ABSOLUTE MIGRATION OF PACIFIC BASIN MID-OCEAN RIDGES SINCE 85 MA AND THEIR TECTONIC IMPLICATIONS FOR THE PACIFIC PLATE

DCP Masalu
University of Dar Es Salaam, Institute of Marine Sciences
Mizingani Road, P O Box 668, Zanzibar, TANZANIA
Email: masalu@ims.udsm.ac.tz

ABSTRACT

Mid-ocean ridges are major physiographic features that dominate the world seafloor. Their absolute motion and tectonics are recorded in magnetic lineations they created. The absolute migration of mid-ocean ridges in the Pacific basin since 85 Ma and their tectonic implications was investigated in this work and the results indicates that at about anomaly 21 (47 Ma) the East Pacific Rise (EPR) and Juan de Fuca ridge experienced an abrupt change in their migration direction that persisted until about anomaly 6 (20 Ma), probably due to changes in subduction-zone configuration in the northern Pacific. This may represent a period of tectonic instability for the Pacific plate during which the EPR was probably subducted beneath the North American continent. This period culminated by the appearance of the Galapagos propagator and a major reorganization of the East Pacific Rise south of the Galapagos.

INTRODUCTION

The discovery of magnetic lineations in the Vine-Matthew-Morley hypothesis (Vine and Matthew 1963, Morley and Larochelle 1964) is one of the most important discoveries of the plate tectonic revolution. They are formed as ocean basalts, cooling through the Curie temperature at the axis of a spreading ridge, record the polarity flips of the geomagnetic field. Such magnetic lineations have proven invaluable in deciphering the plate tectonic evolution of the Pacific plate (e.g., Sager *et al*. 1988, Atwater 1989, Nakanishi *et al*. 1989), the largest and wholly oceanic plate. The various events recorded in the pattern of magnetic lineations are changes in plate motions.

Changes in Pacific plate motions are also recorded in the linear oceanic seamounts and island chains, e.g., the Hawaii-Emperor chain, assumed to have been formed as the Pacific plate drifted over mantle hotspots that are considered to be relatively fixed with respect to the mantle (Morgan 1972). Very abrupt corners in the chains, especially those seen consistently in several chains, almost certainly indicate abrupt changes in Pacific plate motions. However, one most surprising observation in the Pacific basin is that the very great change of about 60° in Pacific plate motion at 43 Ma as recorded in the linear chains, shown by the Hawaii-Emperor bend, is very poorly recorded in the Pacific magnetic lineations (Atwater 1989, Norton 1995, Whittaker *et al*. 2007). The observed miscorrelation makes further investigations in order.

Several studies have been done in the effort to understand and resolve the mystery ranging from ascertaining the hotspot fixity hypothesis (Tarduno *et al*. 2003, Duncan and Keller 2004, Steinberger *et al*. 2004, Tarduno 2007), the timing of the Hawaii-Emperor chain bend (Norton 1995, Sharp and Clague 2002, Wessel *et al*. 2006, Sharp and Clague 2006) to correlate it with observable contemporaneous events in which two ages, 47Ma and 50Ma, have been proposed from the original age of 43Ma. Additionally, studies of absolute motion of the Pacific plate to improve its correctness and accuracy and/or incorporating some of the results mentioned above (e.g., Wessel and Kroenke 1997, Wessel *et al*. 2006). One major outcomes of these efforts is the results from paleomagnetic analyses from the Ocean Drilling Program (ODP) Leg 197 that indicate that the Hawaii hotspot moved southward during the formation of the Hawaii-Emperor seamounts prior to 50Ma (Tarduno *et al.* 2003, Tarduno 2007). The cession of southward motion of the Hawaii hotspot about 50Ma resulted in the formation of the bend on the chain (Tarduno *et al.* 2003, Tarduno 2007). Following this a model for absolute motion of the Pacific plate which incorporates motions of hotspots was developed for the Pacific plate (Wessel *et al.* 2006). However, several investigators still believe that the Hawaii-Emperor bend is mainly a result of plate motion change (e.g., Sharp and Clague 2006, Whittaker *et al.* 2007).

In this study the behavior of Pacific basin mid-ocean ridges, Juan de Fuca and East Pacific Rise (which includes the Pacific – Nazca and Pacific - Cocos ridges), since anomaly 34 to Present was investigated by mapping absolute migration of ridge segments that created the selected magnetic lineations (Fig. 1). The results indicate that the change in Pacific plate motion at the time of the Hawaii-Emperor bend appears to correspond with events that occurred later about anomaly 6, i.e., reorganization of the EPR and the appearance of the Galapagos spreading center. This suggests that the great abrupt change in Pacific plate motion at 43 Ma caused a state of tectonic instability in the Pacific area that was later equilibrated by the events at anomaly 6. The great Hawaii-Emperor bend and its associated events are well recorded in the absolute migration of the Juan de Fuca and EPR ridge segments.

METHODS

Paleopositions of four ridge segments in the Pacific basin (Fig. 1), one from the Juan de Fuca and three from the EPR were reconstructed by backtracking identified magnetic lineation segments that were formed by those ridge segments back to their zero age positions (Masalu 2007), using the Pacific plate absolute motion model of Duncan and Clague (1985). This technique (Fig. 2) is very similar to "hot-spotting" (Wessel and Kroenke 1997) but here is applied in a conventional way that requires prior knowledge of the age of the feature being back-tracked. The locations of the identified magnetic lineations were obtained from a CDROM of digital data of locations of global magnetic lineations (Cande *et al.* 1989), and age assignment to identified magnetic lineations was done based on the geomagnetic polarity time scale for the Late Cretaceous and Cenozoic time (Cande and Kent 1992).

It is noted here that the method of reconstruction used here has several weaknesses because the reliability of the results and interpretations obtained by this method depend on the correctness and accuracy of the absolute plate motion model used. Plate motion models assume that plates have remained rigid in time. However, this is not very true as both inter- and intra-plate deformation are known to exist (Dixon *et al.* 1996, Kogan *et al.* 2000, Beavan *et al.* 2002, Tregoning 2002, Socquet *et al.* 2006) due to differing plate rigidity. Furthermore, plate models assume that hotspots are fixed or move only very slowly relative to each other. The motion between hotspots has remained poorly understood and the assumption of hotspot fixity controversial (Molnar and Stock 1987, Acton and Gordon 1994, Tarduno and Gee 1995) for decades. However, as mentioned in the previous section recent results from ODP Leg 197 documented the motion of hotspots (Tarduno 2007, Tarduno *et al.* 2003, Tarduno *et al.* 2002). These results indicate that prior to 50 Ma the Hawaii hotspot was moving southwards at rates of 30-50 mm/yr, and underscore the well known observation that reconstructions based on the Indo-Atlantic and Pacific hotspots do not agree with each other.

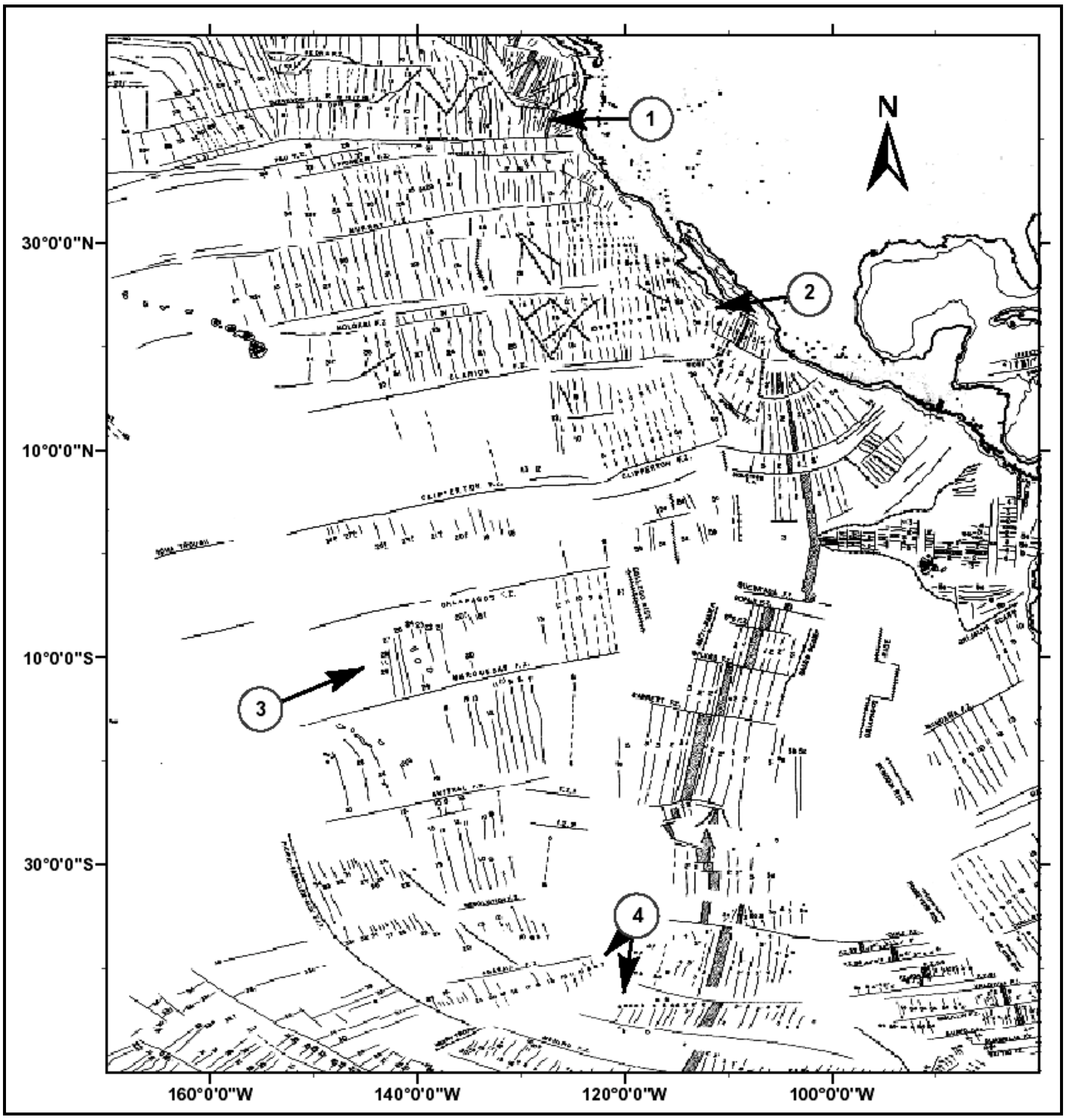

Figure 1: Magnetic lineations of the Pacific basin. Identified magnetic lineations are marked by their anomaly ages. Encircled numbers indicate magnetic lineation segments that were reconstructed in this study. **1:** magnetic lineation segments between the Surveyor and Mendocino Fracture Zones that were created by the Juan de Fuca ridge segment; **2:** magnetic lineation segments between the Molokai and Clarion Fracture Zones; **3:** magnetic lineation segments between the Galapagos and Marquesas Fracture Zones; and **4:** magnetic lineation segments immediately south of the Agassiz Fracture Zone. Figure is adopted from Cande *et. al*. (1989).

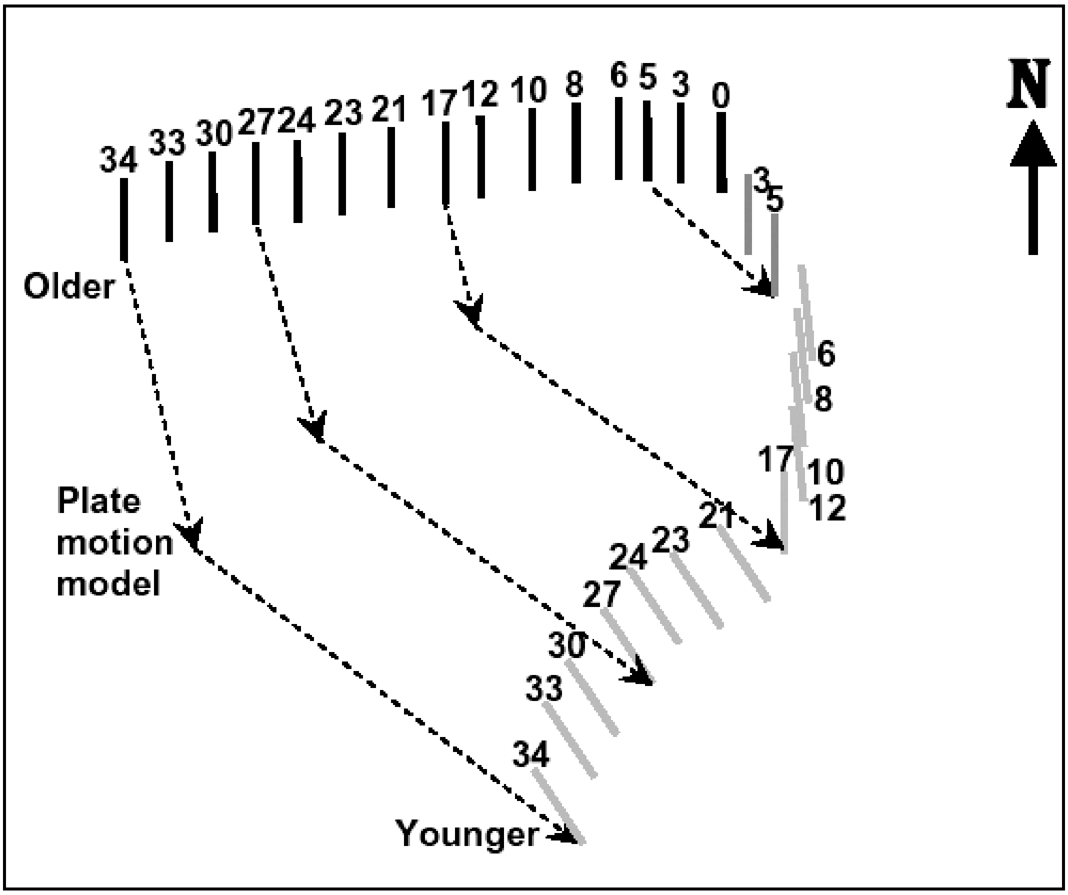

Figure 2: Paleoposition reconstruction cartoon for the Pacific ridges. Solid black line segments are observed magnetic lineation segments. Solid grey line segments are reconstructed palaeopositions (of the ridge segment) by backtracking respective observed magnetic lineation segments along a respective absolute plate motion model (dashed lines with arrows). Characters near the segments are Chron ages.

The main challenge for the present study was therefore on deciding which absolute plate motion model to use. Two models were considered: the Duncan and Clague (1985) model which has been widely accepted and used but does not incorporate motions of hotspots, and the Wessel *et al.* (2006) model which represents modern models that incorporate motions of hotspots. The correctness of a plate motion model is assessed based on how accurately it reproduces observable features such as the chains of seamounts and how it fits the respective plate and other features in the global perspective at various time intervals. Unfortunately, while the consistency and integrity of the Duncan and Clague (1985) model in the global perspective is well known and generally accepted, we can not assess the same for the Wessel *et al.* (2006) until when it is extended to other plates. Fig. 3 shows reconstructions of the Juan de Fuca ridge segment since Chron 34 based on both the Duncan and Clague (1985) and the Wessel *et al.* (2006) models. The figure indicates that the two models are indeed very different and that the Wessel *et al.* (2006) is very different from the other Pacific plate motion models. While the Duncan and Clague (1985) and most other Pacific plate motion models indicate that the Juan de Fuca segment migrated northward, the Wessel *et al*. (2006) indicates that it migrated mainly westward across the Earth. Table 1 shows the distance moved at Chron intervals. Based on the Wessel *et al*. (2006) model the Juan de Fuca segment has moved a total distance of 31,460 km since Chron 34 while based on Duncan and Clague (1985) it has moved only 3,917 km almost same distance it moved between Chron 34 and 33 based on the Wessel *et al*. (2006) model. These results have important implications on the speed at which mid-ocean ridges and plates can move. The Duncan and Clague (1985) model yields migration speeds between 3 and 11 cm/yr for the Juan de Fuca segment while the Wessel *et al*. model yields migration speeds between 8 and 59 cm/yr which is 5 – 13 times higher. At the moment it is difficult to conceive that such huge global systems and plates can move at such higher speeds; and based on this and the other disparities mentioned, the Duncan and Clague (1985) model was favored for this study.

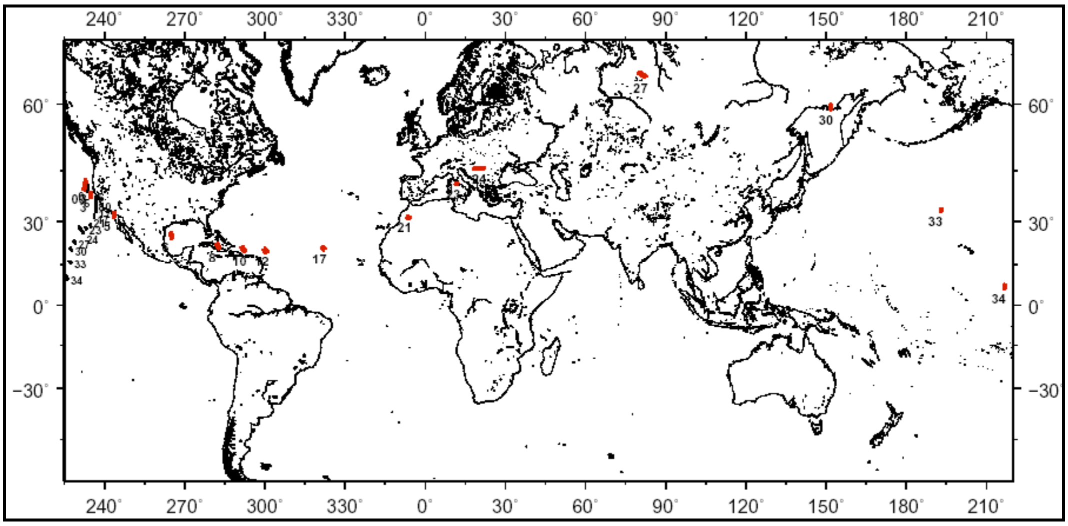

Figure 3: Paleopositions of the Juan de Fuca ridge segment reconstructed based on the Duncan and Clague (1985) model (solid black line segments) and the Wessel *et al*. (2006) model (grey solid lines). Numbers near the segments are Chron ages. Note the difference of the results from the two models.

Table 1: Distance travelled by the Juan de Fuca ridge segment based on the Duncan and Clague (1985) and Wessel *et al*. (2006) models

Chron age intervals	Distance Travelled (km)	
	Duncan & Clague (1985)	Wessel et al. (2006)
34 - 33	633.39	3864.73
33 - 30	532.98	4151.14
30 - 27	330.64	3514.57
27 - 24	486.07	4136.07
24 - 23	181.85	866.26
23 - 21	191.66	1982.49
21 - 17	316.44	3344.14
17 - 12	214.95	2229.87
12 - 11	39.44	461.72
11 - 10	35.87	408.15
10 - 9	39.67	457.04
9 - 8	34.68	530.64
8 - 6	203.38	1857.98
6 - 5	319.73	2271.89
5 - 3	194.54	1014.05
3 - 0	161.87	370.59
Total distance travelled	**3917.16**	**31461.33**

RESULTS

Fig. 4 shows the results of the reconstructions performed. The three northern ridge segments appear to have migrated toward north of northeast to northeast at least since anomaly 34 to about anomaly 21. Thereafter they appear to have experienced an abrupt northerly change in migration direction that persisted until about anomaly 6. After anomaly 6, the Juan de Fuca segment started migrating northwesterly. The fourth, southern, ridge segment appears to have migrated toward southwest at least since anomaly 34 to about anomaly 20. Thereafter, like the three northern ridge segments, appears to have experienced an abrupt northerly change in migration direction from anomaly 20 that persisted until about anomaly 7. After anomaly 7 to present this ridge segment appears to be migrating westerly.

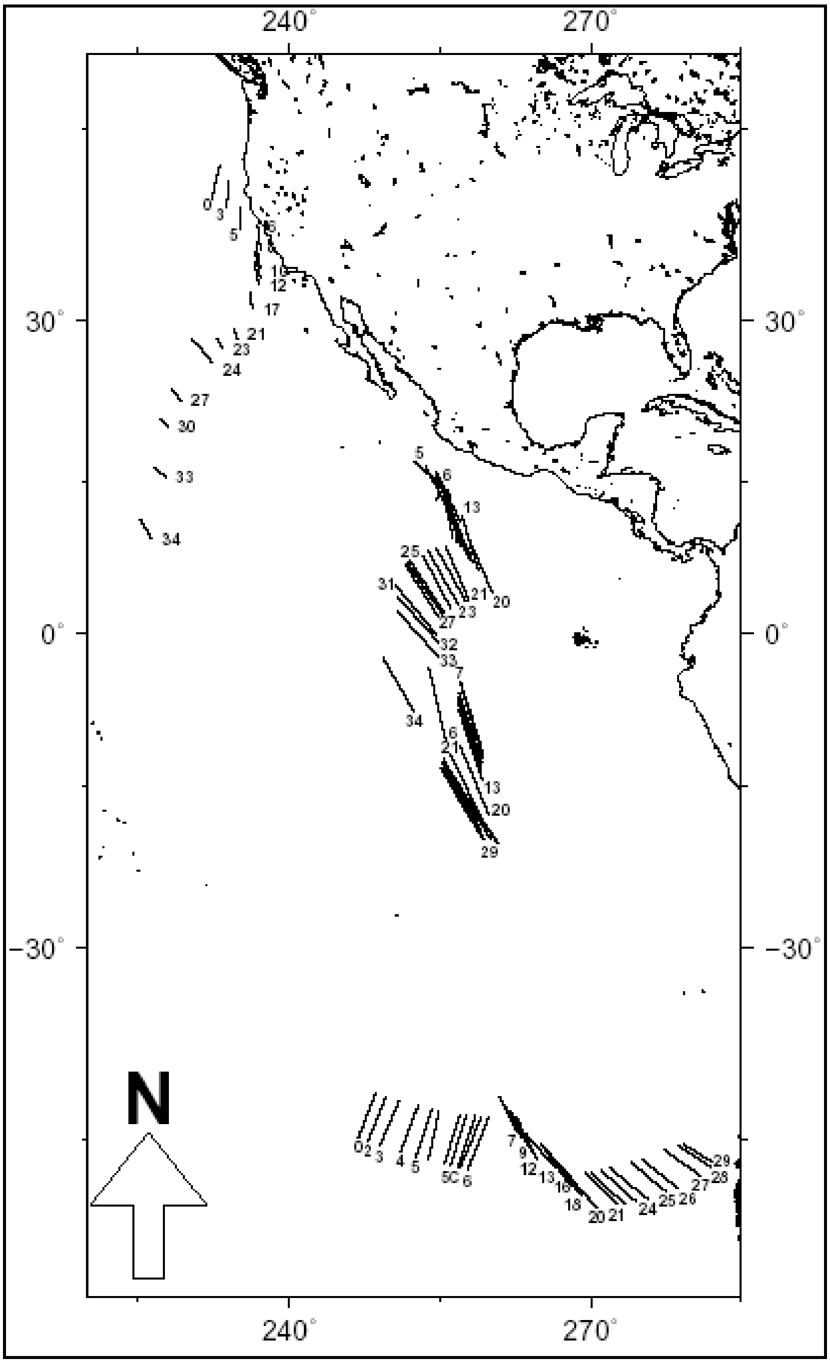

Figure 4: Paleopositions of the selected mid-ocean ridge segments based on the reconstruction performed in this study. Characters near the segments are Chron ages. Note the abrupt change in migration in all segments from about anomaly 20 to 6.

DISCUSSION

The start of the period of abrupt northerly migration of Pacific basin mid-ocean ridges just after anomaly 21 is consistent with the timing of the Hawaii-Emperor bend. On the other hand, the end of this period at about anomaly 6 (20 Ma) is consistent with two major events in the Pacific basin, major reorganization of the EPR (Cande *et al.* 1989) and the appearance of the Galapagos spreading center (Atwater 1989) suggesting correspondence between events at 43 Ma and anomaly 6.

The events at anomaly 6 have been studied extensively and they are commonly explained to be related with the encroachment of North America (e.g., Atwater 1989). However, it was noted that although the events at anomaly 6 are notably recorded in magnetic lineations, Pacific hotspot tracks do not indicate any significant change in drift direction during that time (e.g., Duncan and Clague 1985). It is proposed here that these events are complementary response to the great, abrupt change in drift direction of the Pacific plate at 43 Ma. The intuitive explanation is that the great, abrupt change in drift direction of the Pacific plate, which presumably greatly dictates the tectonics of neighboring plates (e.g., Sager and Pringle 1988), at 43 Ma disturbed the tectonic equilibrium state prevailing during that time in the Pacific area. This state prevailed until about anomaly 6 when events in response to the event at 43 Ma occurred putting the Pacific area back into tectonic equilibrium state. This suggests that responsive events to some tectonic events may take a while before they occur, and may explain why no contemporaneously events to the change of drift direction of the Pacific plate at 43 Ma was recorded magnetic lineations.

The cause of the abrupt, great change in drift direction of the Pacific plate at 43 Ma which caused the state of tectonic instability in the Pacific area is not known, but one possible candidate is changes in the configuration of the western subduction-zone of the Circum Pacific. It is commonly believed that plate motions are primarily driven by the slab pull force, therefore the direction changes of each plate should be primarily related to changes in its own subduction system (e.g., Gordon *et al.* 1978). The subduction of the Izanagi-Pacific spreading ridge (Whittaker *et al.* 2007), the initiation of the Mariana/Tonga-Kermadec subduction system (Gurnis *et al.* 2004) and the Izu-Bonin-Mariana subduction systems (Hall *et al.* 2003) about 50 – 53 Ma may have played a key role as the cause for the abrupt change in Pacific plate drift direction at 43 Ma.

The interpretation proposed above, is also important in explaining the collision of the EPR with North America. Mid-ocean ridges are buoyant features therefore under normal conditions they will tend to run away from closely approaching continents or trenches, probably like the Juan de Fuca ridge appears to be doing at present. Based on the interpretation above, we infer that the EPR collided with North America probably during the period of tectonic instability in the Pacific area, between anomaly 21 and 6.

Having advanced several hypotheses of tectonics in the Pacific area based on absolute migration of mid-ocean ridges, the whole scenario could be summarized as follows: prior to 43 Ma the Pacific plate was drifting toward north of northwest. At 43 Ma a great abrupt change in drift direction of the Pacific plate, from north of northwest to northwest occurred. This abrupt change in drift direction was probably caused by changes in the western Pacific subduction zone. The abrupt change in drift direction caused a state of tectonic instability in the Pacific area that probably also resulted in the collision of the EPR with North America. This period persisted until about anomaly 6, culminating by the appearance of the Galapagos spreading center and a major reorganization of the EPR.

CONCLUSIONS

The absolute migration of four Pacific basin mid-ocean ridge segments since 85 Ma to Present was mapped. The results suggest a complementary relationship between the abrupt change of drift direction of the Pacific plate at 43 Ma and the major reorganization of the EPR between anomaly 7 and 5, and the appearance of the Galapagos spreading center at about anomaly 6. These three major tectonic events have been otherwise commonly considered to be completely unrelated.

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