Speculations on Cretaceous tectonic history of the Northwest Pacific and a tectonic origin for the Hawaii hotspot

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ABSTRACT

Current interpretations of Cretaceous tectonic evolution of the Northwest Pacific trace interactions between the Pacific plate and three other plates, the Farallon, Izanagi and Kula plates. The Farallon plate moved generally eastward relative to the Pacific plate. The Izanagi and Kula plates moved generally northwards relative to the Pacific plate, with the Izanagi being the name given to the northward-moving plate prior to the Cretaceous Normal Polarity Superchron and the name Kula applied to the post-Superchron plate. In this paper I suggest that these names apply to the same plate and that there was only one plate moving northwards throughout the Cretaceous. I suggest that the tectonic reorganization that has previously been interpreted as formation of a new plate, the Kula plate, at the end of the Superchron was actually a plate boundary reorganization that involved a 2,000 km jump of the Pacific-Farallon-Kula/Izanagi triple junction. Because this jump occurred during a time of no magnetic reversals it is not possible to map or date it precisely, but evidence suggests mid Cretaceous timing. The Emperor Trough formed as a transform fault linking the locations of the triple junction before and after the jump. The triple junction jump can be compared with an earlier jump of the triple junction of 800 km that has been accurately mapped because it occurred during Late Jurassic formation of the M-sequence magnetic lineations. The Northwest Pacific also contains several volcanic features, such as Hawaii, that display every characteristic of a hotspot, although whether deep mantle plumes are a necessary component of hotspot volcanism is debatable. Hawaiian volcanism today is apparently independent of plate tectonics, i.e. it is a center of anomalous volcanism not tied to any plate boundary processes. The oldest seamounts preserved in the Hawaii-Emperor Chain are located on Obruchev Rise at the north end of the Emperor Chain, close to the junction of the Aleutian and Kamchatka Trenches. These seamounts formed in the mid Cretaceous close to the spreading ridge abandoned by the 2,000-km triple junction jump. Assuming that Obruchev Rise is the oldest volcanic edifice of the Hawaiian hotspot and thus the site of its initiation, the spatial and temporal coincidence between these events suggests that the Hawaii hotspot initiated at the spreading ridge that was abandoned by the 2,000-km jump of the triple junction. This implies a tectonic origin for the hotspot. Other volcanic features in the Northwest Pacific also appear to have tectonic origins. Shatsky Rise is known to have formed on the migrating Pacific-Farallon-Izanagi triple junction during the Late Jurassic-Early Cretaceous, not necessarily involving a plume-derived hotspot. Models for formation of Hess Rise have included hotspot track and anomalous spreading ridge volcanism. The latter model is favored in this paper, with Hess Rise forming on a ridge axis possibly abandoned as a result of a ridge jump during the Superchron. Thus although a hotspot like Hawaii could be associated with a deep mantle plume today, it would appear that it and other NW Pacific volcanic features originally formed as consequences of shallow plate tectonic processes.

INTRODUCTION

The Hawaii Hotspot

Hawaii, with its long age-progressive chain of volcanic islands and seamounts, has been regarded as the type example of a hotspot since Wilson (1963) first proposed the concept. Hotspots have been invoked as the source for many other sites of excess volcanism such as other island/seamount chains and oceanic plateaus. Since Morgan (1971, 1972) suggested that hotspots like Hawaii are fed by mantle plumes originating possibly as deep as the core-mantle boundary, hotspots have been associated with plumes and have typically been regarded as features originating from deep enough within the earth and that they develop essentially independently of lithospheric influences such as plate motions. This separation of plumes/hotspots from plate tectonics has persisted in spite of indicators to the contrary, such as the observation by Aslanian et al. (1994) that many, if not most, of the global ocean's large volcanic plateaus are associated with triple junctions.. Subsequent work has shown that many hotspots in fact have a plate tectonic origin (see summary by Anderson, 2005). Tomographic interpretations suggest that the Hawaii hotspot may presently be located on a mantle plume (Lei and Zhao, 2006). Even if a plume is associated with the hotspot today, it is not clear whether the plume existed from the time of inception of the hotspot. Geochemical evidence, for instance, shows that seamounts at the old end of the Hawaii-Emperor chain have an oceanic MORB-type signature not typical of mantle plumes (Keller et al., 2000). However, tectonic setting of the Northwest Pacific at the time of initiation of the Hawaii hotspot is poorly known, so relationships between spreading ridges and the early hotspot are not obvious. In this paper I re-examine plate tectonic history of the area, especially the far northwest corner of the Pacific plate, and suggest that the hotspot initiated at a ridge axis abandoned during plate boundary reorganizations. This implies that Hawaii can join the growing list of hotspots whose origin can be associated with plate tectonics.

Overview of Northwest Pacific tectonics

Tectonic information from the Northwest Pacific comes from mapping of oceanic spreading magnetic lineations, fracture zones and other topographic features (Figures 1 and 2). Figure 1 is a view of the satellite gravity using the current version of the data (Sandwell, 2005) described by Sandwell and Smith (1997). Although bathymetry maps are available for the area (e.g. Mammerickx and Sharman, 1988 and Mammerickx, 1989), there are large areas with only scattered data. Satellite-derived gravity provides a regionally consistent and detailed (one minute grid interval) view of sea floor structure. In this area of mostly thin sediment cover (Mammerickx and Smith, 1988), a good correlation between gravity and basement topography is expected (Smith and Sandwell, 1997). Image processing used in Figure 1, with artificial illumination from the northwest, is designed to enhance subtle features in the data; fracture zones are especially clear. In Figure 2 the magnetic lineations are identified, with a more subdued gravity background. The most prominent feature is the Hawaii-Emperor chain, accentuated in the figure by the negative gravity anomaly due to the loading-induced flexural moat (Watts, 2001), but for now we will concentrate on other tectonic information. Magnetic lineations (Figure 2) are in two groups. Jurassic to Early Cretaceous lineations of the Mesozoic (M) sequence lie to the west. Lineations to the east start with Chron 34 of Campanian age and young to the north towards the Aleutian Trench and also off the figure to the east towards North America. These two zones of magnetically dated oceanic crust are separated by large areas of sea floor created during the Cretaceous Normal Polarity Superchron (abbreviated as simply Superchron in this paper).

Campanian and younger magnetic lineations were the first to be mapped in the Northwest Pacific (Pitman and Hayes, 1968; Grow and Atwater, 1970). These authors showed how these lineations display two trends. Lineations that strike approximately north-south young to the east and record spreading along the Pacific-Farallon ridge, with the Farallon plate moving east relative to the Pacific. Direction of relative motion between the Pacific and Farallon plates is recorded by the Mendocino, Pioneer and other large fracture zones (Figure 2). Atwater (1989), Searle et al. (1993) and Atwater et al. (1993) showed how these fracture zones indicate a change in spreading direction of about 30° during the Superchron with a further change of 10 to 15° during Chron 33 (75 Ma according to the Gradstein et al., 2004 time scale used in this paper). Lineations directly south of the Aleutian Trench strike east-west. They young to the north and record spreading at a ridge that separated the Pacific from a plate that has since been subducted. This plate was named the Kula plate by Grow and Atwater (1970). The Kula and Farallon lineations meet at a magnetic bight that traces progress of the Pacific-Farallon-Kula triple junction (heavy solid black line in Figure 2). Fracture zone orientations and magnetic lineation ages have been used to derive details of plate motions between these three plates by Engebretson (1984), Engebretson et al. (1984a and b, 1987), Atwater and Severinghaus (1989) and Atwater et al. (1993).

M-sequence lineations, termed the Japanese and Hawaiian lineations by Larson and Chase (1972), are seen mostly west of the Hawaii-Emperor Chain in Figure 2. These lineations track evolution of spreading centers from first formation of the Pacific plate at 170 Ma (Bartolini and Larson, 2001) through to Chron M0 at 125 Ma. The Hawaiian lineations strike northwest-southeast and young to the east. They record spreading between the Pacific and Farallon plates. The Japanese lineations strike northeast-southwest and young to the northwest towards the Japan-Kamchatka subduction zone. Early workers who reported on these lineations (Hayes and Pitman, 1970; Larson and Chase, 1972 and Larson and Pitman, 1972) pointed out that, like the Kula plate, a plate that has since been subducted must have been moving away from the Pacific plate to form the Japanese lineations. These workers assumed that this plate was the Kula plate. Woods and Davies (1982), however, suggested that it was a different plate that they named the Izanagi, with the Kula plate only coming into existence at Chron 32b (72 Ma). Woods and Davies (1982) used this age because Chron 32b was the oldest post-Superchron magnetic anomaly mapped in this area at the time; Mammerickx and Sharman (1988) and Atwater and Severinghaus (1989) extended mapping of the Kula lineations to Chron 34 (83 Ma), as shown in Figure 3. Later in this paper I will discuss whether the Kula and Izanagi are in fact the same plate. For now, though, I will use the name Kula for the Chron 34 and younger plate and Izanagi for the M-sequence plate that moved generally north to northwest away from the Pacific.

Hilde et al. (1976 and 1977), Handshumacher et al. (1988), Sager et al. (1988), Sharman and Risch (1988) and Nakanishi et al. (1989 and 1992a and b) showed how the Hawaii and Japanese lineations meet at a magnetic bight that traces motion of the Pacific-Farallon-Izanagi triple junction (heavy solid black line in Figure 2) and that for about 1,000 km the path of the triple junction follows the axis of Shatsky Rise, a prominent bathymetric feature in this part of the Pacific. More recent papers (Nakanishi et al., 1999, Sager et al., 1999) emphasize magnetic lineations on Shatsky Rise itself, showing how evolution of the rise was directly tied to spreading ridge axis intersections at the Pacific-Farallon-Izanagi triple junction. Detailed interpretations of the plate kinematics implied by the Hawaii-Japanese lineations were carried out by Engebretson

(1984), Engebretson et al. (1984a and 1987) and Nakanishi et al. (1989). These authors showed how spreading rates varied from 37 to 79 mm/yr on the ridge systems involved and that the Izanagi may have been separated into two plates moving in slightly different directions for some of the spreading history. Sager et al. (1988) and Nakanishi et al. (1989) showed that there was at least one significant jump of the triple junction to a new location, shown by the dashed line at the southwest end of Shatsky Rise in Figure 2. This 800 km jump occurred at M21 time (147 Ma) and was approximately coincident with a change in direction of relative motion of 25-30° between the Pacific and Izanagi plates, although there was no simultaneous Pacific-Farallon motion vector change (Sager et al., 1988; Nakanishi et al., 1999). Excess volcanism that created Shatsky Rise began at the new triple junction location (Sager et al., 1988). A mantle plume sourcing a hotspot as the source for anomalous volcanism that produced Shatsky Rise has been a common model for origin of the rise since the hotspot paradigm was first proposed, as summarized by Sager (2005). Sager (2005) points out, however, that a plume origin for a hotspot has several inconsistencies. One is the coincidence between the triple junction jump at M21, the change in Pacific-Izanagi motion direction and initiation of Shatsky Rise. If a plume was associated with initiation of Shatsky Rise, it is not easy to explain why motion direction of the Izanagi plate changed at the same time (Sager, 2005). Limited geochemical data (Mahoney et al., 2005) and interpretations of heat flow (Verzhbitskii and Komonov, 2004; Kotelkin et al., 2004) on Shatsky Rise suggest a spreading ridge rather than plume origin for the rise although, as Sager (2005) concludes, there is as yet not enough information to decide on a plume/hotspot or ridge origin.

There are several other topographic features in this part of the Pacific that bear on a discussion of tectonic evolution of the area. The Emperor Trough (Figure 1) is a dramatic linear topographic feature more than 1500 km long and up to 100 km wide with more than 2000m of relief in places (Mammerickx and Sharman, 1988). Larson and Chase (1972) and Hilde et al. (1977) postulated that it formed as a transform fault during the Superchron. In the tectonic scenarios of Rea and Dixon (1983) and Mammerickx and Sharman (1988) the trough is shown as a spreading center, but no estimates of how much sea floor was created while it was a spreading center are given. Woods and Davies (1982) and Atwater (1989) treat it as a rift but also do not give quantitative estimates of rift duration or amount of extension. East of the Emperor Trough is the east-west trending Chinook Trough. This discontinuous structure lies close to the southern edge of the Kula spreading lineations (Figures 1-3). Woods and Davies (1982), noting that the trough is approximately parallel to the Mendocino fracture zone, suggested that the Chinook Trough was originally a Pacific-Farallon transform fault that served as the locus for spreading that initiated when the Kula plate formed and commenced its northward motion. Mammerickx and Sharman, (1988) and Atwater (1989) agreed with this interpretation. To the west of the Emperor Chain on Cretaceous Quiet Zone sea floor there is another topographic feature, Hokkaido Trough (Figure 1), that morphologically resembles Chinook Trough in this figure. It trends approximately parallel to the Japanese M-sequence lineations and perpendicular to fracture zones, suggesting an origin related to post M-sequence sea floor spreading. In the rather complicated tectonic model of Mammerickx and Sharman (1988), Hokkaido Trough is interpreted as a failed oceanic rift in which rifting propagated westward along the trough. North of Hokkaido Trough and still on Quiet Zone sea floor are several northwest-trending fracture zones, including the Kruzenstern. As these fracture zones are approximately parallel to spreading direction during the time represented by the Japanese lineations, they are assumed here to have formed by Pacific-Izanagi spreading during the Superchron.

Hess Rise is another large topographic feature. It is located within Cretaceous Quiet Zone sea floor so details of age of surrounding sea floor are unknown except for the Aptian to Campanian bounding ages of the Superchron. Age data from the rise itself are sparse. Vallier et al. (1983) suggest an uppermost Aptian to Albian age (112 to 100 Ma), based on stratigraphic ages of sediments cored in four DSDP wells on the rise. Radiometric ages for the rise summarized by Clouard and Bonneville (2005) show an age of 87.1 Ma for a seamount near the southern margin of the rise. Taking this age plus the uppermost Aptian age for the northern rise from Vallier et al. (1983) and other younger ages from the Wentworth seamounts which lie between Hess Rise and the Hawaiian chain, Pringle et al. (1993) suggested that the rise formed over a fixed hotspot with the rise moving north over the hotspot. Sager (2005) points out that age progression along Shatsky Rise and Hess Rise is consistent with the concept that both of these features formed over the same hotspot, although with a tortuous path. Verzhbitskii and Komonov (2004) suggest that Hess Rise, like Shatsky Rise, formed along the track of the Pacific-Farallon-Izanagi triple junction during the Superchron. Vallier et al. (1983), noting that northern Hess Rise parallels the Hawaii lineations to the west and that in their interpretation all of Hess Rise formed simultaneously (i.e. no age progression), prefer a model where Hess Rise was created at the Pacific-Farallon spreading center. This is the model adopted in this paper. Possible formation of Hess Rise at a ridge axis during a spreading direction change is similar to models proposed for South Pacific island chains by Hieronymus and Bercovici, (2000), who relate these features to plate stress changes with a ready supply of melt.

The Hawaii-Emperor chain, stretching from Meiji Seamount to the Hawaiian Islands (Figure 1), is the most dominant morphologic feature in the Northwest Pacific. The hotspot model for origin of the chain, first proposed by Wilson (1963), has remained the leading explanation for its creation (Duncan et al., 2006; Clouard and Bonneville, 2005). Meiji is thought to be the oldest preserved seamount in the Hawaii-Emperor seamount chain (Duncan and Keller, 2004). It is located at the junction between the Kamchatka and Aleutian trenches. We will examine age data for this area later in this paper.

As summarized above, data available for constraining tectonic scenarios for the development of the Northwest Pacific are concentrated on the areas and times represented by the Hawaii-Japanese lineations and the Kula lineations. As Atwater (1989) pointed out, it is not obvious how plate boundaries evolved through the Superchron. Variations in published models center on different interpretations of Emperor Trough and on the origin of the sea floor between Chinook Trough and the Mendocino Fracture Zone. Larson and Chase (1972), Hilde et al., (1977) and Smith (2003) interpret Emperor Trough as a transform fault that linked spreading on the Kula lineations with spreading on since-subducted sea floor near the north end of the Emperor seamounts. Woods and Davis (1982) suggested that Emperor Trough formed as a rift during early stages of Kula plate initiation. As in their model the Kula plate initiated along the Chinook Trough, the portion of the Emperor Trough that lies to the south of Chinook Trough was explained as a rift, although they did not give an estimate of total extension amount. In a variation of this model, Rea and Dixon (1983) introduced an extra plate, the Chinook plate, as a way of creating the sea floor between Chinook Trough and the Mendocino fracture zone. In their model the Emperor Trough is shown as a rift with motion across the feature lasting from 83 to 72 Ma. Rea and Dixon (1983) suggest that the Emperor Trough accommodated 132 km of extension (11 my at 12 mm/yr) south of the Chinook Trough and more than 800 km (11 my at 78 mm/yr) north of the Chinook Trough. There is no morphologic evidence for such very different tectonic regimes along the Emperor Trough on either side of Chinook Trough (Figure 1), casting some doubt on the interpretation of different plates on either side of Chinook Trough. Mammerickx and Sharman (1988) present a tectonic scenario for the area which also includes the separate Chinook plate and substantial extension across the Emperor Trough (64 mm/yr for 13 my or a total of 700 km), which is unlikely based on preserved morphology. In addition, Atwater et al. (1993) discount existence of the Chinook plate as it would require a large section of the Mendocino Fracture Zone to be a strike slip boundary between the Chinook and Pacific plates, for which there is no evidence.

In this paper I suggest that tectonic evolution of this area of the Pacific can be fairly simply understood in terms of evolution of the triple junction that moved through the area. Motion of this triple junction is known from preserved magnetic lineations during both M-sequence time and Kula lineation time. It moved to the northeast during both these times, as shown by the heavy black lines in Figure 2 (actually north-northwest prior to M21). The heavy dashed lines in this figure show the triple junction track across Quiet Zone sea floor as postulated in this paper. I suggest that during the early part of the Superchron the triple junction continued moving northeast away from the M-sequence sea floor. It then jumped nearly 2,000 km to the southeast in a reorganization of plate boundaries, before continuing its northeast motion along the post-Chron 34 magnetic bight that records its motion. One implication of this model is that there was always just one plate moving generally northward away from the Pacific and that the Kula and Izanagi plates are in fact the same plate, as originally suggested by Larson and Chase (1972) and Hilde et al., (1977). Another implication comes from tracking of spreading centers along the northern boundary of the Pacific plate. When the triple junction jumped to the southeast, it left an abandoned spreading center that I suggest was the site of excess volcanism that initiated the Hawaii hotspot and started development of the Emperor Seamount chain. Tectonic evolution is illustrated with a series of maps depicting evolution of the spreading plate boundaries and then this evolution is used to draw inferences about tectonic origin of the Hawaii hotspot.

TECTONIC EVOLUTION OF THE NORTHWEST PACIFIC

Fracture zone and magnetic isochron data summarized above provide the primary constraint on deciphering tectonic history of the Northwest Pacific. As there is no isochron information in the large area of Quiet Zone sea floor, it is worth taking a closer look at data either side of this area. M-sequence lineations are well-mapped with fairly dense data (Nakashini et al., 1989; Sager et al., 1999), but data for the young side of the Superchron are not as good. Figure 3 is a detail of the data used to map these younger lineations, taken directly from Plate 1 of Atwater and Severinghaus (1989). Chron 31 shows the east-west strike that is displayed by all the younger Kula lineations. Older lineations, though, are more broken up, with several pseudofaults mapped by Atwater and Severinghaus, especially in Chron 32. There is a difference of about 15° in strike between Chrons 34 and 31 as mapped, although there is little data constraining mapping of Chron 34. The structuring seen in mapped lineations could be caused by readjustments of the spreading centers to this 15° change in spreading direction. It could also be the cause of the rough-smooth transition mapped by Mammerickx and Sharman (1988). These authors mapped a transition between rough and smooth sea floor in Chron 32b and associated it with a change in spreading rate, but it is possible that it represents ridge reorientations responding to changes in spreading direction. As can be seen in Figure 3, data for precise mapping of Chron 34 are rather sparse, but it appears that Kula-Pacific relative motion underwent a 15° change in direction at about the same time as Pacific-Farallon motion, mentioned above. Chron

34 is not perpendicular to the Emperor Trough, as would be expected if Emperor Trough is a transform active at Chron 34 time, but the west end of Chinook Trough is perpendicular to Emperor Trough where they meet. This is consistent with Chinook Trough being formed at the location of a spreading ridge axis perpendicular to Emperor Trough, if Emperor Trough is assumed to be a transform.

The model for tectonic evolution of the north Pacific presented in this paper is shown with a series of figures showing progressive changes in the Pacific, Izanagi, Kula and Farallon plate boundaries. I use the gravity and tectonic data map, Figure 2, as a base. Figures step though time showing areas of sea floor appearing as they are created. Figure 4 is a copy of Figure 2 with the Hawaii-Emperor chain shaded as a visual reminder that this feature is mostly younger than the sea floor on which it is built. Also shaded is the area north and west of the trench. This is done to emphasize that the sea floor we are dealing with was a long way from any continental margin when it formed, as shown in Figure 5. This is a Pacific-wide reconstruction for 80 Ma, using the plate circuit approach for calculating relative plate positions (rotation poles from Norton, 1995). It is not possible to calculate position of the Pacific plate relative to the surrounding continents earlier than about 90 Ma, as the Pacific was totally surrounded by subduction zones prior to this time. The plate circuit can only be used for times less than 90 Ma, when the Pacific became attached to New Zealand and rifted from West Antarctica (Cande et al., 1995). It would be useful if the fixed hotspot reference frame assumption could be used for earlier plate reconstructions, but this assumption can no longer be regarded as valid, as shown for the Hawaii hotspot by Tarduno and Cottrell (1997), Tarduno and Cottrell (2003) and Doubrovine and Tarduno (2004).

The record of motion of the Pacific-Farallon-Izanagi triple junction and formation of Shatsky Rise during M-sequence time is well-understood (Sager 2005). Following is a summary of pertinent tectonic information during this time span:

1) The triple junction moved to the north-northwest from M29, the oldest magnetic lineation in the M-sequence (157 Ma), to M21 (147 Ma), then moved northeast until M0, the youngest lineation in the M-sequence (125 Ma).
2) Shatsky Rise formed on the migrating triple junction over a time span of about 20 my, from M21 (147 Ma) to M1 (127 Ma); (Nakanishi et al., 1999, Sager et al., 1999, Sager, 2005).
3) There was at least one significant jump of the triple junction to a new location, shown by the dashed line at the southwest end of Shatsky Rise in Figure 2. This 800 km jump occurred at M21 time and was approximately coincident with a change of relative motion of 25-30° between the Pacific and Izanagi plates (Sager et al., 1988; Nakanishi et al., 1989). Significantly, there was no coincident change in Pacific-Farallon relative motion.
4) Geochemical and heat flow data suggest a MORB-like origin, not mantle plume, for basalts on the rise (Verzhbitskii and Komonov, 2004; Kotelkin et al., 2004, Mahoney et al., 2005), although a plume origin cannot be unequivocally ruled out (Sager, 2005).

Figure 6 shows plate configuration at M0 time (125 Ma, the beginning of the Cretaceous Normal Polarity Superchron) for the area. Pacific plate boundaries are constrained by magnetic lineations; the Pacific-Izanagi-Farallon boundaries are drawn assuming a RRR triple junction. Figure 7 shows plate boundaries for about 15 million years later, with ridge axis positions extrapolated using spreading rates at the end of the M sequence given by Nakanishi et al. (1989). This extrapolation ignores possible complications posed by Hokkaido Trough if the trough is associated with a ridge jump or change in spreading rate. Ridge-transform geometry is copied from that at M0 time. Note that the Pacific-Farallon spreading center straddles Hess Rise, with the ridge axis north of the Mendocino fracture zone located along northern Hess Rise and the ridge axis south of Mendocino FZ located along Liliuokalani Ridge, which is a feature apparently in structural continuity with the rise. This coincidence of inferred spreading ridges and greater Hess Rise suggests that the rise formed by excess volcanism associated with the spreading process. Whether a ridge jump was also involved is not known, although it does seem to be associated with a spreading direction change of about 15° early in the Superchron. As discussed above and as shown by Atwater et al. (1993), there must have been spreading ridge reorganizations, including ridge jumps, during the Superchron. As part of these reorganizations, total offset across the Mendocino fracture zone increased from 300 km at the end of M-sequence time to nearly 1,400 km at Chron 34 time.

Figure 8 shows plate boundaries for later in the Superchron, at about 90 Ma. The scenario presented is similar to that proposed by Larson and Chase (1972), Hilde et al., (1977) and Smith (2003). The Pacific-Farallon spreading center is extrapolated backwards from the Chron 34 configuration, i.e. this assumes that the ridge-transform configuration seen at Chron 34 was formed by ridge jumps prior to (or at) 90 Ma. The Pacific – Kula/Izanagi plate boundary is drawn assuming that spreading on this boundary proceeded from 110 Ma (Figure 7) in a north-northwest direction relative to the Pacific, with motion parallel to the Kruzenstern and nearby parallel fracture zones. The triple junction would migrate to the northeast, following the dashed black line. The area of sea floor shown by the crosshatch pattern is postulated to be Pacific sea floor that was captured by the Farallon plate at the time of the next figure.

Figure 9 shows interpreted spreading patterns for a short time, probably a few million years, after Figure 8. It is proposed that the triple junction jumps 2,000 km from point A, where it was in Figure 8, to point B in Figure 9. In this scenario, the Emperor Trough is created as a sinistral transform fault separating Pacific crust from crust that is now part of the Kula/Izanagi plate. This crust would be captured from the Farallon plate or, for the crosshatched area in Figure 8, from the Pacific. This triple junction jump is a larger version of the jump that happened at M21 time, see Figure 2. There would be significant reorganizations on the boundary between the Farallon and Kula/Izanagi plate, but the crust involved has all been subducted so we have no data to show what happened.

Figures 10 and 11 show, respectively, the tectonic setting at Chron 34, 84 Ma and Chron 32, 71 Ma. At 84 Ma, Figure 10, the Farallon plate is moving almost directly east relative to the Pacific plate. Farallon motion changed by 15° to N75°E by 71 Ma (Engebretson et al., 1984; Figure 11). At 84 Ma the Kula/Izanagi was moving north-northwest, but was starting to change direction to more nearly directly north, the motion direction it achieved by Chron 32 (Figure 11). As discussed above (Figure 3), the change of 15° in Pacific – Kula/Izanagi motion after Chron 34 is not well constrained. In the tectonic scenario presented here, with the Emperor Trough as a transform during the Superchron, there would have been a total change of about 35° in Pacific – Kula/Izanagi motion direction from the time of the triple junction jump (motion direction N35°W, Figure 9) to Chron 32 time (Figure 11) when motion was directly north. For comparison, the total change in Pacific-Farallon motion during the Superchron was about 25°, from N65°E at M0 to east-west at Chron 34 (directions measured along the Mendocino fracture zone, Figure 2). In the tectonic scenario presented here, the Chinook Trough formed as the spreading ridge reorganized in response to changing spreading directions close to Chron 34 time. This means that it is not as significant a tectonic feature as suggested by Woods and Davies (1982), who argued that it formed at the site of first formation of the Kula plate. The ridge-transform configuration on the Pacific-Kula boundary shown in Figure 11 at the northern end of the Stalemate fracture zone is speculative. It must have been something like as shown, however, as the spreading fabric around Meiji seamount is all northwest and probably formed in the earlier spreading phase (Figure 10). An implication of this model is that Meiji seamount could have formed on an abandoned spreading center. As Meiji is the oldest preserved seamount of the Hawaii-Emperor Chain, a further implication is that the Hawaii hotspot originated on this abandoned spreading center, i.e. it has a tectonic origin.

DISCUSSION

In the simple model proposed here the Kula and Izanagi plates are actually the same plate. Consideration of the general tectonic setting of the area lends support to this hypothesis. Magnetic lineations and fracture zones tell us that from the beginning of M-sequence time in the Jurassic until well into the Cenozoic there was a plate moving in a generally northward direction (in present-day coordinates) away from the Pacific plate. During M-sequence time this plate, commonly referred to as the Izanagi, was moving in a north-northwest direction. During the Superchron the triple junction changed location (all models for tectonic evolution of this area must include a scenario for initiation of this triple junction) and shortly before Chron 34 (84 Ma), motion direction changed until by Chron 32 (71 Ma) motion was directly north. This northward-moving plate is commonly called the Kula plate. It would appear to be much simpler to have a single plate moving away from the Pacific plate through all these events. Referring back to Figure 5, the Pacific-wide reconstruction for 80 Ma, it can be seen that when the triple junction jumped it was more than 4,000 kilometers (40 degrees latitude) from the continental margin flanking the northern edge of the Pacific Ocean. If a new plate was formed at 84 Ma (Chron 34), the time of formation of the Kula plate in the Woods and Davies (1982) model, then a new 4,000 km long plate boundary would have to be formed; the new boundary would be 6,000 km long if the new triple junction location is included. I suggest that a reorganization of existing boundaries, even with a 2,000 km relocation of the triple junction, is a more likely scenario.

The hypothesis presented here, that the triple junction jump was coincident with initiation of the Hawaii hotspot, implies that ages for these two events must be similar. Knowledge of sea floor age at either end of the jump would constrain timing of the jump. Available age control for these events is examined in the next section.

Age of sea floor at either end of triple junction jump

Timing of the triple junction jump as proposed here, occurring as it did during the Superchron, is poorly constrained. At best the data allow us to speculate that the triple junction was located near the north end of the Emperor Chain before relocating to the southern end of the Emperor Trough. If the age of the sea floor at either end of the Emperor Trough was known, this would provide an age for the jump. This location is on sea floor created by Pacific-Farallon spreading north of the Mendocino Fracture Zone and at the west end of a structured area named the ‘Non Surveyor’ by Mammerickx and Sharman (1988). The unmapped ridge jumps (including the one proposed here) between M0 and Chron 34 along this plate boundary (Engebretson et al., 1984; Atwater et al., 1993) introduce additional uncertainty in estimating sea floor age. Nevertheless, some idea of this age can be obtained by examining available data. Engebretson et al. (1984) calculated parameters of motion between the Pacific, Farallon and Kula plates that can be used for interpolation or extrapolation of an age estimate. Choices are interpolation between Chrons M0 and 34 generated by Pacific-Farallon spreading and extrapolation of Chron 34 and younger spreading rates backwards to the Emperor Trough for both Pacific-Farallon and Pacific-Kula spreading. Engebretson et al. (1984) calculated two possible rates for Chron M0 to 34 Pacific-Farallon motion, depending on whether ridge jumps occurred north or south of the Mendocino Fracture Zone. Table 1 summarizes results of the interpolation and extrapolation calculations. Age estimates for the southern end of the Emperor Trough from the four different calculations range from 96 to 106 Ma.

Another estimate of the time of the jump can be obtained from extrapolation of plate motion rates calculated from the M-sequence lineations to the position of the abandoned triple junction at the north end of the Emperor Chain. A simple method that incorporates data from both the Japanese and Hawaiian lineations is to use calculated motion of the triple junction. Nakanishi et al. (1989) show velocity triangles for the Pacific-Izanagi-Farallon triple junction for several times, with Chron M3 (129 Ma) being the youngest. This diagram shows the triple junction moving at 4 cm/yr to the north-northeast. The youngest lineation with a well-defined magnetic bight, M1 (127 Ma), is about 1,100 km from Meiji seamount, which at 4 cm/yr yields a travel time of the triple junction to Meiji of 27.5 my, or a time of arrival of 99.5 Ma. Uncertainties in this estimate are large; it assumes constant and symmetric spreading within the Superchron and assumes there are no complications introduced by possible spreading ridge reorganizations at Hokkaido Trough which are not possible to map with existing data.

Structure of the northern end of the Emperor Chain is shown in Figure 12. Meiji is the northernmost seamount; it is located on the Obruchev Rise, an elongated plateau that trends northwest-southeast and includes Detroit Seamount. The 4 km isobath around Obruchev Rise is highlighted in Figure 12. This covers an area of about 57,000 km^2. Although Obruchev Rise is not separated from the Hawaii-Emperor Chain in the global catalog of large igneous provinces by Coffin and Eldholm (1994), this area is comparable in size to some oceanic plateaus listed such as the Cape Verdes or Conrad Rise. There are several structural grains to consider in Figure 4. On the east side of the figure Rat and Buldir fracture zones strike north-south; these features track Pacific-Kula relative motion. The northern Emperor Seamounts strike N15°W, as shown by the pale blue dashed line. The northwest grain of sea floor structure is apparent in the area west of Buldir fracture zone. The Kruzenstern fracture zone, which traces Pacific-Izanagi/Kula relative motion (Mammerickx and Sharman, 1988) for at least part of Superchron time, strikes N30°W. This is the same strike as the northern end of Emperor Trough. Joining these two features is Tenji seamount, which shows a strong linear grain perpendicular to both the Kruzenstern fracture zone and Emperor Trough; this structural relationship resembles what would be expected if Tenji was a fossil spreading center. This is not the postulate here, as Tenji (for which there are no direct age data) should be about 20 million years younger than its surrounding sea floor, but the relationship could bear further investigation. The Stalemate fracture zone strikes N60°W. Shown in white numbers on Figure 12 are magnetic lineations 23 (51 Ma) to 20 (43 Ma) and a postulated extinct ridge (RR) as mapped by Lonsdale (1988). Lonsdale (1988) interpreted these lineations to have formed during large plate motion direction changes perhaps associated with the bend in the Hawaii-Emperor chain. Mapping of these lineations is, however, tenuous, as they are based on data from just a few ship tracks and incorporate extremely asymmetric spreading (Atwater, 1989). The southwest flank of Obruchev Rise also strikes N60°W. This trend could be a reflection of relative motion between the early Hawaii hotspot and the Pacific plate. This trend is 30° different from the trend of the Emperor seamounts. This change in apparent motion of the hotspot relative the Pacific, which is half the angle of the more famous Hawaii-Emperor bend, has not, as far as I am aware, been incorporated into any published models of Pacific-hotspot relative motion, but it probably should be. Finally, visible in Figure 12 is a weak N25°W structural grain running obliquely across the Obruchev Rise towards the intersection of the Aleutian and Kamchatka trenches (one of these features cuts through the 'R' of the label Rise in figure 13). Origin of this grain is not known, although if it is fault related, it could be a fruitful area for future studies of relationships between hotspot tracks and stress-induced fracturing, as has been proposed for some hotspot tracks (Smith, 2003, 2005; Natland and Winterer, 2005).

Age of the northern Emperor Seamounts

There are no reliable basement age data for Meiji Seamount itself. Dalrymple et al. (1980) reported a minimum K-Ar age of 61.9 ± 5 Ma from basalts cored at DSDP site 192 on the seamount. Fossil assemblages in overlying sediments yield a Maastrichtian age (68-70 Ma; Worsley, 1973). These ages are younger than the next seamount down the chain, Detroit seamount (Figure 12), for which there are reliable age data, so unless the general assumption about age progression along the chain is incorrect, these ages do not reflect age of formation of Meiji (Duncan and Keller, 2004). Basalts from ODP site 884 on the northeast flank of Detroit seamount yield a ^{40}Ar/ ^{39}Ar plateau age of 81.2 ± 1.3 Ma for a plagioclase free component and an isochron age of 80.0 ± 0.9 Ma (Keller et al., 1995). This age is consistent with reversed magnetic polarity measured at the site (Keller et al., 1995). Later sampling from ODP sites 1203 and 1204 located on the seamount summit (Figure 4) yielded younger ages (Tarduno et al., 2003; Duncan and Keller, 2004). These authors report a mean age of 75.82 ± 0.62 Ma from plateaus in ^{40}Ar/ ^{39}Ar incremental heating spectra from three whole rock basalt samples and two feldspar separates in site 1203. This age agrees with a Campanian age (75 to 76) Ma obtained from nannofossils found in sedimentary beds within the basement sequence in the site (Tarduno et al., 2002). Basalt samples from site 1204 (Figure 4) did not yield reliable radiometric ages, but a 71-76 Ma (late Campanian) biostratigraphic age from overlying sediments is similar to ages measured from site 1203. Site 884, which yielded the older age of 80-81 Ma, is situated about 48 km NE of site 1204 on the flank of Detroit seamount. Duncan and Keller (2004) refer to this location as 'Detroit North'. These authors suggest that drilling on seamount summits will of necessity sample the younger shield-building stage of seamount formation. They suggest that the older age is a result of sampling of an older volcanic portion of the seamount, implying that the minimum age for initial formation of Detroit seamount is 81 Ma.

Age data for the sample locations shown on Figure 12 and other area data are summarized in Figure 13, a diagram modified from Duncan and Keller (2004). This figure shows reported ages versus distance from Hawaii. Symbols show age data summarized above, with trend lines (solid lines) of 5 cm/yr and 10 cm/yr motion relative to the Pacific. Also shown with a dashed line is the trend line for all data older than 15 Ma for the chain from Clague & Dalrymple (1987). The rectangle represents Obruchev Rise. The width of the rectangle represents the 500 km length (NW-SE axis) of the rise. Rectangle height represents age, ranging from the Maastrichtian sediment age at Site 883 to an age of close to 90 Ma found by linear extrapolation from Suiko through Detroit North. As shown by the arrow symbol in the lower right of Figure 13, the Obruchev Rise area has experienced significant post-hotspot volcanism, as evidenced by ash layers found within the sedimentary column (summary in Duncan and Keller, 2004), Eocene age dates on some basalt samples (Duncan and Keller, 2004) and lava flows seen on seismic data (Kerr et al., 2005). The northeast flank of Obruchev Rise is also the site of an unusual sedimentary package, the Meiji Drift, which is an Oligocene and younger sequence of fans and contourites sourced from the northwest (Scholl et al., 1977 and 2003; Kerr et al., 2005).

Other evidence that Obruchev Rise was created close to a spreading center comes from gravity and geochemical data. As can be seen in Figure 1 and in more detail in Figure 12, the free air gravity signature of the Obruchev Rise is subdued when compared to younger seamounts in the Emperor Chain. Younger seamounts are rimmed by a negative gravity anomaly (blue in the figure) which is the gravity effect of a flexural moat, caused by loading of a seamount onto pre-existing crust (Watts, 2001). Presence of a moat can be used as an indicator of relative age. Lack of a flexural moat around a seamount or oceanic plateau is an indication that it may have formed close to, or on, a spreading ridge (Watts, 2001). Shatsky Rise, Figure 1, is a good example. Lack of a flexural moat around Obruchev Rise suggests that it formed close to a recently-active spreading center. One problem with this simple interpretation, however, is location of the Obruchev Rise close to the Aleutian-Kamchatka trenches. The Obruchev Rise is located within the topographic high associated with flexural downwarping of the Pacific plate into the subduction zone, so it is possible that any flexural moat around Obruchev is obscured by this extra flexural effect (Watts, personal communication, 2006). There is other evidence that Obruchev Rise formed close to a spreading center. Geochemical evidence presented by Keller et al. (2000), particularly strontium, lead and neodymium ratios, are consistent with formation of Meiji and Detroit seamounts close to a ridge axis. As inferred in Figure 11, the Obruchev Rise may actually have formed at an abandoned spreading center left behind as north-directed spreading became established.

In summary, in this section several approaches to understanding age control for the suggested tectonic events have been attempted. Using sea floor spreading information, age of ocean crust at either end of the Emperor Trough is estimated in the range 96 to 106 Ma. Radiometric and biostratigraphic data for the northern Emperor Seamounts suggest a minimum age for Meiji Seamount of about 90 Ma. Thus oceanic crust ages tend to be slightly older than the estimated oldest seamount age, although, as already emphasized, uncertainties in these estimates are large and not easily quantified. More data are needed from the area to collaborate the suggested age of 90 Ma for the triple junction jump and initiation of the Hawaii hotspot. Gravity and geochemical data are consistent with initial formation of Obruchev Rise close to a spreading center. In the scenario presented here, this spreading center would be the one abandoned by the triple junction jump.

Tectonics of the Kamchatka-Aleutian trench intersection

The Obruchev Rise is inferred to be the oldest preserved volcanic feature in the Hawaii-Emperor seamount chain. Whether there were older seamounts in the chain that have been subducted is, of course, not known. There is no evidence that any seamount material has been accreted to Kamchatka, as accretionary material preserved there is all arc-sourced (Solotiev et al., 2002, 2006). However, if the inference from gravity data, isotopic data and the plate boundary scenario presented above that the Obruchev Rise formed at a ridge axis is correct, it is highly likely that this is in fact the oldest volcanic feature in the chain. It is feasible that a pre-existing hotspot crossed the ridge axis, but then we must say that it is coincidence that none of the older seamounts are preserved.

The sharp corner between the Kamchatka and Aleutian subduction zones north of Obruchev Rise (Figure 14) could be a result of collision of Obruchev Rise with the subduction zone. Indirect evidence for this is in Komandorski Basin, the basin across the subduction zone north of Meiji Seamount. This basin is very young, Miocene to Pliocene, in age (Baranov, 1991). It has a northwest-southeast structural grain (Baranov et al., 1991; grain also visible in Figure 14) that is parallel to Pacific plate motion (magenta line on Figure 14). It is possible that the basin was rifted open by the Obruchev Rise colliding with Kamchatka when Kamchatka was further east. If Kamchatka was originally part of what is now the Shirshov Ridge, when the Pacific plate moved along the path annotated in Figure 14 the Obruchev Rise would have collided with it about 7-8 my ago. As Obruchev Rise is an oceanic plateau, it may have been difficult to subduct and it may have pushed Kamchatka to the west, opening the Komandorski Basin. Early collision of this portion of the Pacific plate containing Obruchev Rise with the Aleutian-Kamchatka system may also explain existence of the Meiji Tongue. Mentioned earlier, this Neogene sediment wedge was deposited by bottom currents sourced from continental terranes to the north (Scholl et al., 1977; Kerr et al., 2005). It is possible that these source terranes were the ancestral Shirshov Ridge or even Bowers Ridge, an enigmatic structure (Marlow et al., 1990) preserved today on the north side of the Aleutian Trench. Sediment sourced from either or both of these structures could have been deposited on the Pacific plate as it moved by. Full explanation of this tectonic scenario, however, is beyond the scope of this paper; it will be developed elsewhere.

Data constraints for the plate model

This paper presents a model for the tectonic evolution of the Northwest Pacific and initiation of the Hawaii hotspot. Until better age control for the tectonic events discussed is available, however, this model is still, as the paper title implies, more speculation than observation-based fact. Data that could help to constrain the model are:

1) Data for the age of oceanic crust at either end of the Emperor Trough. If this feature is a transform fault, oceanic crust at either end of the trough should be the same age.

2) A difference between this model and models in which the Chinook Trough is the initiation rift for the Kula plate lies in predicted age of crust on either side of the trough. In the Woods and Davis (1982) model the Chinook trough separated new crust created when the Kula plate started moving north from older Pacific crust. Their model predicts an age difference of about 20 million years for crust north or south of the western end of the Chinook Trough, while the model in this paper predicts a very similar age for this crust. Age data from this region would help to differentiate between the models.

3) The Stalemate fracture zone is located adjacent to the Aleutian Trench. It trends approximately parallel to the Kruzenstern and other fracture zones that, in the model presented here, were created by sea floor spreading during the mid to late Superchron. This suggests that the Stalemate fracture zone should also be of the mid Cretaceous age. Magnetic lineations on the northeast side of the Stalemate fracture zone mapped by Lonsdale (1988) yield a Paleocene to Eocene age for this crust, implying a similar age for the Stalemate fracture zone. Better age constraints from this region would help to show whether the Stalemate is, in fact, an older feature. This would help to show that the crust in the area around the northern Emperor seamounts is all Superchron age and was created by Pacific-Izanagi spreading.

4) Determination of a similar age for the onset of the Hawaii hotspot and cessation of spreading when the triple junction jumped would validate the model.

5) Between Hess Rise and the Emperor Trough (Figure 1) is a triangular zone of sea floor with a subtle north-south grain; some of the lineaments are highlighted. If this grain was caused by north-south sea floor spreading, it does not fit any existing tectonic models, including the one presented here. More age and structural data are needed from this area to understand whether its tectonic evolution will require further updates to NW Pacific tectonic history.

CONCLUSIONS

As presented here, Jurassic through Cretaceous tectonic evolution of the North Pacific involved just three plates. These were the Pacific, Farallon and Kula/Izanagi plates. There is no reason to invoke extra plates like the Chinook (Rea and Dixon, 1983) or to have one plate, the Izanagi, bordering the northern Pacific plate during the Jurassic and Early Cretaceous and another, the Kula, from Late Cretaceous time onwards. Changes in spreading direction implied by changes in fracture zone and magnetic lineation strike can all be accounted for with a simple three-plate system. Anomalous topographic features in the area were created in several ways: Shatsky Rise by excess volcanism at a triple junction; Hess Rise by excess volcanism at a ridge-transform intersection perhaps associated with a spreading direction change; Chinook Trough by ridge reorganization also associated with a spreading direction change; Emperor Trough as a fracture zone and Meiji Seamount at a spreading ridge associated with both a spreading direction change and perhaps at the ridge left behind by a ridge jump. This tectonic reorganization which took place near the end of the Superchron is probably linked to changes in motion of the entire Pacific plate. This was the time when subduction along the southern boundary of the Pacific plate ceased and the Pacific rifted from West Antarctica (Cande et al., 1995), which implies major plate motion direction changes at this time.

The tectonic scenario for the Northwest Pacific leads to the suggestion that the spreading center abandoned as a result of the triple junction jump became the site of anomalous volcanism that evolved into the Hawaii hotspot. This implies that the hotspot originated through shallow, i.e. asthenospheric or lithospheric processes. There is no need to invoke a mantle plume for early history of the hotspot, although it is quite possible that a mantle plume later intersected this shallow structure and the combined center of anomalous volcanism evolved into the Hawaii hotspot as it exists today. One intriguing possibility is that a mantle plume combined with the shallow hotspot close to the time of the Hawaii-Emperor bend, ultimately causing the hotspot to change motion direction relative to the Pacific plate.

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TABLE 1. ESTIMATED AGE OF SEA FLOOR AT THE SOUTHERN END OF THE EMPEROR TROUGH

Source	Rotation pole			Start point		End point (S end of Emperor Trough)		Implied age of S end of Emperor Trough
	Lat °N	Long °E	deg/my	Lat °N	Long °E	Lat °N	Long °E	
Pacific-Farallon, M0 to 34	65.0	56.0	0.43	38.0	-167.5	35.6	-176.2	102 Ma (Chron 34 + 18 my)
Pacific-Farallon, M0 to 34	65.0	56.0	0.63	38.0	-167.5	35.5	-175.7	96 Ma (Chron 34 +12 my)
Pacific-Farallon, 34 to 25	66.0	64.0	0.36	38.0	-167.5	35.3	-176.1	106 Ma (Chron 34 + 22 my)
Pacific-Kula 34 to 32b	18.0	111.0	0.49	44.0	-177.0	37.2	-178.3	96 Ma (Chron 34 + 12 my)

Note: Rotation poles are from Engebretson et al. (1984a). These poles are used to rotate the ‘start point’ to the ‘end point’, with the implied age being estimated from the age of Chron 34 (84 Ma) plus the number of million years required for the rotation at the degrees/my rate of the rotation pole.

Figure captions

Figure 1. Free air gravity map of the northern Pacific (Sandwell 13.1, 2005). Thin magenta lines are mapped fracture zones, thin yellow lines are identified magnetic lineations. AFZ = Amlia Fracture Zone; CT = Chinook Trough; ET = Emperor Trough; HR = Hess Rise; HT = Hokkaido Trough; JP = Japanese Group seamounts; KU = Kruzenstern fracture zone; LR = Liliuokalani Ridge; MFZ = Mendocino Fracture Zone; MS = Musicians Seamounts; MPM = Mid Pacific Mountains; MWC = Marcus Wake chain; NFZ = Nosappu fracture zone; NR = Necker Ridge; NS = Non Surveyor feature; OFZ = Molokai Fracture Zone; PFZ = Pioneer Fracture Zone; SFZ = Surveyor Fracture Zone; SR = Shatsky Ridge; UFZ = Murray Fracture Zone. Magnetic lineations (identified in Fig. 2) are from compilations maintained by Larry Lawver and Lisa Gahagan at the Plates Project, University of Texas at Austin, and my own updates digitized from Nakanishi et al. (1989) and Atwater (1989). Mercator projection; scale bar is for approximately the latitude of Hess Rise.

Figure 2. Identified magnetic lineations in the North Pacific, labeled with Chron number. Heavy black lines track triple junctions, dashed where inferred. Japanese and Hawaiian lineations of the M-sequence are mostly west of the Hawaii-Emperor chain; they are numbered without the M prefix.

Figure 3. Detail of the old end of the Kula magnetic lineation sequence from Atwater and Severinghaus (1989). Data shows magnetic anomalies plotted perpendicular to ship tracks, with red bands showing interpreted and identified lineations. The Stalemate fracture zone shown in this map is named the Buldir by Mammerickx and Sharman (1988).

Figure 4. Same as Figure 2 but with area north and west of the subduction zone blanked out. This is done to emphasize that the area of the Pacific that we are dealing with was tectonically active while it was a long way from the margin. Also shaded is the Hawaii-Emperor chain as a visual reminder that it was created after the times of concern in the following figures.

Figure 5. Plate reconstruction for 80 Ma. Arrows indicate relative motions across plate boundaries (red lines) which are dashed where inferred. Green lines are magnetic lineations, magenta fracture zones. OJP = Ontong Java plateau.

Figure 6. Tectonic setting at M0 time, 125 Ma. Heavy red lines are plate boundaries, arrows show relative motion directions.

Figure 7. Tectonic setting at approximately 110 Ma.

Figure 8. Tectonic setting late in the quiet zone at 90 Ma.

Figure 9. Tectonic setting at 90 Ma after the triple junction jumped from point A to B, creating the Emperor Trough as a sinistral transform fault.

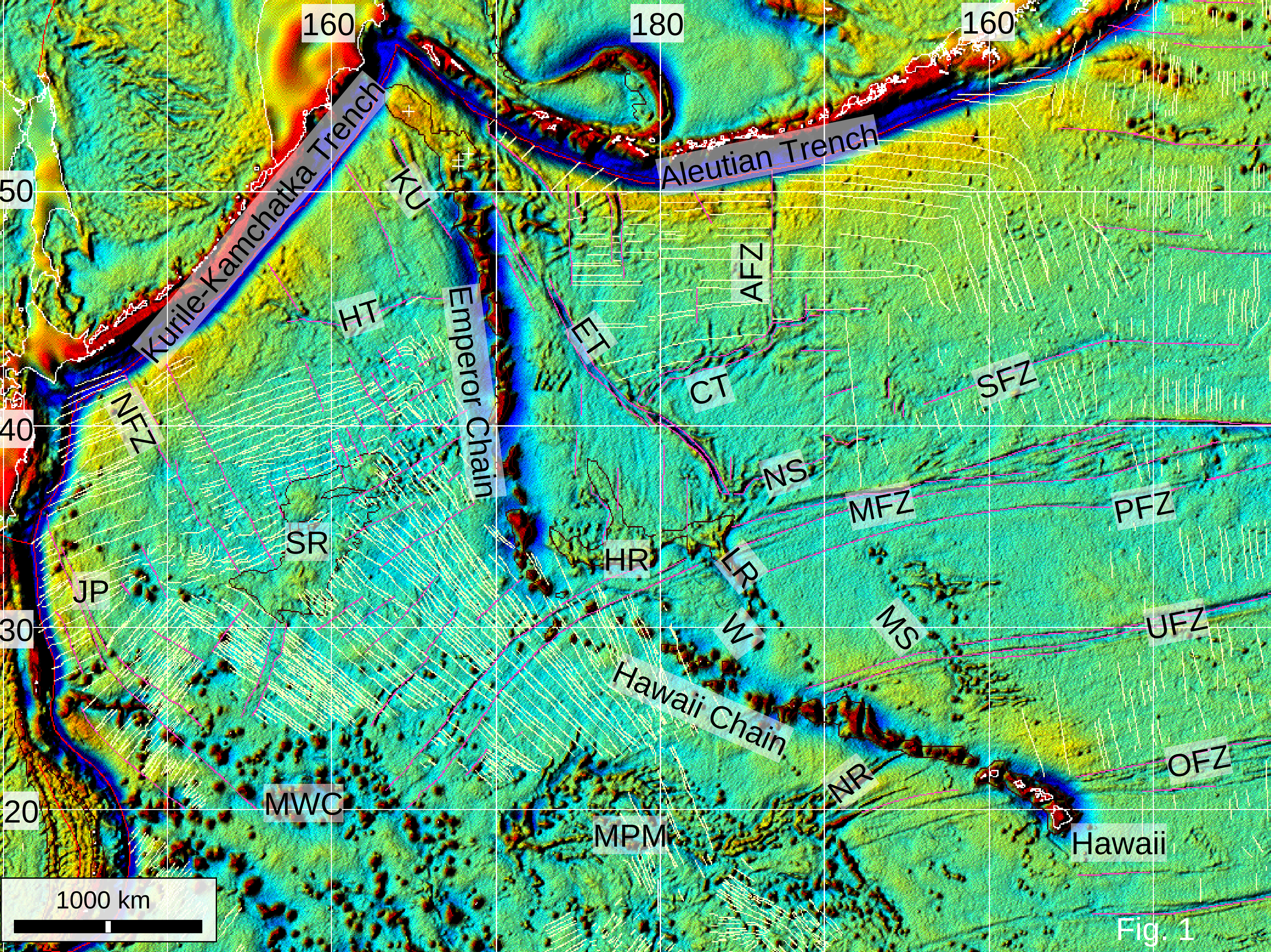
Figure 10. Tectonic setting at Chron 34, 84 Ma.

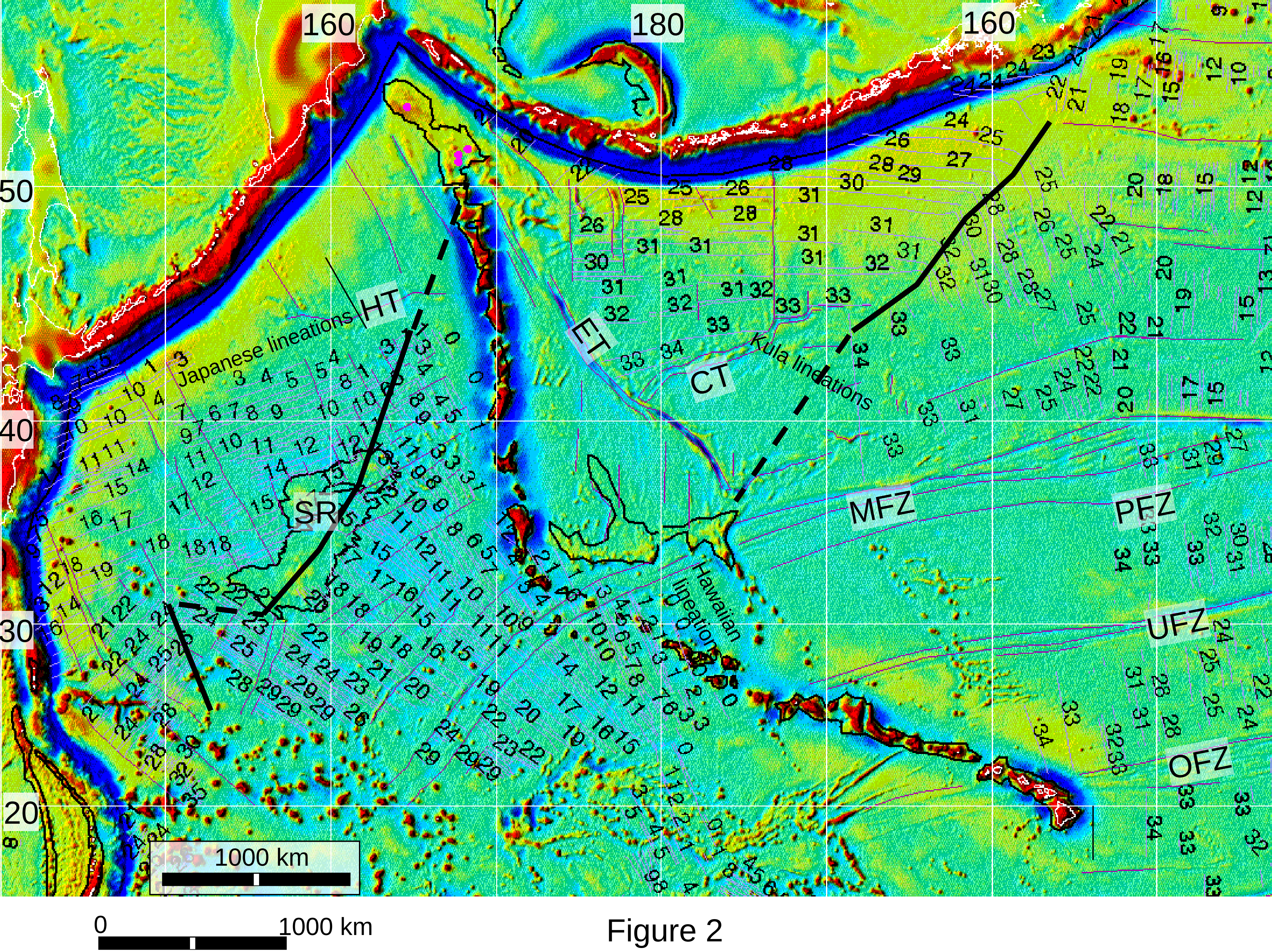
Figure 11. Tectonic setting at Chron 32, 71 Ma. Kula spreading direction has reoriented to north relative to the Pacific plate.

Figure 12.   Detailed view of the northern end of the Emperor Chain. Colored background is the satellite gravity (Sandwell, 2005). White contours are from the Smith and Sandwell (1997) global gridded bathymetry, contour interval 1 km. Numbered points on Obruchev Rise refer to DSDP and ODP drilling sites. White labeled lines in the Aleutian Trench are magnetic lineations identified by Lonsdale (1988).

Figure 13. Age of seamounts in the Emperor Chain plotted vs. distance from Hawaii along the Hawaii-Emperor Chain. Modified from Duncan and Keller (1994).

Figure 14. Detailed view of the satellite gravity (Sandwell, 2005) including the northern Emperor Chain and Komandorski Basin. White contours are from the Smith and Sandwell (1997) global gridded bathymetry, contour interval 1 km. Magenta line is path of Pacific relative to Asia for last 20 my, with times in my annotated, calculated from plate circuit poles in Norton (1995).


160
180
160
50
40
30
20
Kurile-Kamchatka Trench
Aleutian Trench
KU
AFZ
HT
Emperor Chain
ET
CT
SFZ
NFZ
NS
MFZ
PFZ
SR
HR
LR
JP
MS
UFZ
W
Hawaii Chain
OFZ
NR
MWC
MPM
Hawaii
1000 km
Fig. 1



160
180
160
50
40
30
20
HT
Japanese lineations
ET
CT
Kula lineations
SR
MFZ
PFZ
UFZ
OFZ
Hawaiian lineations
1000 km
0
1000 km

Figure 2

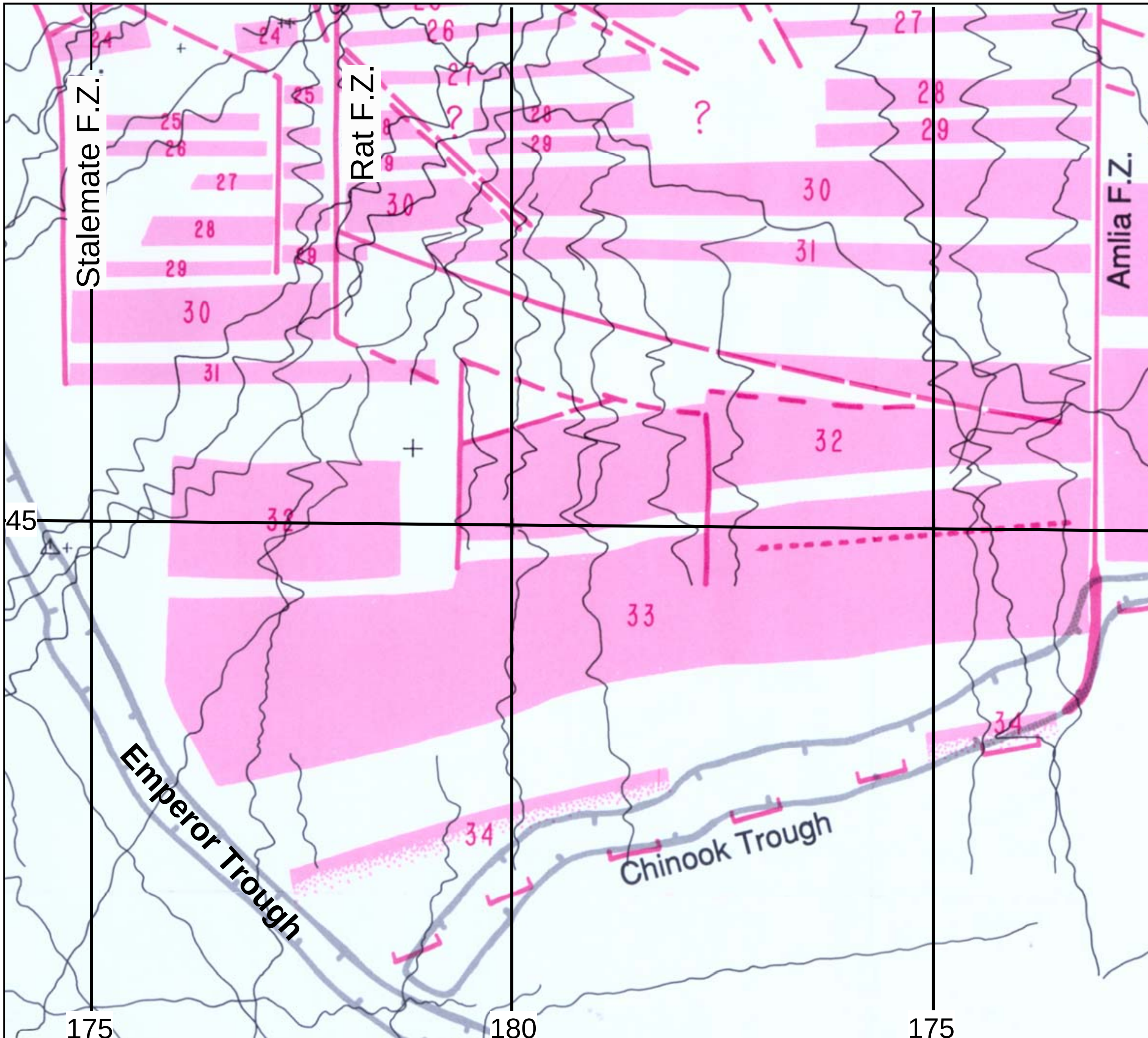

Stalemate F.Z.
Rat F.Z.
Amlia F.Z.
Emperor Trough
Chinook Trough
45
175
180
175
24
26
27
25
28
29
30
31
32
33
34
?

Fig 3

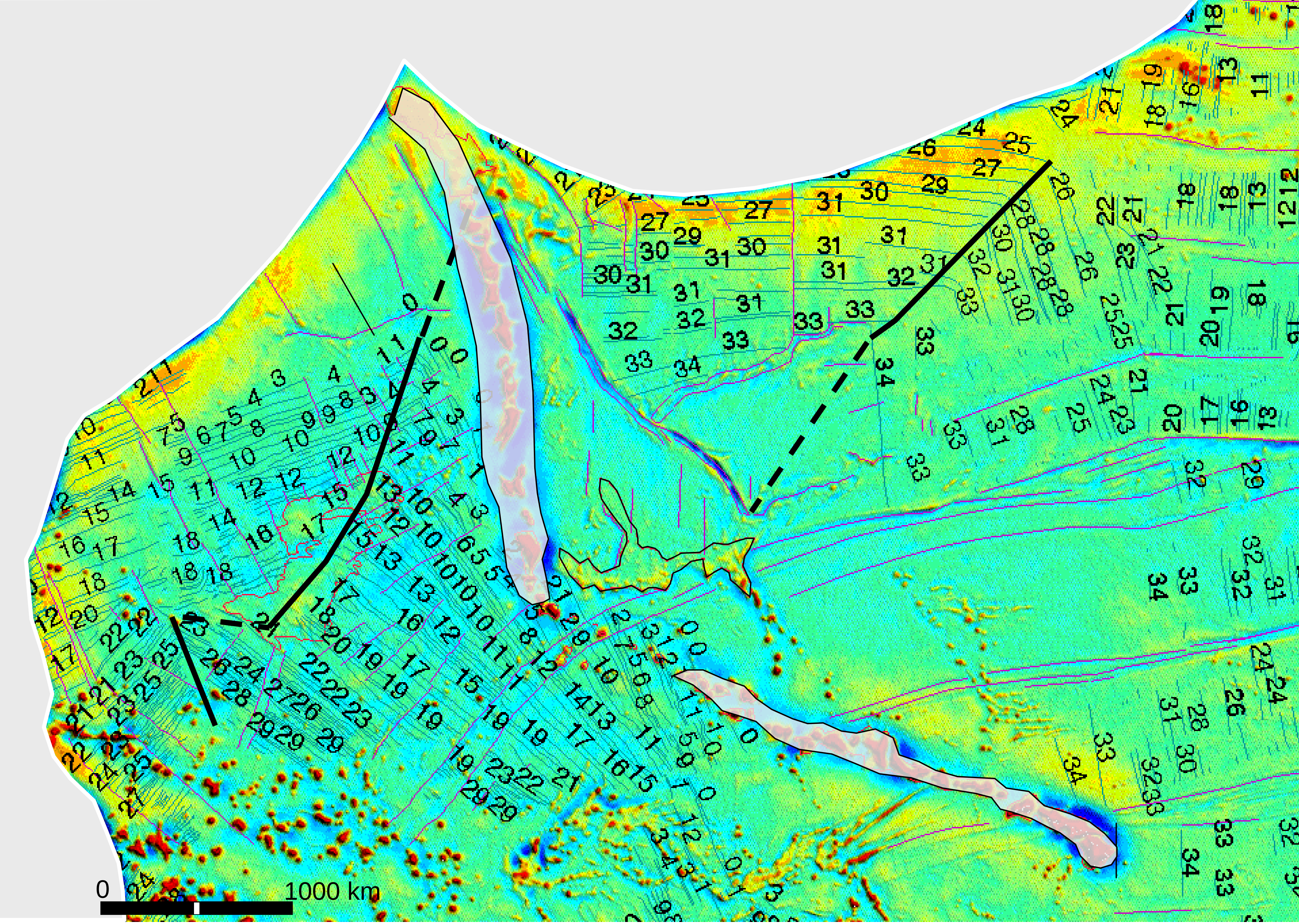


Figure 4

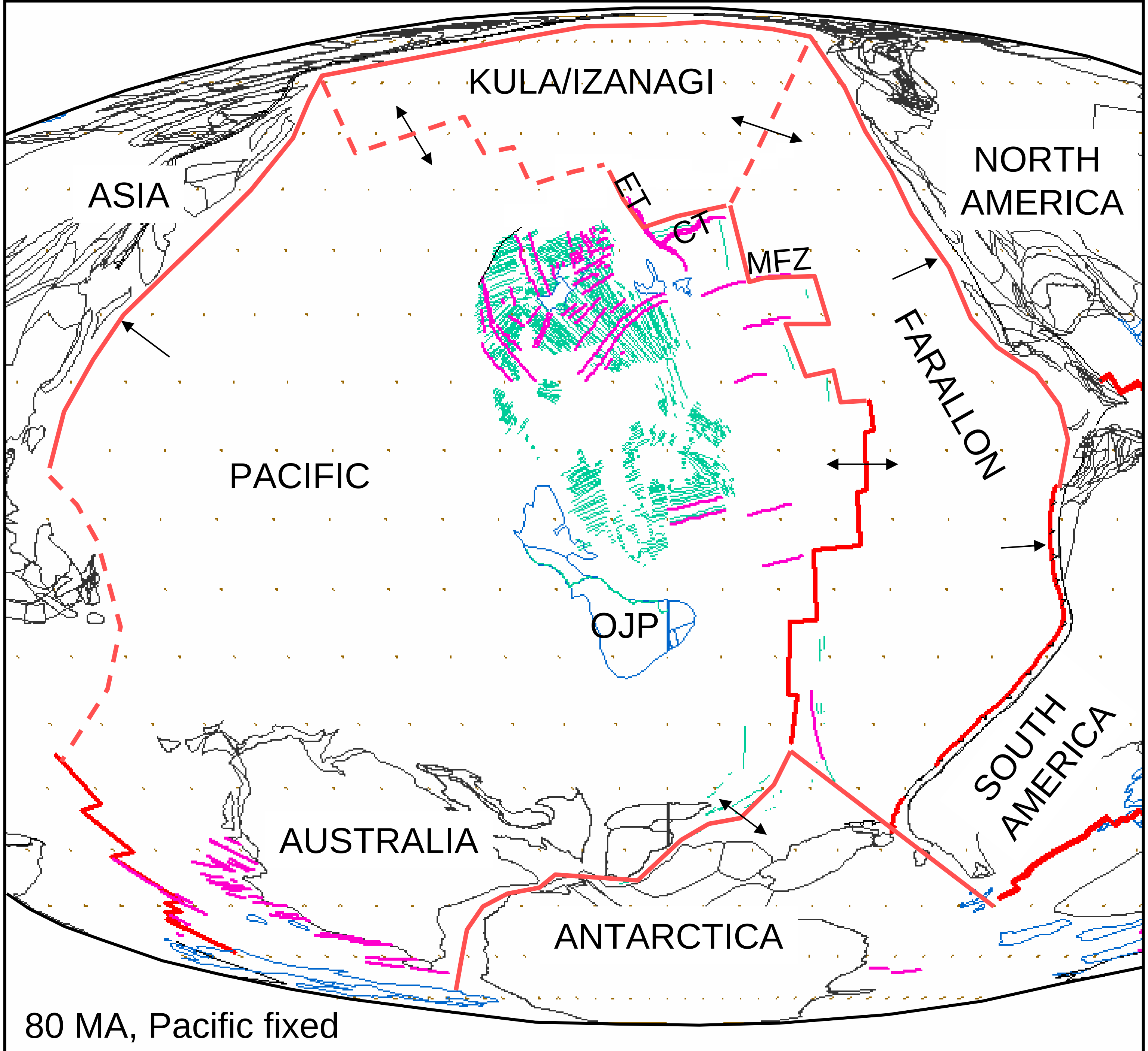

KULA/IZANAGI
ASIA
NORTH
AMERICA
ET
CT
MFZ
FARALLON
PACIFIC
OJP
SOUTH
AMERICA
AUSTRALIA
ANTARCTICA
80 MA, Pacific fixed

Fig. 5

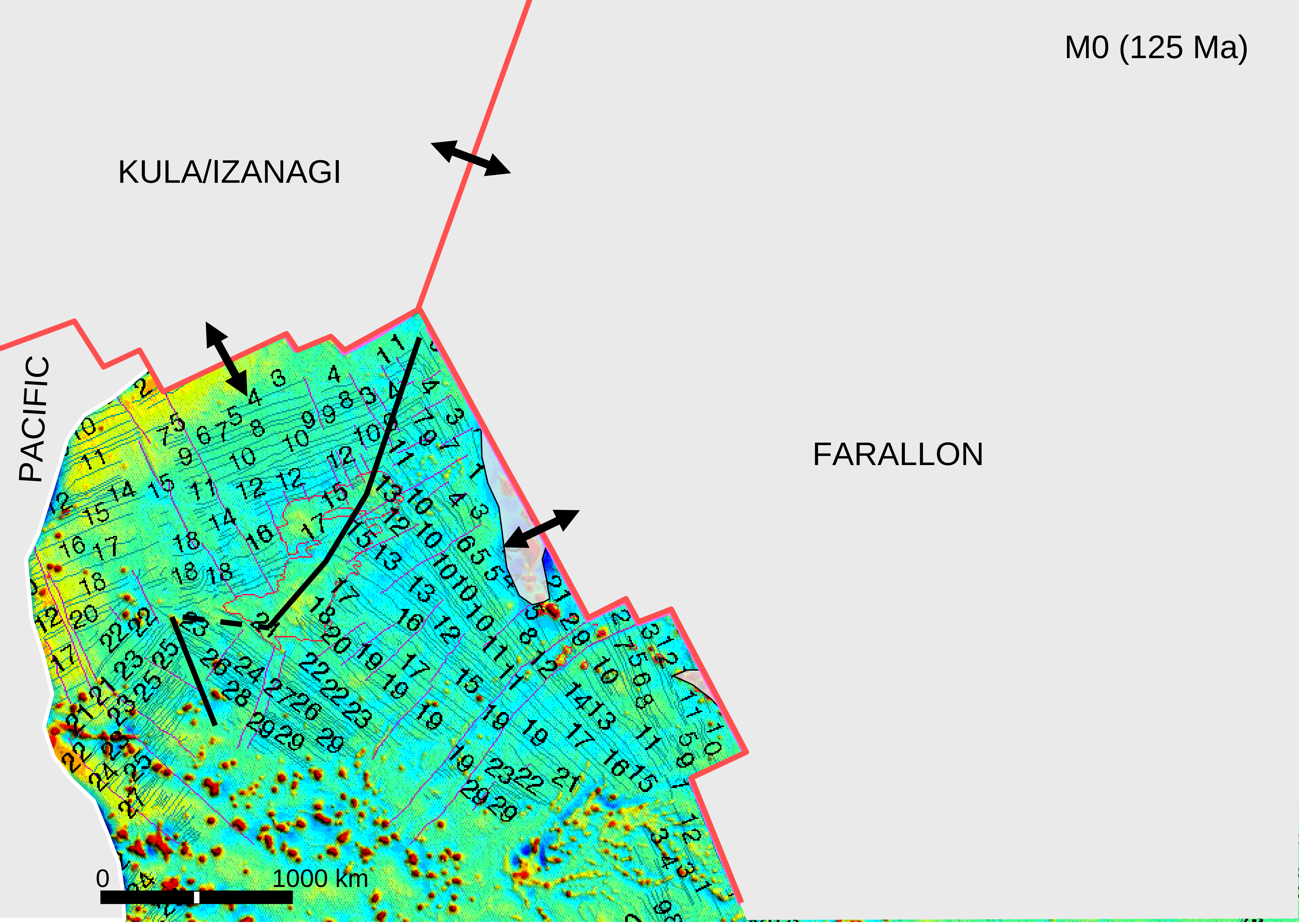


Figure 6. TECTONIC SETTING AT M0 TIME (125 Ma)

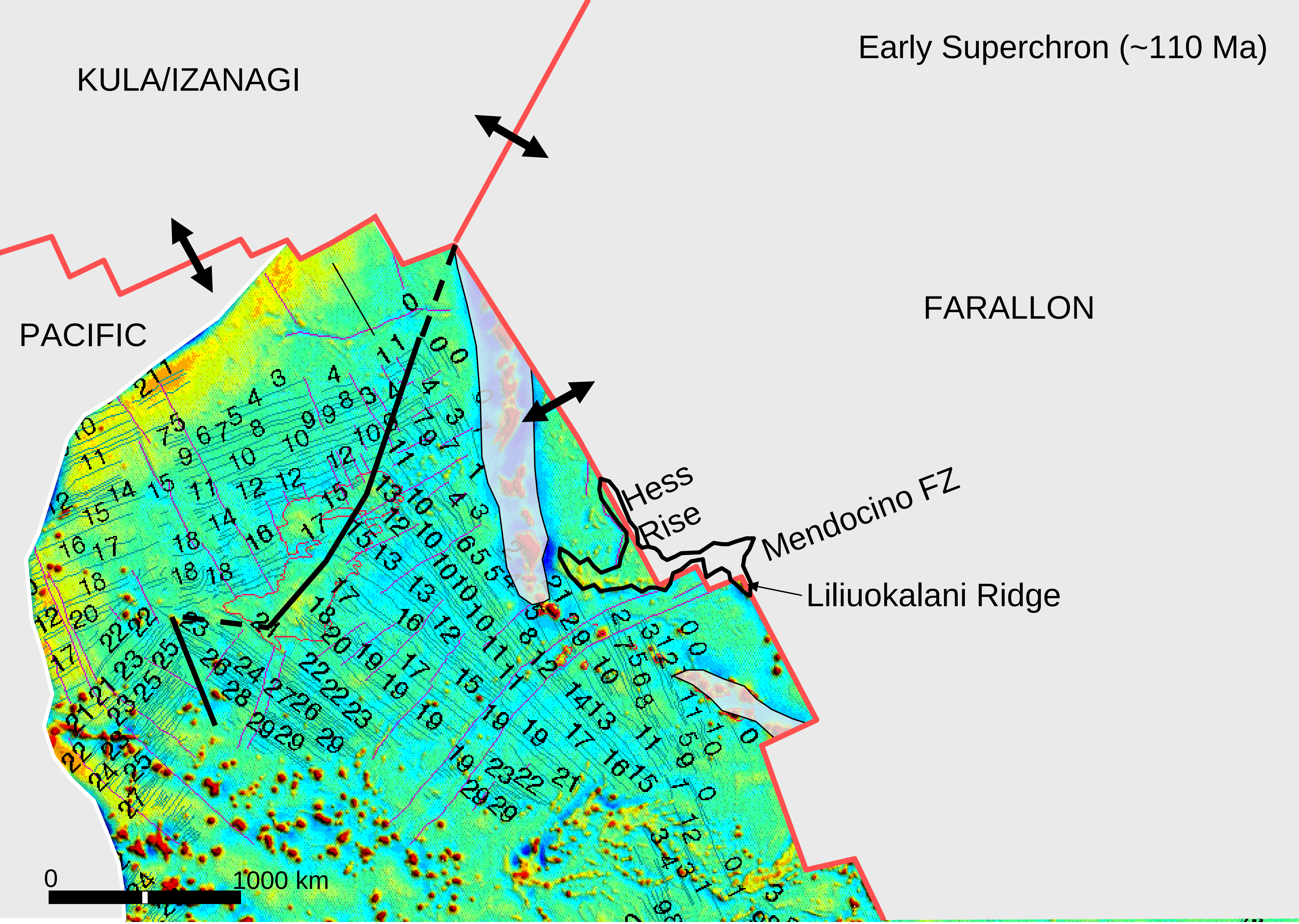


Fig. 7. TECTONIC SETTING IN EARLY KQZ TIME (~110 Ma)

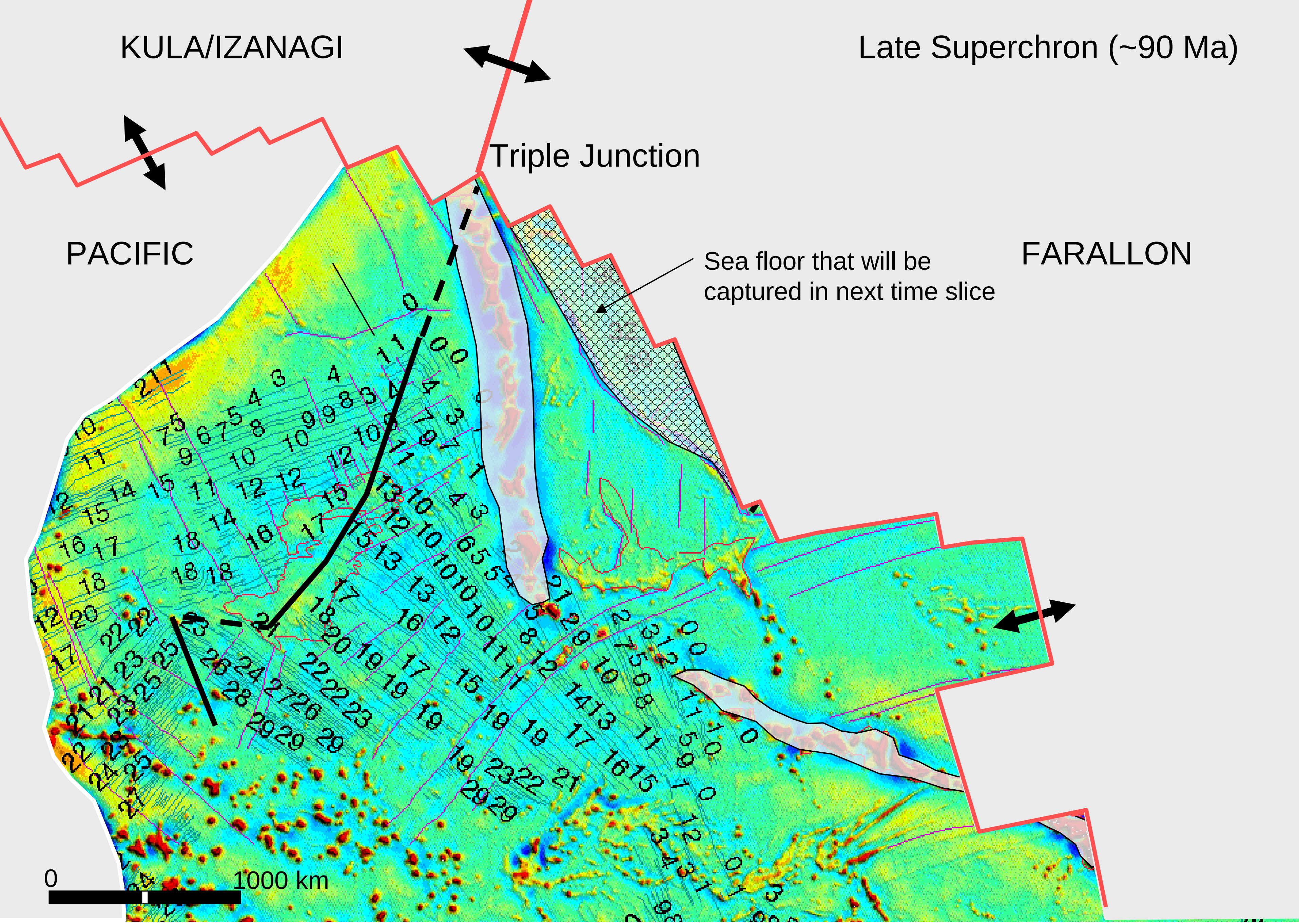


Fig. 8. TECTONIC SETTING IN LATE KQZ TIME (~90 Ma)

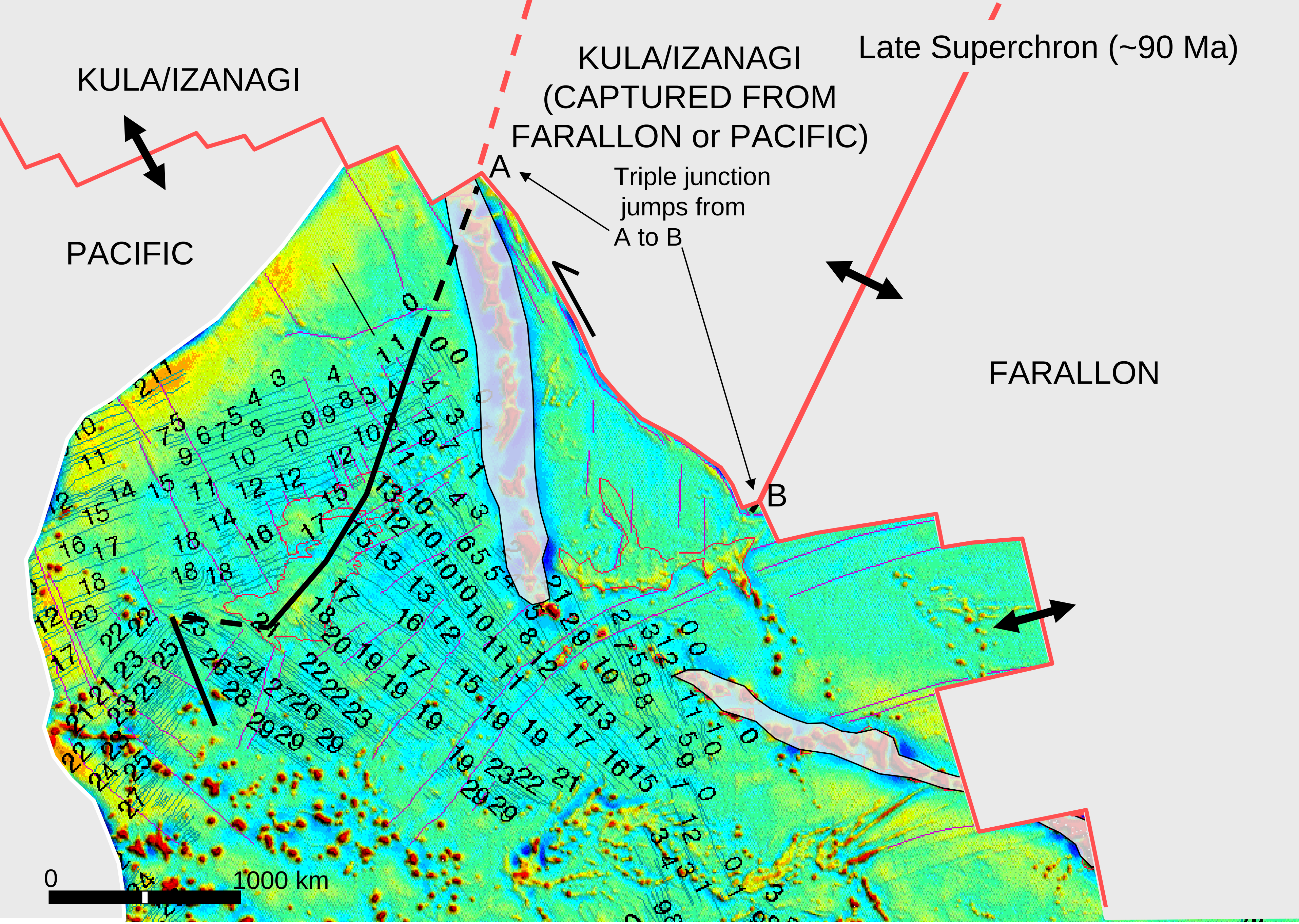


Fig. 9. TECTONIC SETTING IN LATE KQZ TIME (~90 Ma)

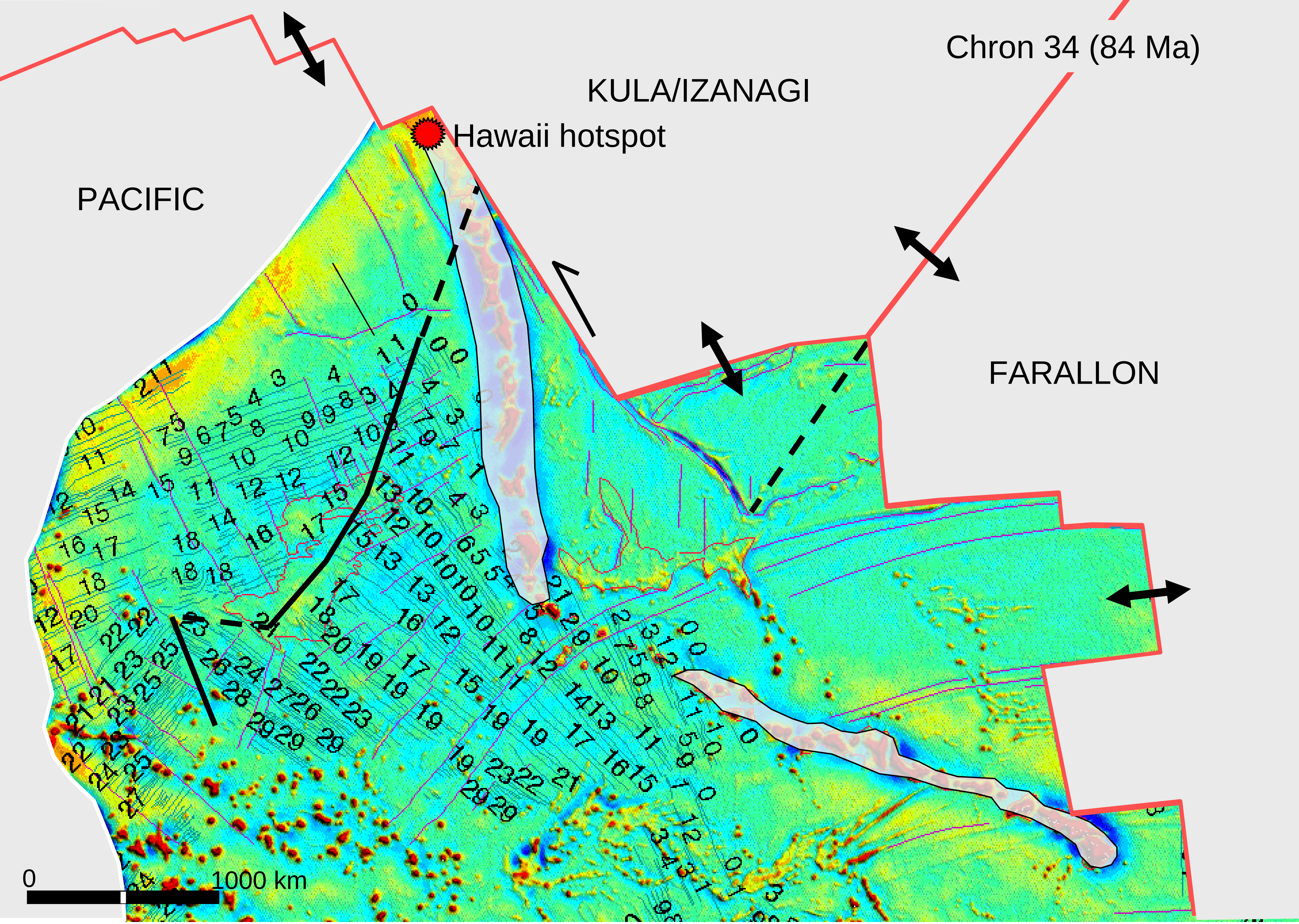


Fig. 10. TECTONIC SETTING AT CHRON 34 TIME (~84 Ma)

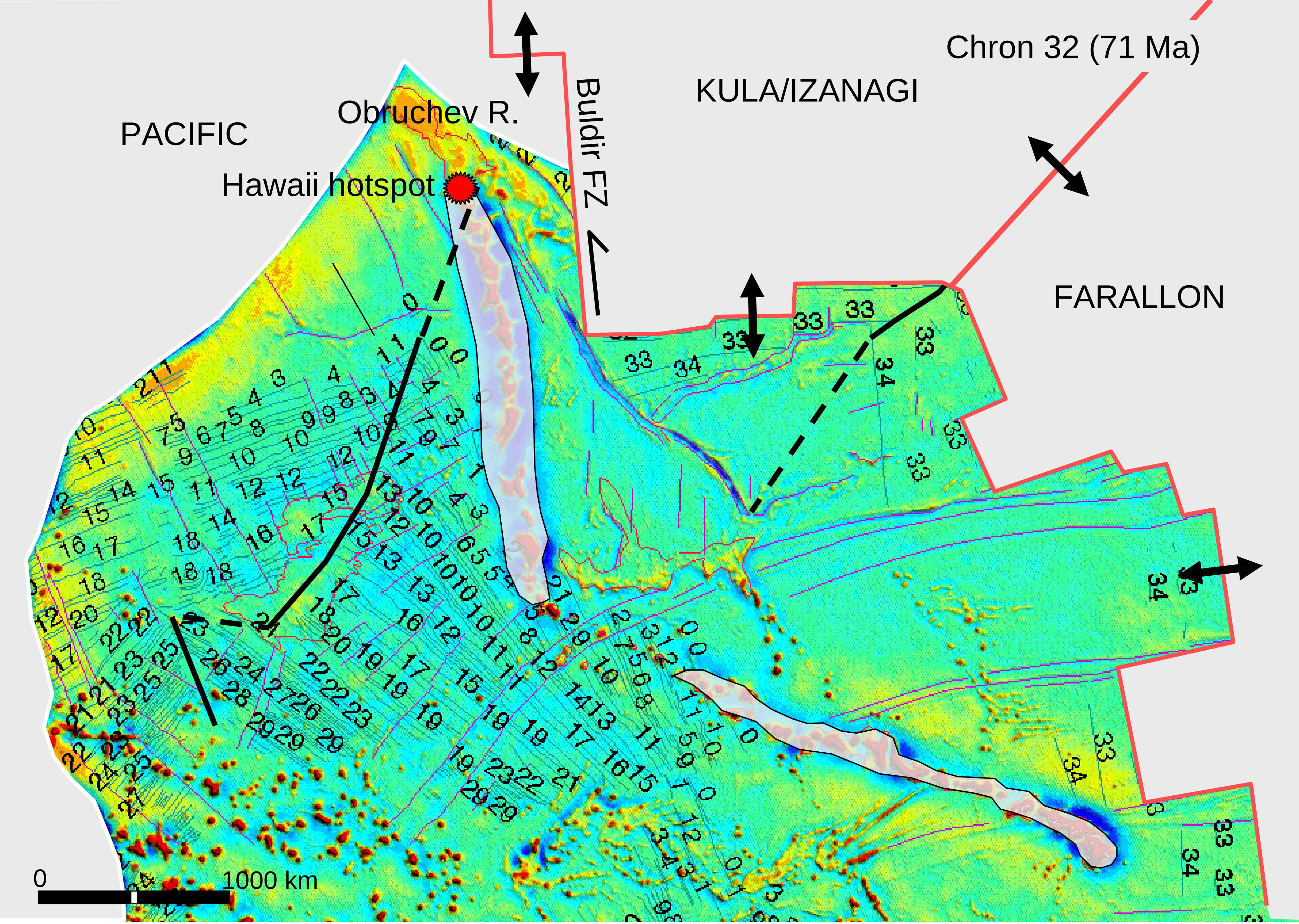
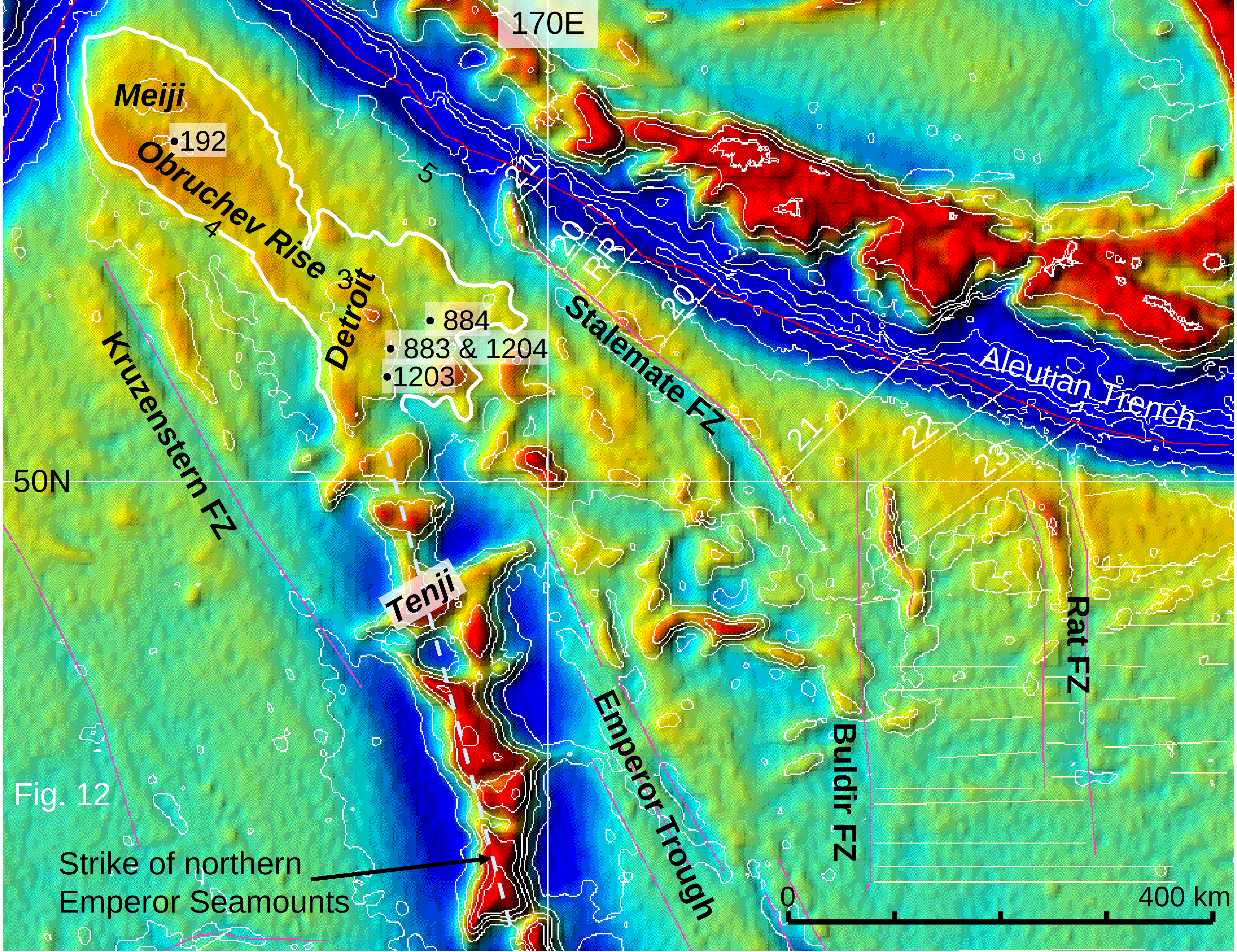


Fig. 11. TECTONIC SETTING AT CHRON 32 TIME (~71 Ma)


170E
Meiji
•192
Obruchev Rise
Detroit
• 884
• 883 & 1204
•1203
Kruzenstern FZ
Stalemate FZ
Aleutian Trench
50N
Tenji
Emperor Trough
Buldir FZ
Rat FZ
0
400 km
Strike of northern
Emperor Seamounts
Fig. 12

Age-Distance plot for data at northern end of Emperor Chain

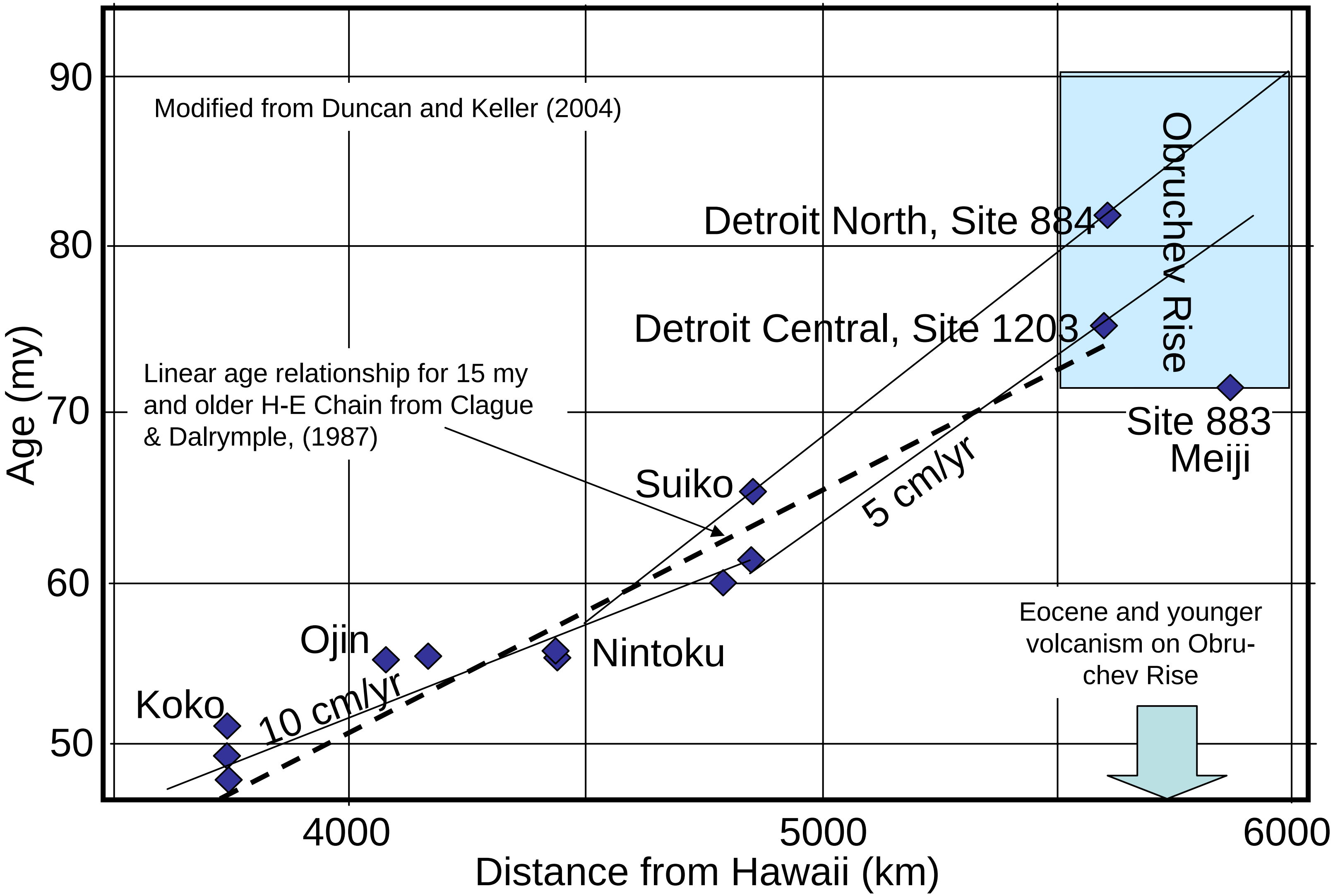


Fig. 13

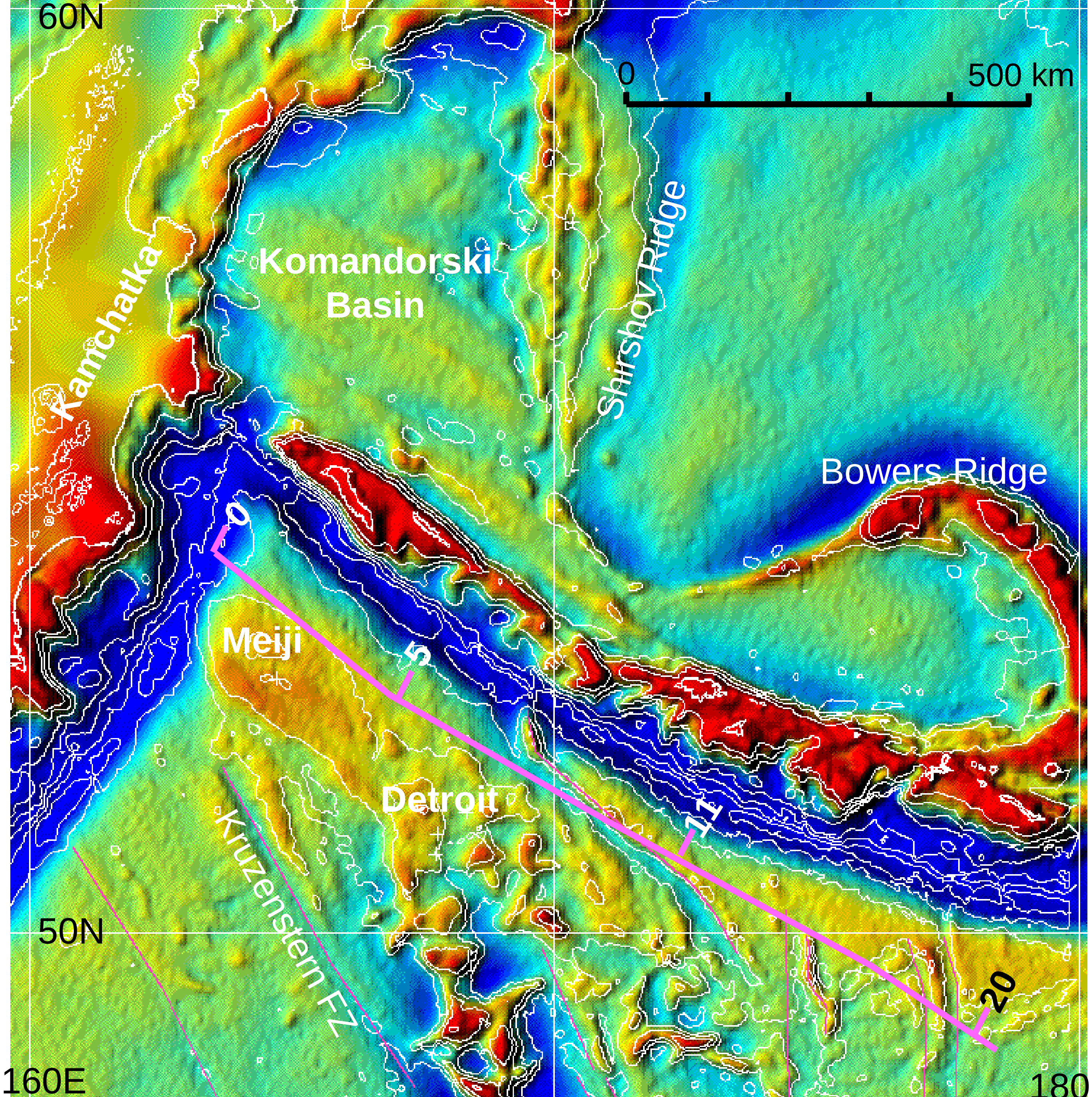

60N
0
500 km
Komandorski
Basin
Kamchatka
Shirshov Ridge
Bowers Ridge
0
Meiji
5
Detroit
11
Kruzenstern FZ
50N
20
160E
180

Fig. 14