Plate-tectonic reconstructions predict part of the Hawaiian hotspot track to be preserved in the Bering Sea

Bernhard Steinberger*
Carmen Gaina
Center for Geodynamics, Geological Survey of Norway, Leiv Eirikssons vei 39, N-7491 Trondheim, Norway

ABSTRACT

We use plate reconstructions to show that parts of the Hawaiian hotspot track of ca. 80–90 Ma age could be preserved in the Bering Sea. Based on these reconstructions, the Hawaiian hotspot was beneath the Izanagi plate before ca. 83 Ma. Around that time, the part of the plate carrying the hotspot track was transferred to the Kula plate. After 75–80 Ma the Hawaiian hotspot underlay the Pacific plate. Circa 40–55 Ma, subduction initiated in the Aleutian Trench. Part of the Kula plate was attached to the North American plate and is preserved as the oceanic part of the Bering Sea. We show that for a number of different plate reconstructions and a variety of assumptions covering hotspot motion, part of the hotspot track should be preserved in the Bering Sea. The predicted age of the track depends on the age of Aleutian subduction initiation. We speculate that Bowers and Shirshov Ridges were formed by paleo-Hawaiian hotspot magmatism.

Keywords: Hawaii, hotspots, plate motion, Kula plate, Bering Sea, Bowers Ridge.

INTRODUCTION

Age-progressive, intraplate volcanism along the Hawaiian-Emperor Chain (Pacific plate) led Wilson (1963) to first suggest a causal relationship with an upwelling from deep inside Earth (later called "mantle plume") that is overridden by a moving plate. However, the Hawaiian-Emperor Chain ends at the Aleutian subduction zone. Its northernmost part, north of, and possibly including, the Detroit seamount, aged 76–81 Ma (Keller et al., 1995; Duncan and Keller, 2004), and oceanic basalts from accretionary complexes in eastern Kamchatka (Portnyagin et al., 2006), may have formed through channeling of plume material to the ridge (Tarduno et al., 2003), hence a corresponding track may have formed on the Izanagi and Kula plates. It is not clear whether parts of the hotspot track are preserved beyond the subduction zone.

The ocean basin in the Bering Sea north of the Aleutian Trench is usually interpreted as a captured remnant of the Kula plate, which has for the most part been subducted (Scholl et al., 1975, 1986). Hence, it may have preserved older parts of the Hawaiian hotspot track. Their existence and identification could give important insights about the age and earlier history of the Hawaiian hotspot, thus further constraining the nature of mantle plumes.

In this paper, we show that plate-tectonic reconstructions (Fig. 1) yield a predicted hotspot track through the oceanic part of the Bering Sea. It is possible that two ridges in this basin, Shirshov and Bowers (Fig. 2), were originally formed by the Hawaiian hotspot. However, a hotspot track origin contrasts with other interpretations for the formation of the ridges (e.g., Cooper et al., 1992; Baranov et al., 1991). We therefore commence with a brief review of the tectonic setting and conclude on a somewhat speculative note how what is proposed here may be reconciled with geologic evidence.

REGIONAL TECTONIC SETTING OF SHIRSHOV AND BOWERS RIDGES IN THE BERING SEA

Based on the age of oldest volcanic activity, the Aleutian Arc is believed to have formed at ca. 40–55 Ma (Scholl et al., 1987; Jicha et al., 2006). The ocean floor to the north is probably a piece of captured Kula plate; most of this plate subducted beneath continental crust from Kamchatka to the Bering Shelf (Scholl et al., 1975, 1986). Cooper et al. (1987b) suggested that large structural depressions filled with deformed sedimentary prisms beneath the continental slopes are remnants of ancient trenches. Probably Cenozoic crust formed due to backarc extension in the Komandorsky and possibly Bowers Basins (Cooper et al., 1987a, 1992; Baranov et al., 1991).

Only undated arc-type volcanic rocks have been dredged from Bowers Ridge (Cooper et al., 1987a). Thus the ages of formation of Shirshov and Bowers Ridges are unknown. Bowers Ridge is bordered on its convex side by a sediment-filled trench (Ludwig et al., 1971). Seismic, magnetic, and gravity data support its interpretation as a volcanic arc at a fossil subduction zone (Kienle, 1971). Trench sediments were deposited and subsequently deformed probably during the Cenozoic (Marlow et al., 1990). Shirshov Ridge is characterized by thick sediments along its eastern flank and steep scarps on its western side (Rabinowitz and Cooper, 1977). Various concepts of its uncertain origin are reviewed by Baranov et al. (1991). Rock dredgings on Shirshov Ridge recovered basalts, gabbros, and other datable rocks (Baranov et al., 1991). An $^{40}Ar/^{39}Ar$ (plagioclase) age 27.8 ± 1.1 Ma was determined for an andesite (Cooper et al., 1987a). No oceanic-island basalts are known to have been recovered from these ridges (D. Scholl, 2000, personal commun.). These findings and interpretations do not exclude the possibility that the ridges were fabricated out of pre-existing structures of a different nature. We speculate that a hotspot track localized the later Bowers and Shirshov Ridges.

PACIFIC PLATE-TECTONIC RECONSTRUCTIONS

Reconstructions of relative plate motions (Table DR1 in the GSA Data Repository[1]) and geometries in the Pacific Ocean Basin are based on marine magnetic anomalies. In order to find the location of the plates within the Pacific Ocean Basin relative to the plates surrounding it, and to plot them on a map with latitudes and longitudes, these reconstructions must be embedded in a suitable absolute reference frame. A fixed-hotspot reference frame has frequently been used (e.g., Duncan and Clague, 1985). However, there are a number of indications that the Hawaiian hotspot has moved and was farther north in the geologic past. These include analyses of plate circuits (e.g., Raymond et al., 2000), sedimentological evidence (Parés and Moore, 2005), numerical models (e.g., Steinberger et al., 2004), and paleomagnetic data (e.g., Tarduno and Cottrell, 1997; Tarduno et al., 2003). The latter indicate that the Hawaiian hotspot was at ~30–35° N at 75–80 Ma and had moved to close to its present latitude at the time of the Hawaiian-Emperor bend. True polar wander (e.g., Besse and Courtillot, 2002) appears not to have contributed more than a few degrees of latitude change (Tarduno and Smirnov, 2001), regardless of whether it is computed in a fixed-hotspot reference frame or a mantle reference frame that considers hotspot motion (Torsvik et al., 2006). We determine the best-fitting Pacific plate motion assuming a hotspot motion that is broadly consistent with numerical models for Hawaiian and Louisville hotspot motion (Koppers et al., 2004) and paleomagnetic data.

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*E-mail: bernhard.steinberger@ngu.no.

[1] GSA Data Repository item 2007098, information on the construction of past plate boundaries, Table DR1 (relevant finite plate rotation parameters) and Figure DR1 (magnetic anomalies in the Bering Sea region), is available online at www.geosociety.org/pubs/ft2007.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

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We assume the Hawaiian hotspot moved 13° southward and 3° eastward between 90 and 47 Ma, and 2° southward and 2° eastward since 47 Ma, and the Louisville hotspot has moved 10° eastward and 4° southward since 120 Ma, all at constant speed. Optimization procedure and age data from both hotspot tracks are the same as in Koppers et al. (2004), who showed that new radiometric age data are consistent with relative hotspot motion as assumed here. Results are included in Table DR1 (see footnote 1). Note that the Pacific plate motion is thus determined independent of the global plate circuit and Indo-Atlantic hotspot tracks. Pacific plate rotation rates before 83 Ma are from Duncan and Clague (1985), i.e., finite rotations at 100 and 150 Ma were corrected for inferred hotspot motion since 83 Ma. Construction of plate boundaries is detailed in the GSA Data Repository (see footnote 1).

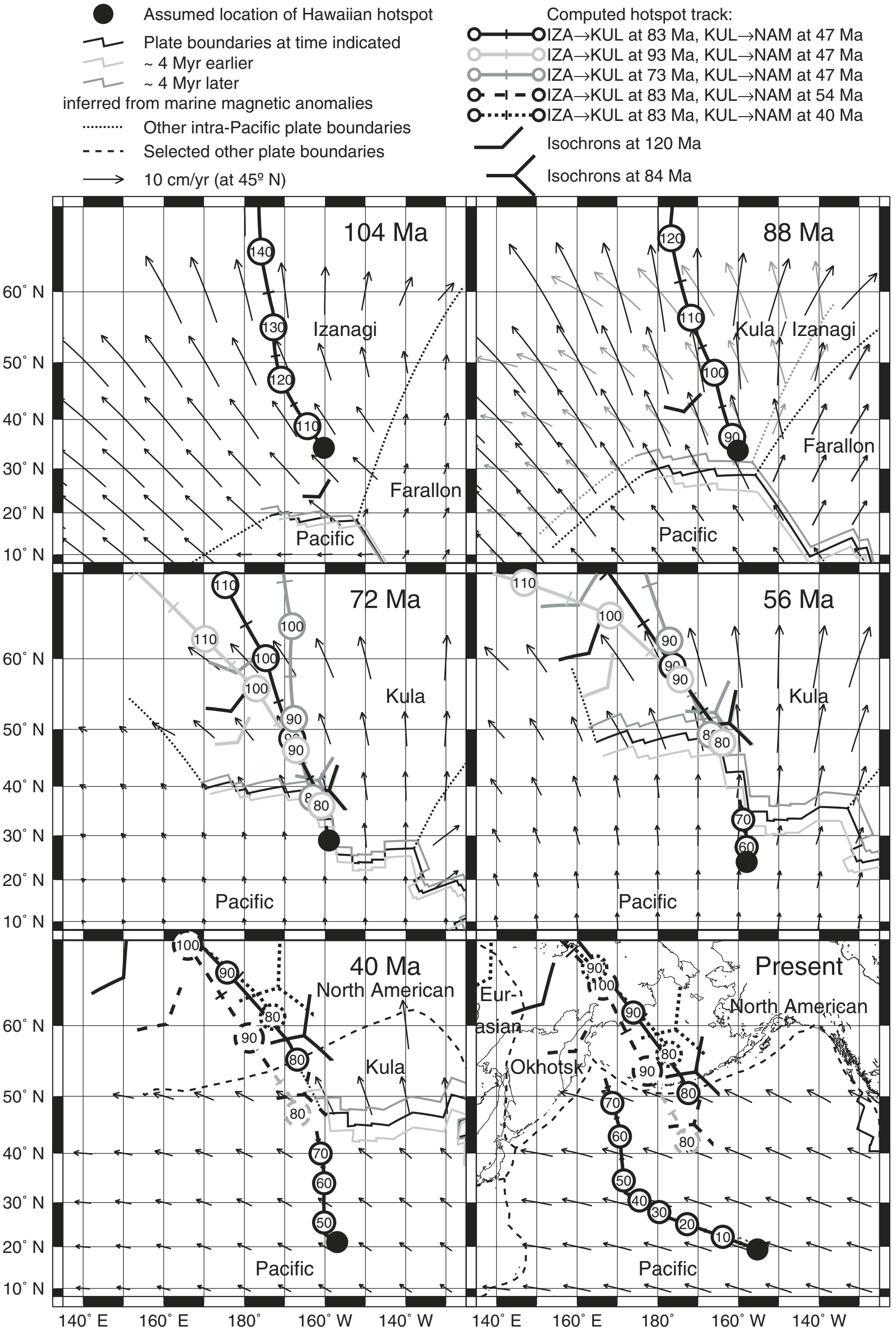

Figure 1. Plate reconstruction explaining how part of the Hawaiian hotspot track could have become preserved in the Bering Sea. Arrows indicate plate velocities. Computed hotspot tracks are shown on Pacific plate for ages younger than 78 Ma, and on Izanagi-Kula–North American plate for ages older than 78 Ma, with ages indicated in Ma. 88 Ma: Black arrows on Kula/Izanagi plate are Izanagi plate velocities, gray arrows are Kula plate velocities. Kula-Pacific relative motion before 67.7 Ma was assumed to be as in the interval 67.7–55.9 Ma. 72 Ma and 56 Ma: Black, light gray, and dark gray lines are for change from Izanagi to Kula plate motion at different times, as indicated. 40 Ma and present: Continuous, dashed, and dotted lines are for transfer from Kula to North American plate as indicated; track extension onto Pacific shown as gray dashed line. Tracks are shown on North American plate regardless of whether this part was on Kula plate before; only in this case (i.e., in the Bering Sea) it may correspond to a real hotspot track. Reconstructed isochrons at 120 Ma and 84 Ma enable comparison with magnetic anomalies. They are shown as lines of the same kind as hotspot tracks for the same cases. They are plotted regardless of location but could only be preserved if located in the Bering Sea. IZA—Izanagi plate; KUL—Kula plate; NAM—North American plate.

Figure 1 shows reconstructions for this case: The Hawaiian hotspot first (top left panel) occupied an intraplate location on the Izanagi plate, which moved northwestward at a speed of >10 cm/yr. After ca. 100 Ma, Pacific plate motion also had a northward component: The Izanagi-Pacific boundary moved northward, approaching the Hawaiian hotspot at ~8 cm/yr. At 100 Ma, the hotspot was ~14° north of the plate boundary, at 90 Ma ~7°. It is more uncertain where the Izanagi-Farallon boundary was, and hence whether the track was emplaced on crust formed at the Izanagi-Pacific or Izanagi-Farallon spreading center. In the first case, it is estimated that the track formed at 100–90 Ma on 35–17.5 m.y. old crust (now 135–107.5 m.y. old), based on an Izanagi-Pacific half spreading rate of ~0.4 degrees/m.y. as extrapolated from isochrons. In the second case, crustal age would be younger. We consider it possible, but unlikely, that part of the track for part of the time was on the Farallon plate.

During the reorganization of plate boundaries in the North Pacific at ca. 83 Ma, the Kula plate formed from older pre-existing crust of the Izanagi, Farallon, and possibly Pacific plates, presumably incorporating the entire Hawaiian hotspot track. At ca. 78 Ma, the northward-moving ridge crossed over the hotspot; subsequently a track was created on the Pacific plate, and the track on the Kula plate was carried northward. At ca. 40–55 Ma, subduction began in the Aleutians, and the oceanic crust of the Bering Sea Basin, being a fragment of the Kula plate, became part of the North American plate at that time. For better visibility, we plot tracks regardless of location (black on North American, gray on Pacific plate for ages older than 78 Ma, in Fig. 1).

DISCUSSION

Plate-tectonic reconstructions of the Pacific region imply that the Hawaiian hotspot was located beneath the Izanagi and Kula plates

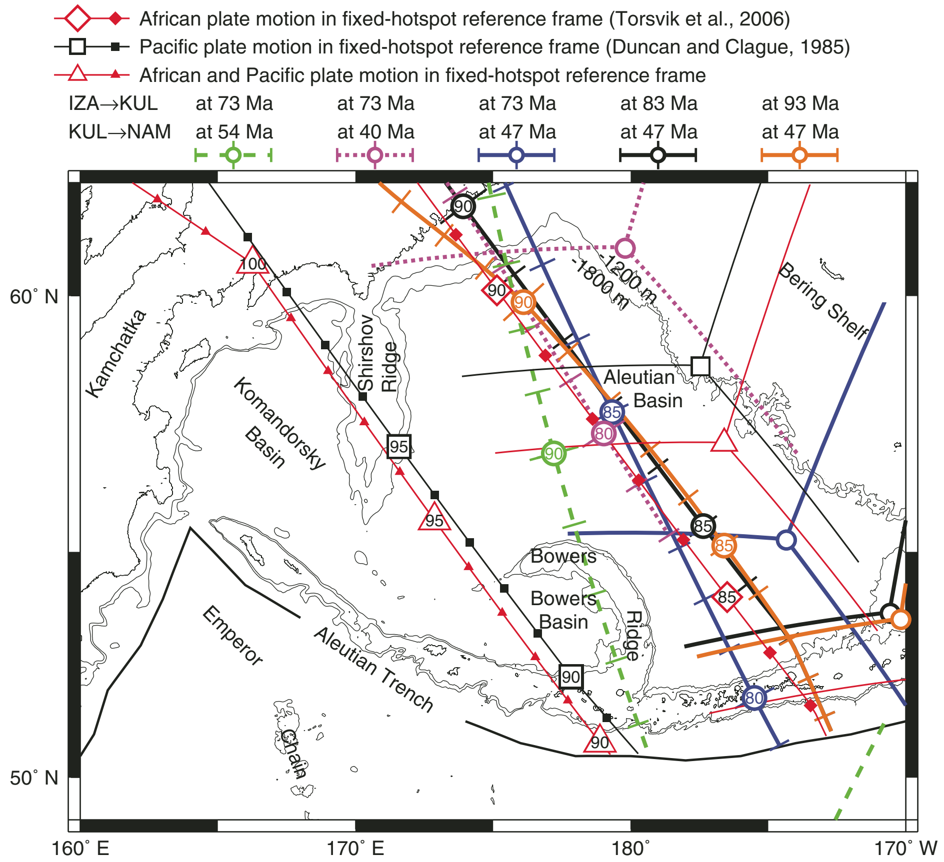

Figure 2. Computed Hawaiian hotspot tracks in the Bering Sea for different plate motion and reference frame scenarios. Depth contours are shown at sea level, –1200 m and –1800 m (Smith and Sandwell, 1997). Black line with tick marks (reference case), and colored lines with tick marks are computed with change from Izanagi to Kula plate motion and transfer from Kula to North American plate as indicated, and Pacific and African plate motions in the moving hotspot reference frame. Red line with diamonds is computed with African plate motion in the fixed (instead of moving) hotspot reference frame after 47 Ma; black line with squares is computed with Pacific plate motion in the fixed (instead of moving) hotspot reference frame before 47 Ma; red line with triangles is computed with both (see Table DR1 [see footnote 1]); otherwise as reference case. Further explanation is given with Figure 1. IZA—Izanagi plate; KUL—Kula plate; NAM—North American plate.

prior to ca. 75–80 Ma. Part of the track produced during that time could still be preserved in the Bering Sea near Bowers and Shirshov Ridges, provided that its ocean crust was part of the Kula plate and became attached to the North American plate ca. 55–40 Ma. We estimate that the preserved part would be ~80–90 m.y. old. Figure 2 shows a close-up look at the predicted present-day location of that part of the track.

The geologic evidence that Bowers Ridge was a volcanic arc in the Tertiary could mean that the proximity of predicted track and observed ridges is pure coincidence. Shirshov and Bowers Ridges may be structurally unrelated (Rabinowitz, 1974). Following Cooper et al. (1992), a strike-slip zone roughly north-south in direction may have formed at the location of a preexisting oceanic plateau after subduction was initiated in the eastern part of the Aleutian Arc, and subsequently, the separate Shirshov and Bowers Ridges developed from the originally continuous and straight strike-slip zone. We suggest here that the supposed oceanic plateau has been part of the Hawaiian hotspot track.

The predicted tracks depend on a number of assumptions, each uncertain to some degree.

1. Motion of hotspots in the Pacific Ocean Basin: In our reference case (black continuous lines in Figs. 1 and 2), the Hawaiian hotspot moved southward relative to the Louisville hotspot. Hence the predicted track is considerably farther north than for fixed Pacific hotspots (squares in Fig. 2); in the latter case it passes through Komandorsky and Bowers Basins instead of the Aleutian Basin. This offset comes from relative motion between hotspots; predicted tracks for coherently moving hotspots are the same as for fixed hotspots.

2. Motion of hotspots in the African hemisphere: Results also depend on the estimated motion of the Tristan and Reunion hotspots over the past 47 Ma. Their motion is likely to be smaller, as discussed in Steinberger et al. (2004), and hence has a smaller effect on the predicted hotspot track: The track with diamonds in Figure 2 was computed with African plate motion in a fixed-hotspot reference frame instead of moving hotspots. A number of further computations with fixed and moving hotspots gave overall similar results.

3. Motion of Kula and Izanagi plates: During the Cretaceous superchron (118–83 Ma), marine magnetic anomalies are absent, and the oldest well-recognized isochron for the Kula-Pacific boundary is 67.7 Ma, although older magnetic anomalies (70–80 Ma) have been recognized by Rea and Dixon (1983) and Mammerickx and Sharman (1988). Black and gray arrows, and black, light gray, and dark gray lines in Figure 1 (black, orange, and blue in Fig. 2) are for three possible spreading history scenarios with change from Izanagi to Kula plate motion at 83, 93, or 73 Ma, and illustrate uncertainties in azimuth of the predicted hotspot track. With the scenario of Cooper et al. (1992), a north-south hotspot track orientation would be most suitable to explain the geometry of Shirshov and Bowers Ridges.

4. Initiation of subduction in the Aleutians: An older track is predicted for an earlier time of the Bering Sea becoming attached to the North American plate. This track would have formed on older ocean floor. In our plate motion model, the Izanagi-Farallon-Pacific triple junction was captured on the Kula plate at 84 Ma, and thus could be preserved east of the hotspot track in the Bering Sea. If spreading at this triple junction had continued for a few million years after 84 Ma, magnetic anomalies of chron 34 and possibly 33 could be preserved there. The predicted location and orientation of these isochrons relative to the hotspot track matches approximately with the location and orientation of the most prominent, approximately north-south–oriented magnetic seafloor lineations in the Aleutian Basin (Cooper et al., 1976) (Fig. DR1; see footnote 1) relative to Shirshov and Bowers Ridges. Magnetic lineations in the southern part of the Bering Sea could have formed along the Pacific-Farallon spreading ridge, i.e., the northern continuation of the Pacific-Chinook spreading ridge preserved in the Emperor Trough south of the Aleutian Trench, as proposed by Rea and Dixon (1983). Older crustal ages, such as in the interpretation of Cooper et al. (1976), would require earlier subduction initiation in the Aleutian Arc than assumed here.

5. Plate motion in the Bering Sea: Our reconstructions assume that the Bering Sea has moved with the North American plate after 40–54 Ma. However, motion along strike-slip faults in Alaska may have accommodated westward motion of the Bering Sea relative to the stable North American plate (Cooper et al., 1992). This would move the hotspot track computed for a moving Hawaiian hotspot toward Shirshov and Bowers Ridges and would move predicted 84 Ma isochrons toward the clearest magnetic

seafloor lineations, which are somewhat east and north of Bowers Ridge. This motion may be a tectonic extrusion driven by Kula–North American convergence (Scholl and Stevenson, 1991), similar to present-day Anatolia. Amounts of motion are, however, difficult to quantify.

A hotspot track crossing the Bering Sea is a prediction based on current knowledge of plate and hotspot motions. This prediction is made regardless of fixed or moving hotspots; the preserved part of the track is predicted to be younger, and farther to the east, for faster southward motion of the Hawaiian hotspot relative to the Louisville hotspot. A relation with Shirshov and Bowers Ridges is plausible although speculative. We expect that our prediction will motivate further work, which may corroborate our proposed relation.

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