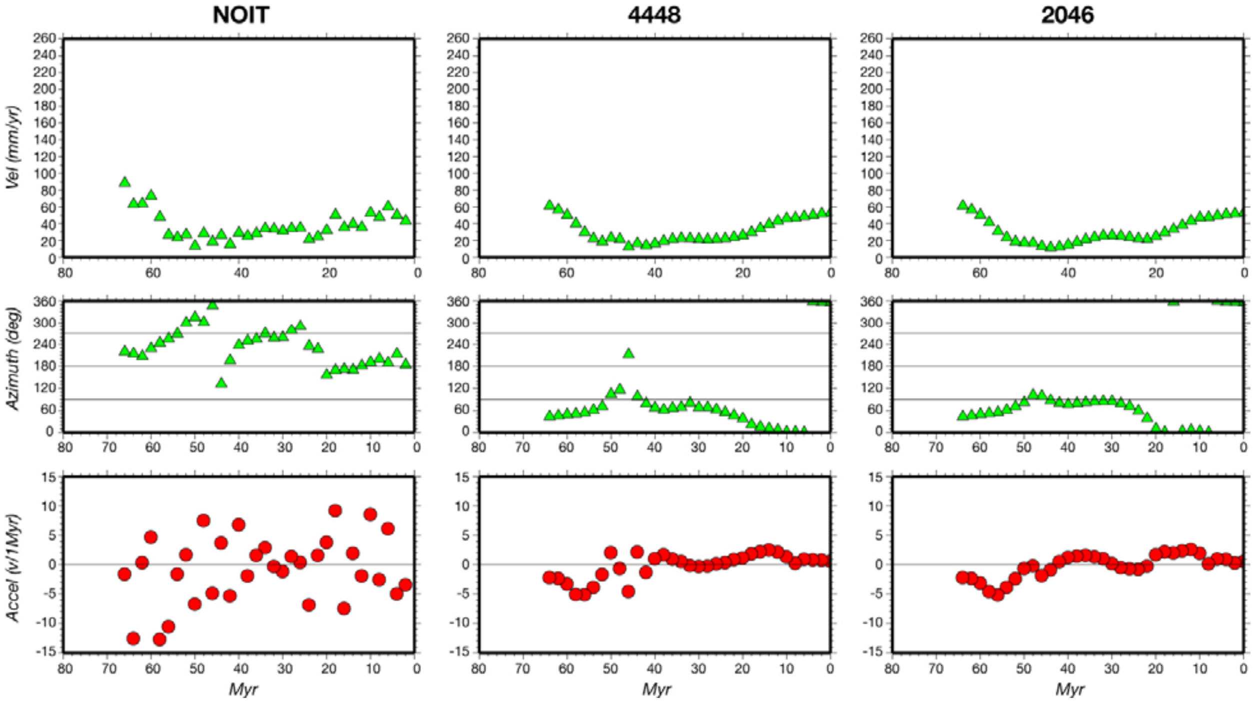

Plate 4 (AU)

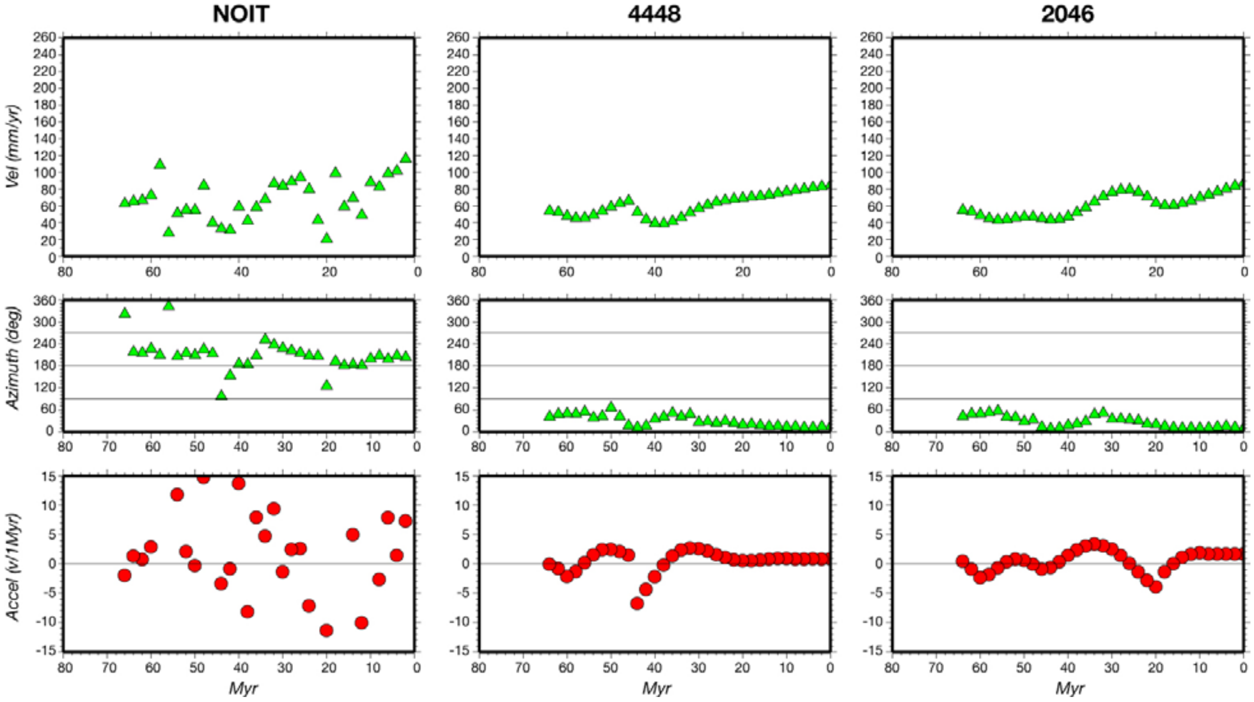

Plate 5 (CA)

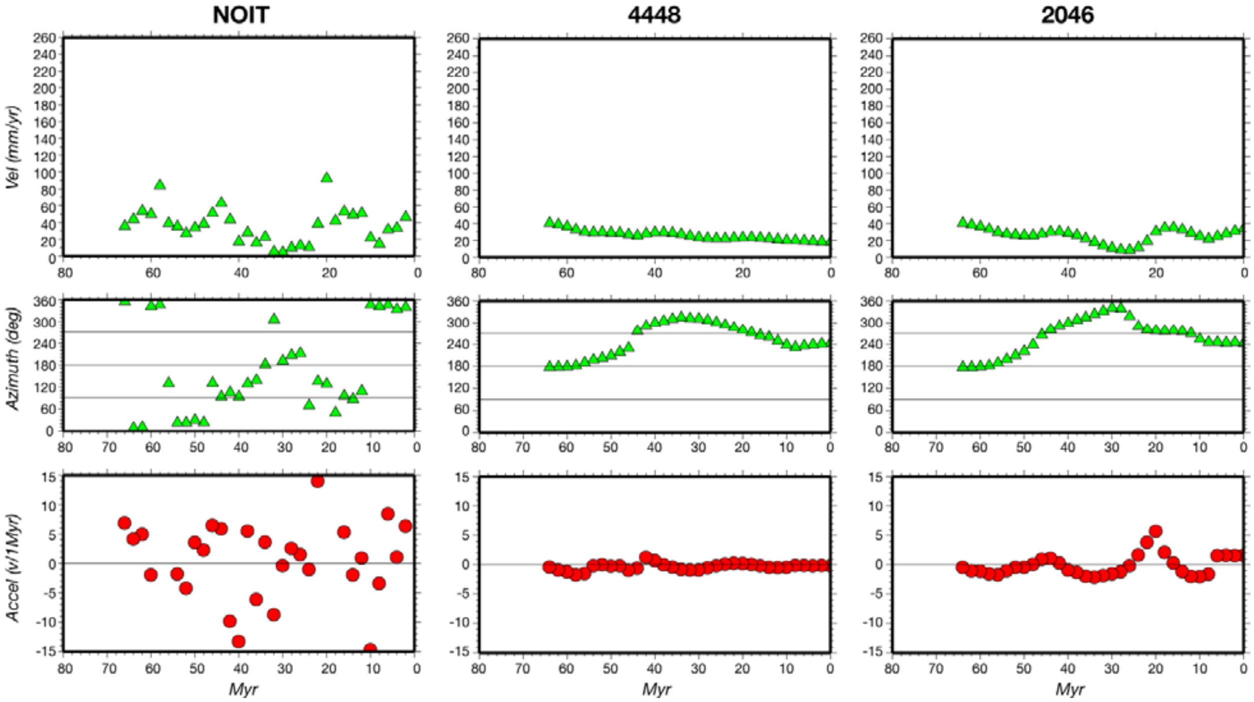

Plate 6 (CO)

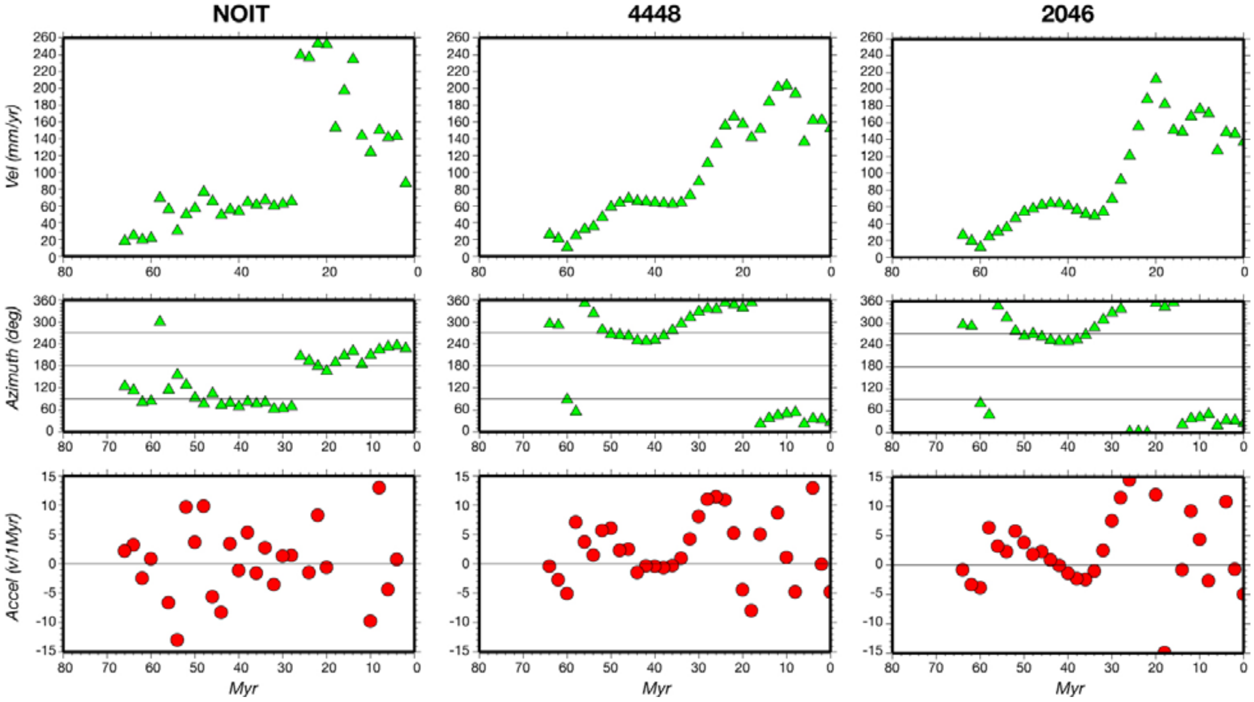

Plate 7 (EU)

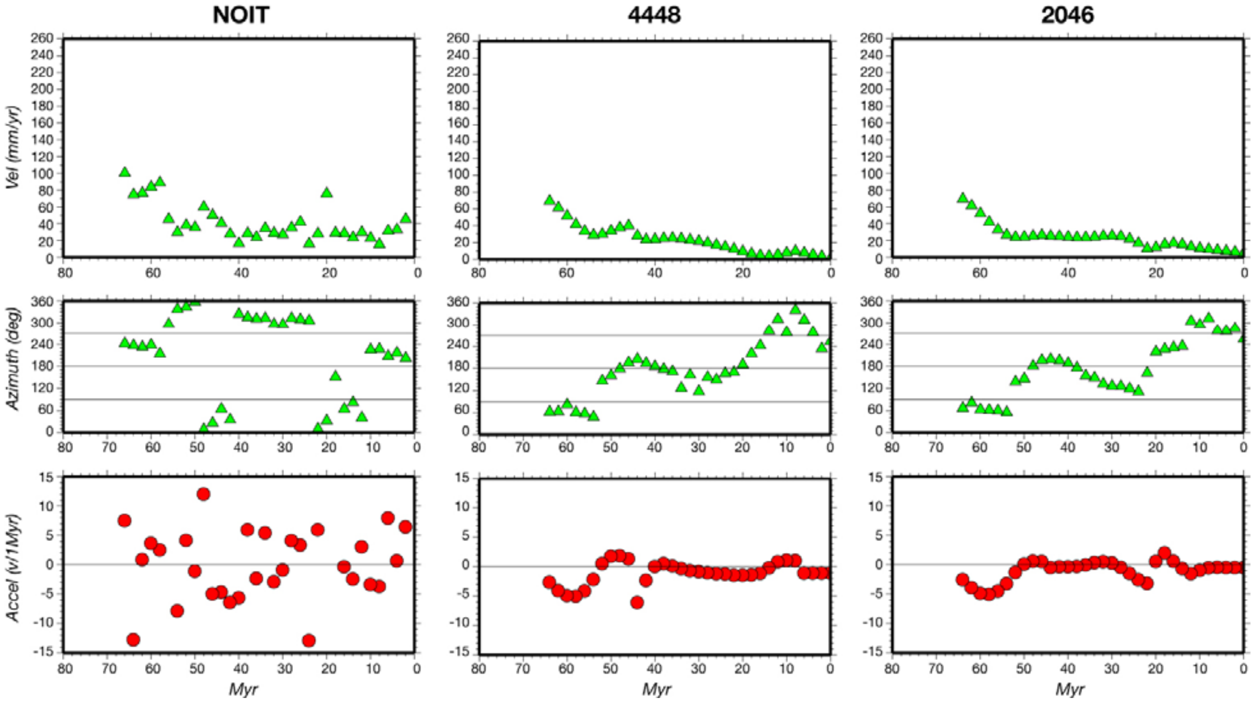

Plate 8 (IN)

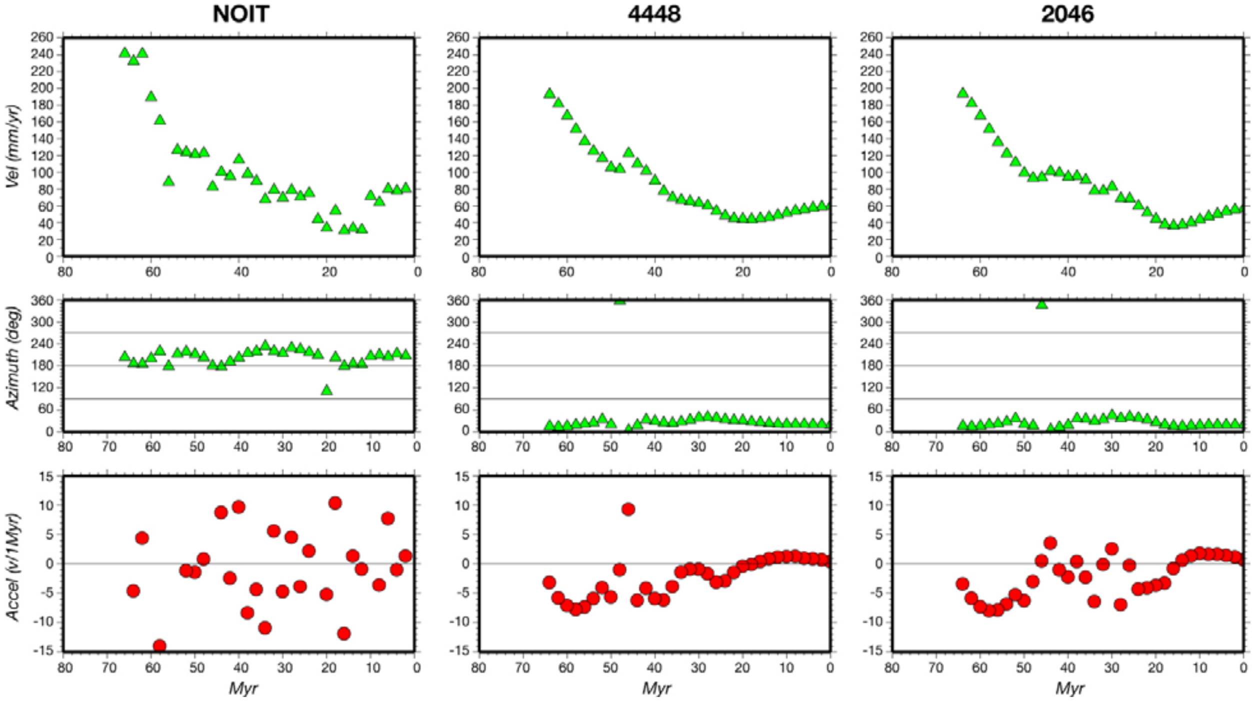

Plate 10 (NA)

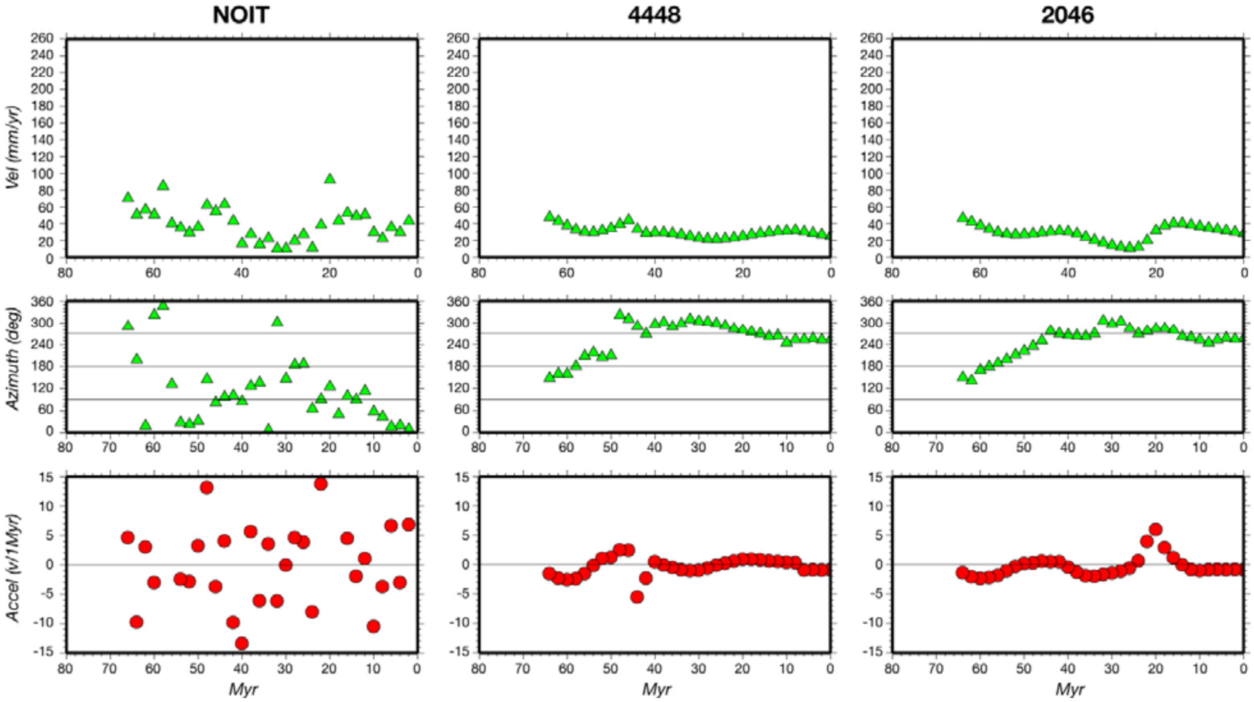

Plate 11 (NZ)

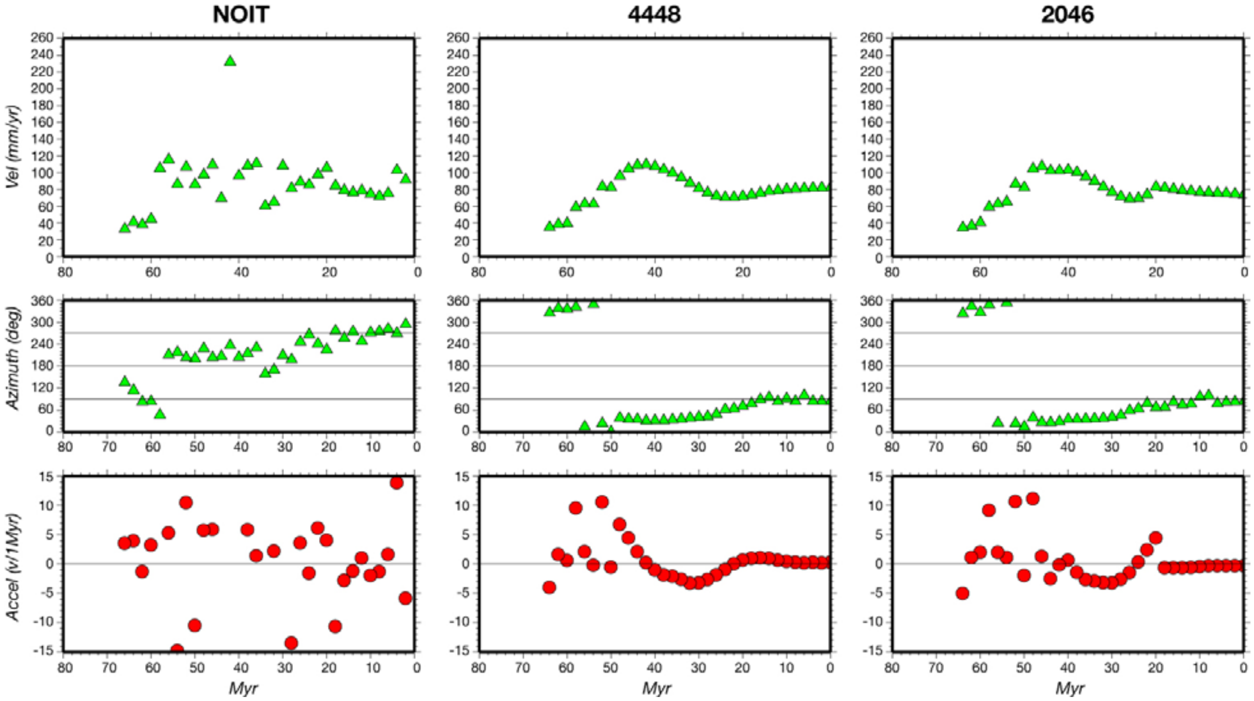

Plate 12 (PA)

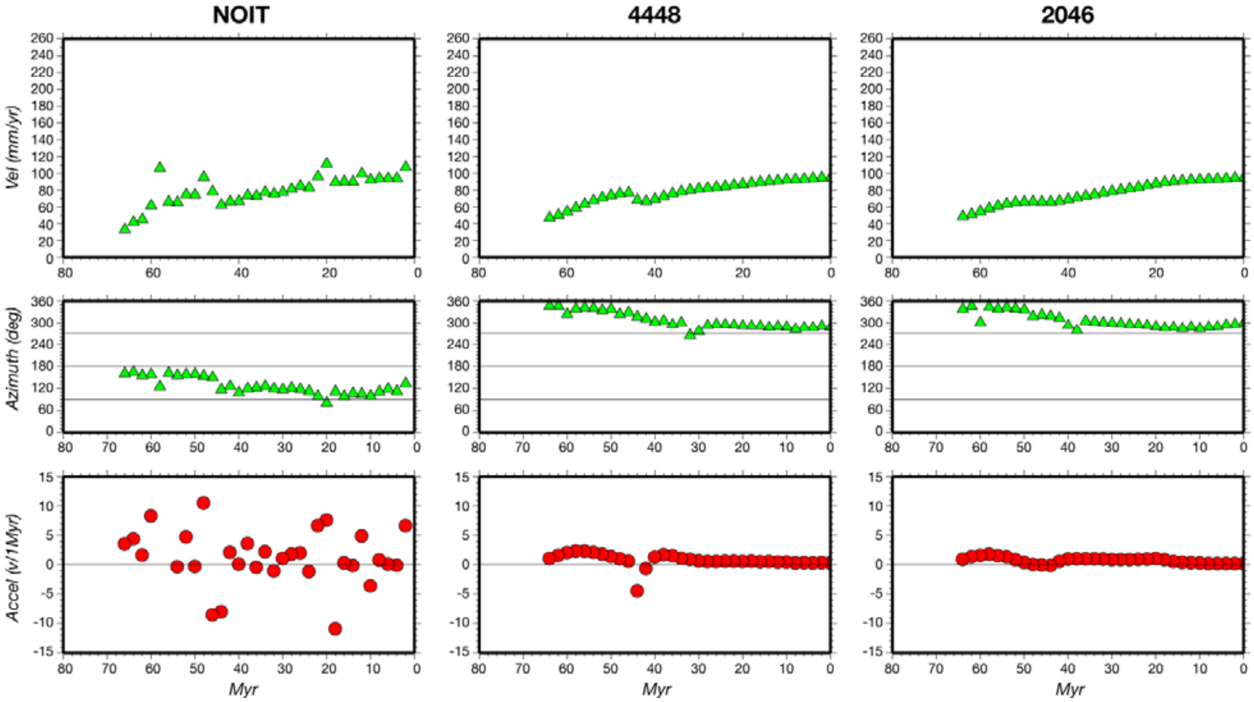

Plate 14 (SA)