

Extrapolating Oceanic Age Distributions: Lessons from the Pacific Region

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ABSTRACT

Extrapolation of the age distribution of oceanic lithosphere has played a significant role in assessments of variations in global mean spreading rate, global mean ocean basin depth, and implications for global mean sea level. Subduction has already removed 50% of oceanic lithosphere younger than 55.7 Ma, making some level of extrapolation a necessary part of global plate reconstructions. An area equal in size to the Pacific Basin oceanic lithosphere must be extrapolated for ages older than 29.1 Ma. Three modes of extrapolation are identified. Mode 1 extrapolation uses the preserved history as recorded on one plate to infer the history of the previously adjacent plate. This mode of extrapolation is exemplified by the inferred history of the Farallon, Vancouver, Nazca, and Cocos plates relative to the Pacific Plate, on which this record is preserved. Mode 2 involves extrapolation beyond the preserved age extent of a given ridge system. No observable data exist that directly constrain the motions beyond the youngest magnetic reversal-dated oceanic lithosphere along such a boundary. This mode has, for example, been employed to extrapolate the age distribution resulting from spreading along the Izanagi-Pacific ridge system for as much as 60 m.yr. beyond the last directly determined record preserved on the Pacific Plate. Mode 3 is extrapolation of age distributions of entirely subducted ocean basins where no information explicitly constrains the relative-motion history of such basins. The age distributions in various neo-Tethyan basins require mode 3 extrapolation. This article examines extrapolations specifically using modes 2 and 3, employing the known spreading histories of the Pacific-Farallon/Vancouver and Pacific-Phoenix plate systems and the Tasman Sea as case studies. These tests demonstrate that extrapolated distributions of ages do not match preserved ages. Important events recorded in the preserved oceanic lithosphere, including both initiation and extinction of spreading ridges, cannot be inferred from the extrapolations and yet constitute important events that control aspects of the preserved oceanic lithosphere age distribution. Hence, reconstructed age distributions that require significant mode 2 and 3 extrapolations cannot provide a rigorous basis for testing hypotheses related to global histories of ridge production, mean age, mean depth, or other potentially correlated phenomena. This may appear to be an obvious result, and hence not worth publishing, but the persistent use of extrapolated age distributions in the published literature suggests that problems with extrapolation have not been appreciated by all.

Why Is Extrapolation Important?

Extrapolation of the spreading history or age distribution of oceanic lithosphere has played a significant role in assessments of variations in global mean spreading rate (Pitman 1978; Kominz 1984), global mean ocean basin depth (Müller et al. 2008), and implications for global mean sea level (Pitman 1978; Kominz 1984; Müller et al. 2008). Figure 1 shows the fractional area of preserved oceanic lithosphere as a function of age, based on the Müller et al. (2008) Age Grid 2.6 data set. The fractional area of preserved oceanic lithosphere is simply the

inverse of the cumulative age curve (Rowley 2002) expressed as a fraction relative to the total area of ocean floor of all ages. The Age Grid 2.6 data are well fitted by a second-order polynomial (fig. 1). This distribution is what is predicted by a system with a nearly constant production rate and nearly constant destruction of areas of oceanic lithosphere independent of age, as shown by Parsons (1982) and updated by Rowley (2002). Subduction has already removed 50% of oceanic lithosphere younger than 55.7 Ma, 70% of that younger than 89 Ma, and 85% of that younger than about 120 Ma, providing the impetus for using substantial extrapolation to reconstruct oceanic lithosphere histories beyond the

Manuscript received April 21, 2008; accepted August 5, 2008.

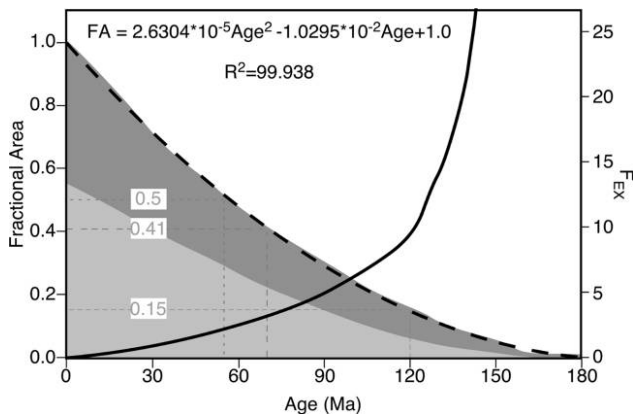


Figure 1. Fractional area of preserved oceanic lithosphere as a function of age (Ma), based on the Müller et al. (2008) Age Grid 2.6 data set: non-Pacific (Atlantic, Indian, circum-Antarctic, and small ocean basins) in lighter gray, Pacific (Pacific, Nazca, Cocos, Rivera, and Juan de Fuca plates) in medium gray. The dashed curve shows a polynomial fit to this distribution and correlation coefficient. This is the relationship expected of nearly constant ridge production and subduction of equal areas of all ages per unit time (Parsons 1982; Rowley 2002). The solid curve shows area of extrapolated oceanic lithosphere as a multiple of the Pacific oceanic lithosphere area.

directly observable record. The above percentages relate to the total oceanic lithosphere area, but the Atlantic, Indian, and circum-Antarctic ocean basins are relatively unaffected by subduction and hence can be reconstructed without extrapolation. In contrast, reconstructions of the Pacific and neo-Tethyan basins require considerable extrapolation of ridge length, spreading rate, and the resulting age distributions as a function of age. As a consequence, it is perhaps more appropriate to express the area requiring extrapolated age distributions as a multiple of the preserved area of the Pacific Basin plates (i.e., Pacific, Nazca, Cocos, Rivera, and Juan de Fuca) as a function of age. Formally, this can be expressed as

$$F_{EX} dt = \frac{\sum_{t=0}^{t=t_{max}} A dt - \sum_{t=t}^{t=t_{max}} A_{NP} dt}{\sum_{t=t}^{t=t_{max}} A_P dt} - 1, \quad (1)$$

where F_{EX} is the multiple of the summation of Pacific Basin oceanic lithosphere area (A_P) as old as or older than t , A is the area of all oceanic lithosphere as a function of age, such that this summation is the total area of the oceanic lithosphere and for this calculation is assumed constant, and the summation of A_{NP} is the area of non-Pacific basin plates as old as or older than t (fig. 1). With

this measure, $F_{EX} = 1$ at 29.1 Ma, i.e., equal to the area of preserved Pacific oceanic lithosphere as old as or older than 29 Ma, $F_{EX} = 3$ at 66 Ma, 10 at 121 Ma, 21.8 at 140.0 Ma, and 432 by 160 Ma. It is therefore important to assess the likely reliability of such extrapolations (fig. 1).

Obviously, a rigorous assessment of the extrapolation of age distributions requires knowledge of "reality." Therefore, the approach adopted here is to use the modeled age distribution from Müller et al. (2008) in three examples, two from the Pacific Plate and the third from the Tasman Sea, in comparison with two of the three modes used to extrapolate age distributions.

Three Modes of Extrapolation

Extrapolation of plate motion histories has played an important part in our understanding of the Earth. Figure 2, based on Müller et al. (2008), represents the reconstruction of the known global age grid, together with extrapolated data to fill the ocean basins at 70 Ma; similar reconstructions extend back to 140 Ma. In order to create figure 2, and as shown in figure 1, a bit more than 59% of the surface area of the oceanic lithosphere has been filled by extrapolation of ages of oceanic lithosphere, corresponding to a bit more than 3.3 times the area of the preserved Pacific Plate at 70 Ma. Three different qualitative modes of extrapolation are identified as important in this figure. Mode 1 can be viewed as constrained extrapolation. Extrapolation in the mode 1 case involves deriving the half-rotations needed to fit one isochron to younger or older adjacent isochrons on the same plate, together with the assumption of symmetric spreading, to estimate the full rotation of the subducted plate to the preserved plate. Stock and Molnar (1988), who refer to these rotations as "half-angle stage rotations," tested this approach using data from the southwest Pacific. Data from the Pacific Plate (Campbell Plateau) were used to determine the plate's history of motion relative to Antarctica. They demonstrated that summing twice the half-angle stage rotations resulted in a reasonably good approximation of the relative-motion history derived from fitting Pacific data directly to Antarctica. Mode 1 extrapolation is perhaps best exemplified by the determination of the Farallon/Vancouver to Pacific relative-motion history (Atwater 1970, 1989; Stock and Molnar 1988, among many others). In this case, much of the history is explicitly preserved on the Pacific Plate. The potential lack of perfect symmetry no doubt leads to some uncertainty but probably not

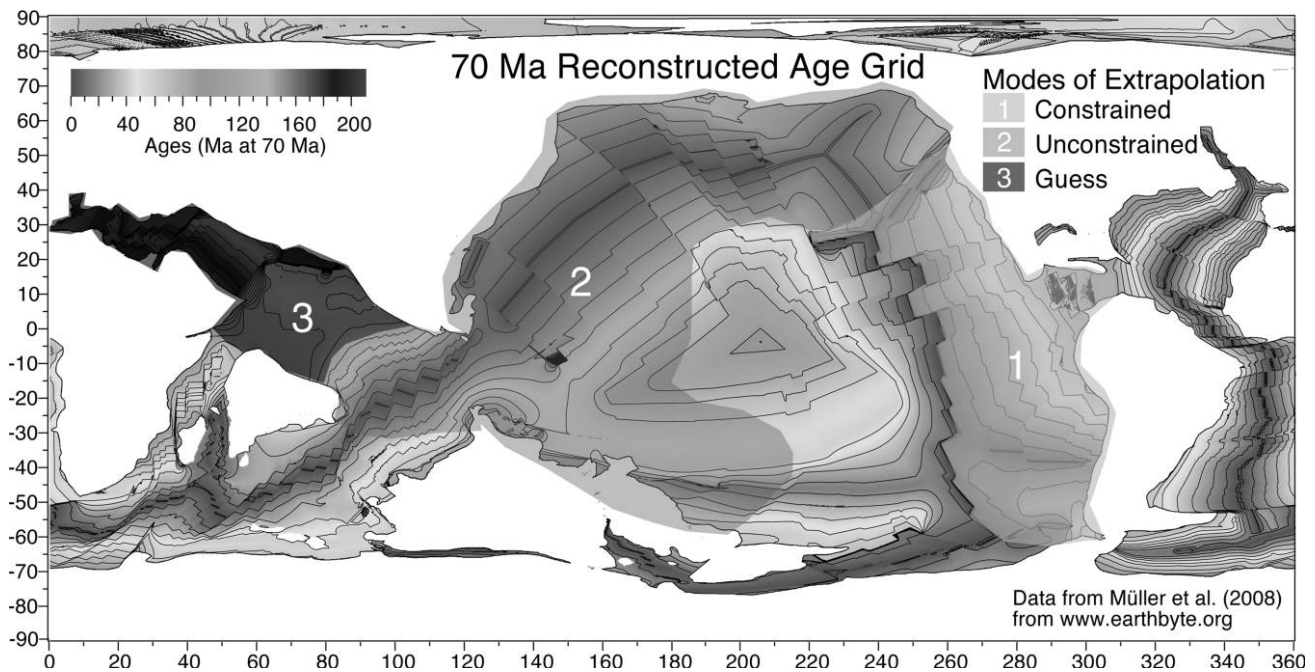


Figure 2. Reconstructed age grid from Müller et al. (2008; downloaded from www.earthbyte.org as file `age_depth_bath_70.xyadb.bz2` on April 9, 2008). Three modes of extrapolation are highlighted on this map as translucent gray overlays. Testing of extrapolation modes 2 and mode 3 is the focus of this article.

enough to call into question the first-order history of these interactions. Mode 1 extrapolation accounts for approximately 25% of the extrapolated age distribution in figure 2 and is not discussed further.

Reconstructing the history of the entire-world oceanic lithosphere as a function of time requires two additional, qualitatively and quantitatively different sorts of extrapolation, as exemplified by Whittaker et al. (2007), Müller et al. (2008), and figure 2. These account for about 75% of the extrapolated ages in figure 2. Mode 2 extrapolation, or unconstrained extrapolation, involves holding known or inferred poles of rotation and rates fixed and evolving plate boundary geometries relative to those fixed poles over long (>50-m.yr.) periods of time. There are no data that constrain this extrapolation, and hence direct tests cannot be performed that even provide bounds on the resultant outcome. Mode 2 extrapolation is exemplified by the Izanagi-Pacific isochrons shown in figure 2. Mode 2 extrapolations have not been rigorously investigated, but Müller et al. (2008) assert that the age uncertainty in their extrapolations is ± 10 m.yr. In order to investigate this type of extrapolation, results of this mode of extrapolated ages are compared with Müller et al.'s (2008) Age Grid 2.6 modeled ages, hereafter referred to simply as "modeled ages," for

two examples from the Pacific Plate. This comparison provides an empirical test of mode 2 extrapolation and allows for insights into the potential reliability of this approach.

Mode 3 extrapolation, extrapolation by guess, involves inferring the timing and duration of entirely subducted ocean basins, as well as the crustal blocks that separated, where no data actually constrain the timing, geometry, or rate of relative motion. Mode 3 extrapolation is best exemplified by the reconstruction of the neo-Tethyan basins (fig. 2) and is discussed separately ("Case 3: Tasman Sea Extrapolated Age Distribution"), with data from the Tasman Sea as an example.

Unconstrained Extrapolation: Two Case Studies from the Pacific

Magnetic-anomaly patterns of the Pacific Plate (fig. 3) demonstrate that its early evolution before the Cretaceous Normal Polarity Superchron (KNPS, starting at approximately 120.4 Ma) resulted from sea-floor spreading along at least three ridge systems associated with divergence between the Pacific Plate and the Izanagi (west and northwest), Phoenix (south), and Farallon (east) plates. Subduction of Pacific Plate lithosphere along the western margin, beneath the Mariana, Izu-Bonin, Japan, Kurile, and Kamchatka arcs has truncated the record of Pacific-

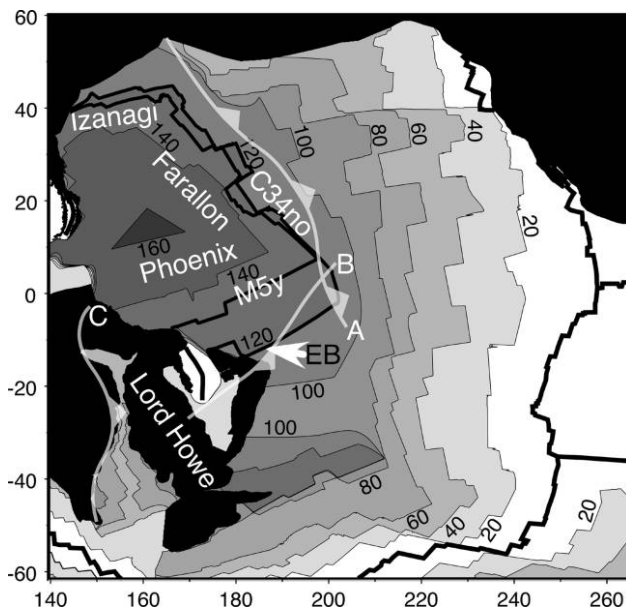


Figure 3. Age structure of the Pacific and adjacent areas based on the Age Grid 2.6 data set of Müller et al. (2008). Isochrons derived by contouring the age grid for reversals M5y and C34no are shown as thicker lines, as are the modern mid-oceanic ridges. *EB* indicates the Ellice Basin region, where Taylor (2006) has described sea-floor fracture zone fabric that parallels the 120-Ma Pacific-Phoenix isochron orthogonal to the trends in older lithosphere immediately to the north. Imaginary subduction zones (*A*, *B*) and a suture zone (*C*) are highlighted as white lines, with triangles representing the equivalent of the extrapolations used, for example, by Müller et al. (2008) along the Pacific-Izanagi ridge and neo-Tethyan basins. Figures 4A, 5A, and 6A correspond to extrapolations related to imaginary subduction zones *A*, *B*, and *C*, respectively.

Izanagi spreading. The age of oceanic lithosphere currently being subducted along this margin ranges from about 150 Ma to about 100 Ma, from south to north. What was the history of spreading between the Pacific and Izanagi plates along this ridge system after the beginning of the KNPS? The approach employed by Whittaker et al. (2007) and Müller et al. (2008) is to employ mode 2 extrapolation to infer it. The underlying rationale is provided in supplementary materials in Whittaker et al. (2007). As shown in figure 2, according to the Müller et al. (2008) extrapolation, Pacific-Izanagi-related oceanic lithosphere occupies a considerable fraction of the Pacific ocean basin at 70 Ma and is primarily responsible for the decrease that those authors infer in both the Pacific and global mean ages of oceanic lithosphere. Mode 2 extrapolation is also required to infer the history of spreading to the south between the Pacific and Phoenix plates, particularly in the west beneath

the array of arcs extending from north of Australia eastward to the Melanesian arcs and then southward along the Tonga-Kermadec–North Island New Zealand arc systems. Farther east, it is not unreasonable to consider the southwestern Pacific extension of the East Pacific Rise to be the current manifestation of this ridge system. The majority of the preserved Pacific Plate was created by spreading along the eastern ridge system, between the Farallon and Pacific plates and the Kula, Vancouver, Nazca, Cocos, Rivera, and Juan de Fuca plates, among others that evolved from this system.

Figure 3 shows the present-day sea-floor age distribution of the Pacific and adjacent plates as modeled by Müller et al. (2008). Two hypothetical subduction zones (*A*, *B*) are placed on the map and are meant to replicate the present situation along the Pacific-Izanagi-related set of anomalies preserved along the western margin of the Pacific Plate. An imaginary suture zone (*C*) is shown along the eastern Australian margin and discussed in “Case 3: Tasman Sea Extrapolated Age Distribution.” Extrapolation via mode 2 requires the determination of the rotation parameters for each plate system—Pacific-Farallon, Pacific-Phoenix, and Pacific-Izanagi—which are then allowed to evolve under the assumption of symmetric spreading. The age distribution of the oceanic lithosphere is then determined by integrating over both the reconstructed remaining oceanic lithosphere and the extrapolated oceanic lithosphere (fig. 2). For example, in the Izanagi-Pacific system, the North Japanese-Kurile-Kamchatka trenches subduct oceanic lithosphere produced during the KNPS. It is not possible to determine pole parameters because there is currently no practical basis on which to determine the synchronicity of oceanic lithosphere within the KNPS and hence of the fracture zone trends themselves. The approach adopted by Müller et al. (2008) is to use the last-stage pole and rotation rate determined for lithosphere just predating the KNPS for the purposes of extrapolation. Note that a wide range of rotation poles, or a collection of poles, are essentially equally justifiable for the purpose of extrapolation, because no data actually constrain either the trajectory or the rate of sea-floor creation in subducted oceanic lithosphere produced along this ridge system.

The rotation poles used for extrapolation in the following examples were derived from the Müller et al. (2008) rotation model, available from www.earthbyte.org/Resources/agegrid2008.html under “Rotations.” This rotation model is the basis for both the modeled preserved age and the extrapolated age distributions. Given the position of the

northwest Pacific subduction zone, as well as imaginary subduction zones A and B, the last known record of relative motion is provided by half-angle stage rotations determined just before the beginning of the KNPS. Reconstruction parameters are provided in the Müller et al. (2008) model for magnetic reversals M5y (126.7 Ma) and C34no (120.4 Ma) for the Izanagi-Pacific, Phoenix-Pacific, and Farallon-Pacific plate pairs. Thus, it is immediately possible to derive the corresponding half-angle stage rotations, and hence extrapolation rotation, through addition of the M5y and C34no finite rotations. The resultant stage rotations, when divided by the age difference between M5y and C34no, provide the corresponding angular velocity. It is then straightforward to use these stage rotations to extrapolate at constant rate the isochron distribution at any arbitrary time after M5y.

Case 1: Pacific-Farallon Extrapolated Age Distribution. How well can the Pacific-Farallon-related age of oceanic lithosphere be extrapolated, given a knowledge of the shape of the ridge at reversal M5y and an extrapolation angular velocity (i.e., a rotation pole and rate) derived from the M5y-to-C34no rotations? Differencing of the M5y and C34no finite rotations for the Farallon Plate relative to the Pacific results in an extrapolation rotation at 27.03°N, 34.28°E, with a rate of 0.917°/m.yr. relative to a fixed Pacific Plate. Recall that subduction beneath imaginary subduction zone A would have removed all of the subsequent evolutionary history and hence any additional constraints that might justify modification. This makes the geometry completely analogous to the Izanagi-Pacific extrapolation in figure 2. For the purposes of extrapolation, the shape of the ridge at reversal M5y was derived by creating a 126.7-Ma contour from Age Grid 2.6 data using the "grdcontour" routine in GMT (Wessel and Smith 1991). This contour was then used as a template for the geometry of the Pacific-Farallon ridge as a function of time.

The question of how well the extrapolated ages correspond to the modeled age distribution preserved on the Pacific Plate is answered in figure 4A. This figure shows the superposition of the extrapolated ages (*solid gray lines*) and modeled ages (*dashed gray lines*) as isochrons at every 10 m.yr. for the Pacific-Farallon ridge. The underlying color shading reflects the difference between the extrapolated ages and model ages. A visual comparison of the extrapolated and modeled isochron patterns reveals several important features. Most striking is that the Kula-Pacific ridge system is not predictable from the pre-KNPS geometry of this boundary. The Pacific-Kula-Farallon system evolved within

the KNPS, presumably by conversion of a portion of the Mendocino transform-fracture zone system into the Kula-Pacific ridge. Thus, there would be no basis from extrapolation for inferring the Kula-Pacific system and its important role in the evolution of the northeast Pacific. A second obvious contrast is that the fracture zone trends of the extrapolated age distribution about a fixed rotation pole have considerable curvature, whereas the observed trends are essentially straight and east-west. A third contrast is that the extrapolated 0-Ma age, along with all other extrapolated ages, transects model ages such that, for example, the extrapolated 0-Ma age intersects the 40-Ma model isochron; hence, not only does the extrapolated age distribution not correlate with the modeled age distribution but it should also be obvious that any inferences regarding the interactions among adjacent plates, including the motion of the extrapolated Farallon Plate toward North America, would be completely different from inferences from the preserved record of motions. This is not surprising, because the Pacific-Farallon motion has evolved in quite a complex fashion not inferable from the pattern preserved in the pre-KNPS magnetic-reversal record of the Pacific-Farallon ridge system.

The color shading of figure 4A shows the difference between extrapolated and model ages. The comparison is limited to data on the present Pacific Plate and within the closed polygon defined by the extrapolated isochrons from 126.7 to 0 Ma. No attempt is made to extrapolate the propagation of the isochrons beyond the limits of the M5y isochron. The age difference can also be graphed as a function of extrapolated age, as shown in figure 4B. This plot shows the median, the 95% distribution, and the total range of the difference between extrapolated and model ages. Not surprisingly, the median age difference is small for extrapolated ages close to 126.7 Ma, because the extrapolation is based on the fit of M5y (126.7 Ma) to C34no (120.4 Ma) reversal data. Although the median age difference averages from close to 0 m.yr. to about 50 Ma, this reflects the intersection of extrapolated ages with model ages both younger and older. This is demonstrated by the 95% ranges and the total age ranges, both of which typically span more than 50 m.yr. Note that even within the first 20 m.yr. of extrapolation the age differences between extrapolated and modeled ages exceed 40 m.yr. If these discrepancies are representative of the errors in mode 2 extrapolation, then figure 4B also demonstrates that the estimated age uncertainty of ± 10 m.yr. quoted by Müller et al. (2008) is almost certainly overly optimistic.

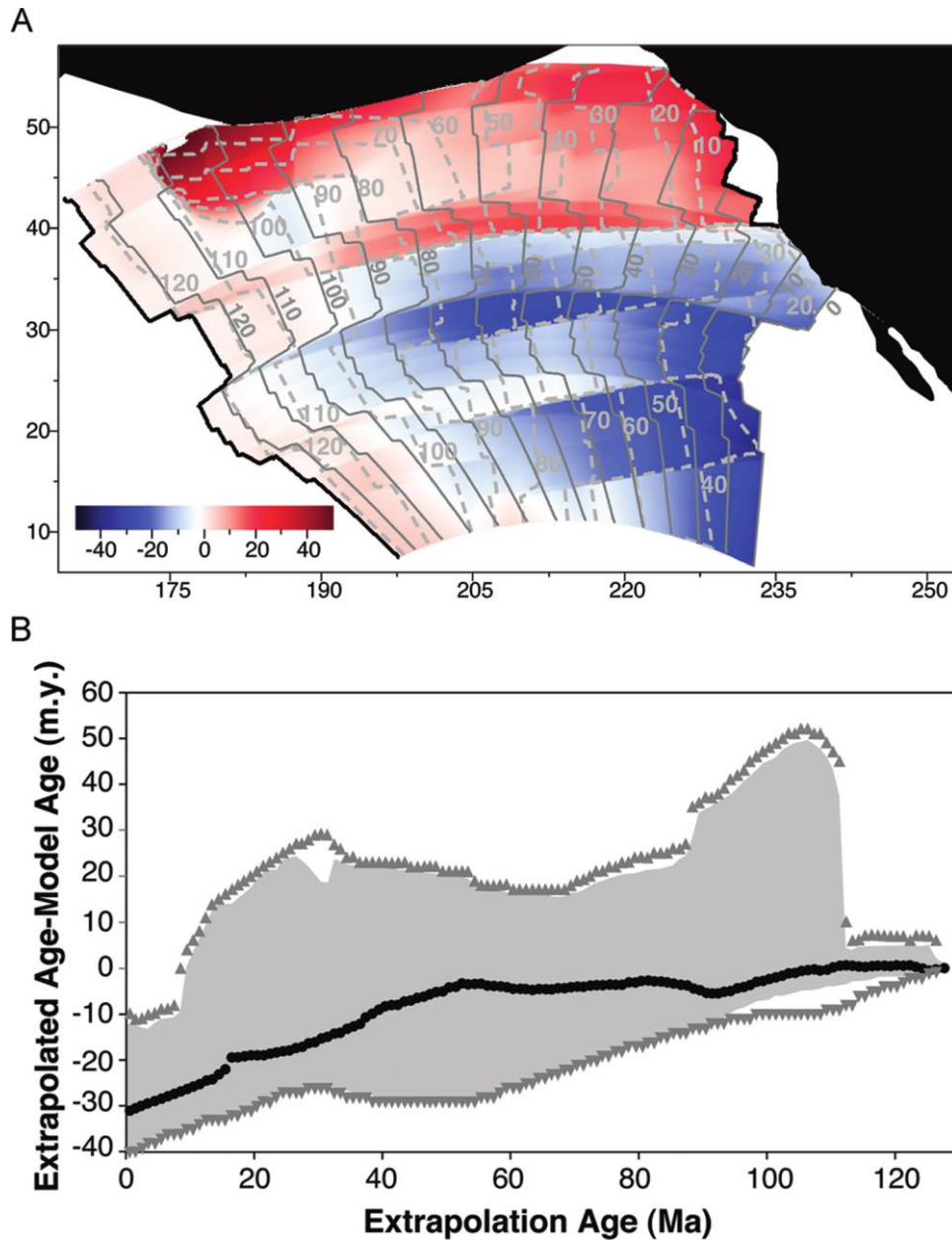


Figure 4. *A*, Extrapolation of isochron M5y (126.7 Ma) to present (*solid gray lines*) at 10-m.yr. intervals, based on the M5y-to-C34no rotation parameters of Müller et al. (2008). Contours of the Müller et al. age grid at every 10 m.yr. (*dashed gray lines*) are also shown. Horizontal labels refer to model age isochrons and tilted labels to the extrapolated isochrons. Closely spaced (0.5-m.yr.) isochrons were extrapolated about this fixed pole and used as the basis for creating an extrapolated age grid using the GMT “surface” routine (Smith and Wessel 1990). Color shading shows the difference between extrapolated and modeled ages. *B*, Extrapolated age versus the median age difference between extrapolated age and the modeled age at each 0.1° cell for the Pacific-Farallon system. Black dots represent the median age difference as a function of extrapolated age. The gray background shows the 95% range of differences between the extrapolated age and model ages about the median. This range can reasonably be considered as representing the 95% confidence interval of the extrapolated ages. Upward-pointing triangles represent the maximum age difference and downward-pointing triangles the minimum value among all model ages along a given extrapolated isochron.

Case 2: Pacific-Phoenix Extrapolated Age Distribution. A second example is provided by the Phoenix-Pacific ridge system. This example also

demonstrates that extrapolation fails to predict important aspects of the history and yields a complete mismatch with observable data. Imaginary

subduction zone B is shown as extending essentially east-west from the present Melanesian arcs to the eastern termination of the Phoenix-Pacific M5y isochron as modeled by Müller et al. (2008). Once again, the M5y-to-C34no stage rotation is used to extrapolate ages for the Pacific Plate. The extrapolation rotation derived from the Müller et al. (2008) rotations is located at 17.09°N, 253.93°E, with a rate of 2.010°/m.yr. Figure 5A shows modeled (*dashed gray lines*) and extrapolated (*solid gray lines*) isochrons derived by contouring the respective grids. The color shading shows the difference between extrapolated and modeled ages. The respective isochrons for 110 Ma are essentially identical, but for all younger ages there is little correspondence. Müller et al. (2008) model ages associated with the evolution of the Phoenix-Pacific ridge following Lonsdale (1997) and subsequent workers (Billen and Stock 2000; Taylor 2006), who interpret the Phoenix-Pacific ridge proper to have become extinct before the end of the KNPS or shortly thereafter, resulting in the symmetry of the 120–90-Ma modeled isochrons in figure 5A. Extinction of this ridge is assumed to be associated with the collision of the Hikurangi oceanic plateau with the now-extinct subduction zone that used to extend along the northern margin of the Chatham Rise east of the South Island of New Zealand. The subsequent propagation of the new ridge that evolved between the Chatham Rise, the Campbell Plateau complex, and Marie Byrd Land in Antarctica resulted in the extension of the southwestern East Pacific Rise (Molnar et al. 1975; Larter et al. 2002). Once again, extrapolation cannot predict any of these complexities. Rather, the high rate of extrapolated spreading predicted by the M5y-to-C34no rotation of Müller et al. (2008) results in a complete mismatch of the extrapolated and modeled ages in this system. This is reflected well in the color shading of the difference between extrapolated ages and modeled ages (fig. 5A). In this case, the analysis is limited to the region of Pacific Plate that lies within the extrapolated limit of the M5y isochron extent. Figure 5B provides an alternative visualization of the age differences. This plot is particularly important because it demonstrates that for virtually all ages younger than about 95 Ma, there is no correlation between the extrapolated and modeled ages. At 90 Ma, about 35 m.yr. into the extrapolation, the median age difference is about –30 m.yr., while after 75 Ma, the median age difference exceeds +20 m.yr. Note that at the modern-day ridge axis, the extrapolated ages are in excess of 44 Ma. The position of the extrapolated Phoenix-Pacific ridge would be in the middle of

South America, while the actual Phoenix-Pacific ridge became extinct along the Osborn Trough (Billen and Stock 2000) or, as discussed below, along the northern margin of the Ellice Basin (fig. 3). This provides a clear example where there is effectively no relation between the modeled history and that derived by extrapolation.

It is worth noting here that the Age Grid 2.6 model completely ignores the recent analysis of Taylor (2006), which suggests that both the Hikurangi and Manihiki plateaus appear to be rifted fragments of the Ontong-Java Plateau and, more importantly, presents clear evidence that the Ellice Basin (fig. 3) is characterized by essentially east-northeast-striking fracture zone traces orthogonal to the pre-KNPS Pacific-Phoenix-related flow lines. The Ellice Basin fracture zone fabric essentially parallels the M-series anomalies to the north, implying a 90° change in spreading direction after M1. The Müller et al. (2008) extrapolation within the preserved Pacific oceanic lithosphere misfits the fabric of the region immediately south of reversal M1y, or perhaps C34no (fig. 2). The Ellice Basin data presented by Taylor (2006) also provide a cogent argument against the Whittaker et al. (2007, p. 85) claim regarding the relation between the unlikelihood of spreading termination and the evidence of rapid motion. Clearly, the evidence provided by Taylor (2006) indicates that the Phoenix-Pacific ridge ceased spreading and underwent an orthogonal reorientation in spreading direction despite rapid motions just before the onset of the KNPS.

Case 3: Tasman Sea Extrapolated Age Distribution

The final example examines mode 3 extrapolation, which is best thought of as extrapolation by guess. Mode 3 extrapolation is used in cases where no data constrain the geometry, rate, and history of spreading and there is considerable uncertainty as to the crustal fragments that separated to produce the basin. Mode 3 extrapolation is reflected in the various neo-Tethyan basins that evolved and then were destroyed by subduction and collision within the broader Alpine-Himalayan system (fig. 2). In these basins, the age distribution is again extrapolated but without any direct constraint from any preserved, in-place oceanic lithosphere. Rather, the analysis is predicated on inferences of the age of the initiation of spreading, the ages of collision of the presumed departed fragments, and the final closure of the neo-Tethyan basin produced by the initial separation. No observation actually constrains the location of the pole of rotation or the rate of open-

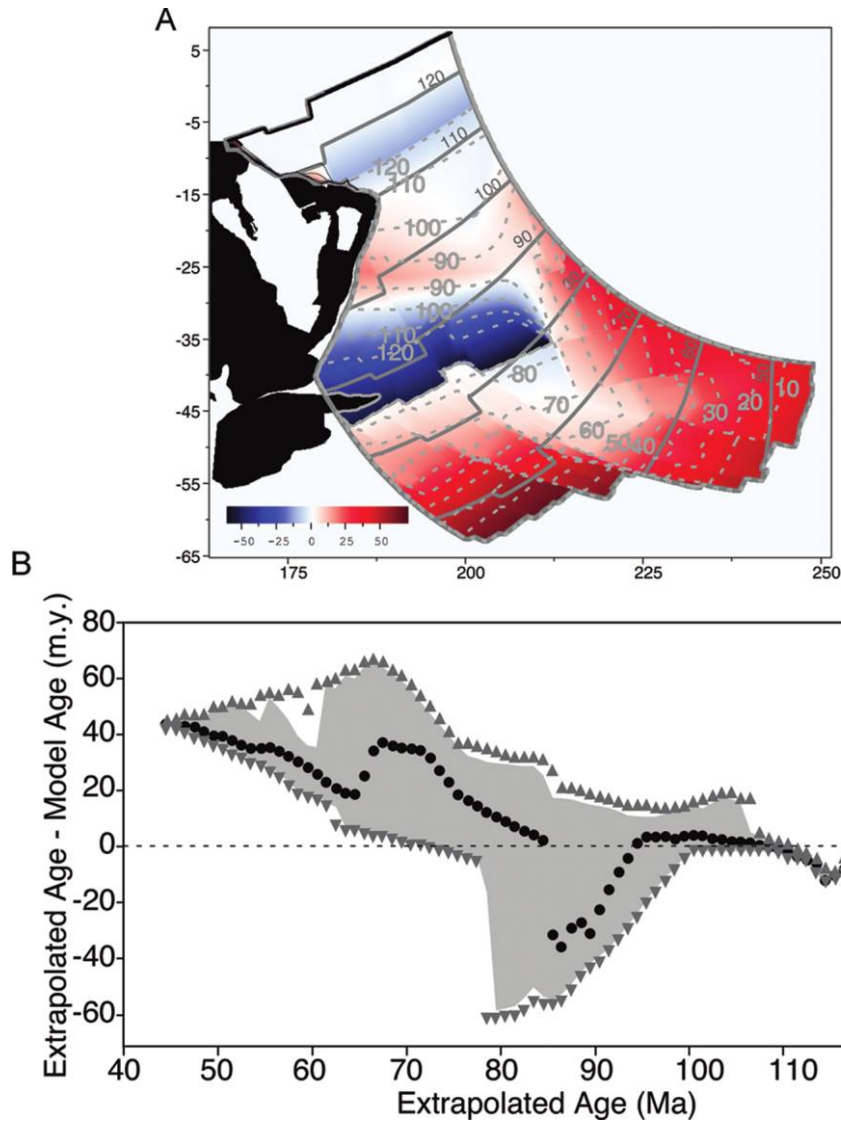


Figure 5. *A*, Comparison of extrapolated (*solid gray lines*) and modeled ages (Müller et al. 2008; *dashed gray lines*) for the Phoenix-Pacific ridge system (contours at 10-m.yr. intervals). Horizontal labels refer to model age isochrons and tilted labels to the extrapolated isochrons. The modern southwest Pacific extension of the East Pacific Rise defines the southeast boundary of the color-shaded region. Color shading represents the difference between extrapolated and modeled ages in each 0.1° cell. Note the symmetric disposition of the 90-Ma model age contours marking the vicinity in the model of the extinction of the Phoenix-Pacific ridge, corresponding to the Osborn Trough (Billen and Stock 2000; Taylor 2006; Müller et al. 2008). *B*, Comparison of the extrapolated and modeled ages for the Phoenix-Pacific system shown in *A*. Symbols and shading as in figure 4*B*. Note that no extrapolated ages younger than 44 Ma are on the Pacific Plate. The decreasing extent of the vertical lines at younger ages simply reflects the truncation at the modern plate boundary.

ing. In addition, the actual initial positions of most fragments within the Pangean realm are poorly understood.

How well can the age distribution of such a basin be extrapolated? The case of the Tasman Sea may be an extreme example, but it nonetheless demonstrates potential issues with such extrapolations. The imaginary suture shown in figure 3 (*C*) is

intended to reflect some future closure of the Tasman Sea. In this imaginary example, inferences have to be made regarding the age of initiation of spreading, the duration of spreading, and the age of final suturing. Such inferences may be based on stratigraphic and facies patterns, back-stripped subsidence analysis, or ages of magmatism or have some other basis. Such estimates typically have a

resolution of, at best, ± 5 to ± 10 Ma, with considerable ranges, depending on the data used. The geometry of the margin would be inferred from the shape of the suture zone, preferably palinspastically restored. Finally, the duration of spreading would be inferred from its having to be less than the age of final collision or on some other basis. From these inferences, the opening history and corresponding age distribution of oceanic lithosphere would be extrapolated.

For this example, data from the actual Tasman Sea margin and early opening history are used to extrapolate the age distribution of the Tasman Sea. Neither of these data sets would be available in real examples. This choice should obviously improve the correlation. The extrapolated isochrons are based on rotation of the continent-ocean boundary of the eastern Australian passive margin derived from the Age Grid 2.6 data set. For the purposes of this extrapolation, the initiation of spreading is assumed to date from 85 Ma, effectively identical to the known age at the southern end of the Tasman Sea (Gaina et al. 1998). The opening history is extrapolated by using a stage rotation derived by addition of C34ny (83 Ma) and C31y (73.62 Ma) rotations, published by Gaina et al. (1998) and used by Müller et al. (2008). The extrapolation rotation is located at 76.30°N, 72.00°E, with a rate of 0.300°/m.yr. for the Lord Howe Rise relative to Australia (fixed). Gaina et al. (1998) developed a complex model involving 13 separate fragments for the opening history of the Tasman Sea. There is almost certainly no way, given data typically preserved in collisional systems, to realistically infer this level of differentiation. Thus, the entire Tasman Sea and Coral Sea margin is modeled as opening with the same rotation. Figure 6A shows the modeled and extrapolated isochrons. In this case, we extrapolate both the Australian and the Lord Howe Rise isochrons to reflect the final extrapolated age distribution before any subsequent closure.

The extrapolated ages extend to the present (i.e., 0 Ma), as there is no observation from the sedimentology or subsidence history of the eastern Australian Tasman Sea margin that would allow an inference that spreading stopped at any time before the present. There is a clear mismatch between the history of the actual Tasman Sea and that of the extrapolated Tasman Sea, because the Tasman Sea ridge stopped spreading at about 52 Ma (Gaina et al. 1998). It is important to note that the extent of the extrapolated Tasman Sea basin is about six times that of the real Tasman Sea. Figure 6B shows the relationship between extrapolated ages and modeled age differences

based only on the extent of the actual Tasman Sea-modeled oceanic lithosphere age distribution. The misfit is obvious despite the use of the margin as a template and rotation parameters related to the actual opening history. The misfit would almost certainly be worse were the analysis to have used virtually any other rotation pole with an arbitrarily chosen rate.

Discussion

It is extremely tempting to extrapolate ages of ocean floor, given that the median age of oceanic lithosphere is only 55.7 Ma. Constrained extrapolation in the case of the former Farallon Plate, based on the preserved record of the Pacific Plate, for example, is probably reasonable, although some uncertainty due to asymmetry in spreading must be recognized.

Unconstrained extrapolation—that is, extrapolation beyond the constraints of the preserved age of oceanic lithosphere, as, for example, is required for the Izanagi-Pacific ridge system for the interval of the KNPS and younger—is much more problematic. There are no observable constraints on this type of extrapolation. Hence, conclusions derived from this type of extrapolation must be judged very carefully. Two examples from the Pacific Plate are used as simple case studies of this type of extrapolation. In both cases, the extrapolated age distribution, when compared with the modeled ages, is significantly misfitted. The 95% ranges of ages are typically greater than ± 30 m.yr. about the median age difference, where artificial truncation does not limit the range, even close to the beginning of the extrapolation. These particular examples make clear that the actual history of much of the world's ocean basins is more complex than any reasonable set of assumptions that would or do underlie any given extrapolation. Thus, in the northeast Pacific example, the development of the Kula Plate cannot be inferred from the pre-KNPS age structure of the Pacific Plate. Similarly, the modeled extinction of the Phoenix-Pacific ridge north of the Campbell Plateau is not inferable from the pre-KNPS age structure of the Pacific Plate. The complete reorganization of the Phoenix-Pacific system, as interpreted by Taylor (2006), cannot be predicted by the pre-KNPS structure of this boundary. No extrapolation can incorporate these sorts of events, despite the fact that they significantly affect the age distribution not only of the specific plates involved but also of all other plates linked through corresponding triple junctions.

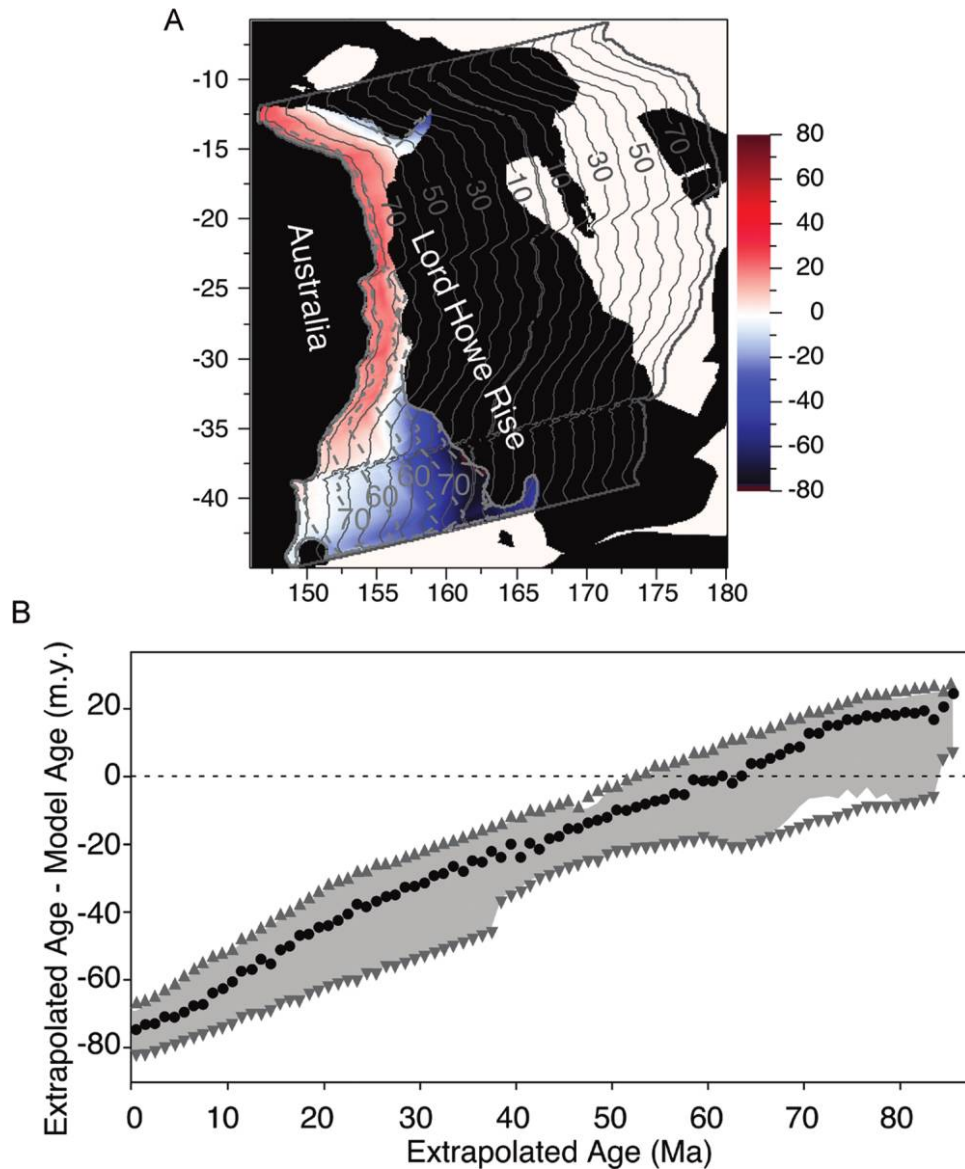


Figure 6. *A*, Comparison of extrapolated (*solid gray lines*) and modeled ages (Müller et al. 2008; *dashed gray lines*) for the Tasman Sea region between eastern Australia and the Lord Howe Rise (contours at 10-m.yr. intervals). Horizontal labels refer to model age isochrons and tilted labels to the extrapolated isochrons. Note the symmetric disposition of the 60-Ma contours of the modeled ages, reflecting the extinction of the Tasman Ridge at about 52 Ma. Color shading highlights the difference between the extrapolated and modeled ages at each 0.1° cell. The extrapolated area of the Tasman Sea is about eight times its actual size. The plot in *B* compares only the fraction of the extrapolated ages with the modeled ages that actually exist within the Tasman Sea (i.e., the color-shaded region of this figure). *B*, Comparison of the extrapolated and modeled ages for the region shown in *A*. Symbols and shading as in figure 4B. The decreasing extent of the vertical lines at younger ages simply reflects the truncation at the Lord Howe Rise margin of the Tasman Sea. This comparison includes only grid cells with ages specified in the modeled age grid within the Tasman Sea region; hence, it excludes the regions shown as black in *A* as well as younger oceanic lithosphere in the Fiji and adjacent basins to the north and east of the Norfolk Rise, unrelated to the Tasman Sea.

Figure 1 should make it obvious that extrapolation plays a major role in any attempt to assess any aspect of past age distributions of oceanic lithosphere or correlated phenomena. If the three cases

presented above are representative of the misfits between extrapolated ages and the actual record that once existed and if 50% or more of the age distribution is extrapolated, then it should also be

clear that it is impossible to derive statistically significant results from such analyses. The results of these explicit tests of unconstrained extrapolation or extrapolation by guess indicate that the uncertainties are sufficiently large as to preclude the use of extrapolation to rigorously test models of, for example, global ridge production (Rowley 2002; D. Rowley, unpub. manuscript) and/or mean age of oceanic lithosphere as a function of time and hence ocean basin volume, as was done by Müller et al. (2008). Further, although the above discussion has been couched in terms of age distribution, the same arguments obviously extend to ridge length as a function of time. The modeled extinction of the Phoenix-Pacific ridge and creation of the Kula-Pacific ridge clearly significantly affect calculation of global ridge length as a function of time. Thus, extrapolated ridge length is equally uncertain.

Both Whittaker et al. (2007) and Müller et al. (2008) use evidence from the geology of Japan to augment their inferences. A necessary assumption is that there were no subduction zones east of Japan during Cretaceous and early Tertiary times. A counterexample today is provided in southern Japan and the Ryukyu system. The Pacific-Philippine-Japan triple junction at the north end of the Izu-Bonin and Mariana arcs isolates the western boundary of the Pacific Plate from southern Japan by the intervening Philippine Sea Plate. An unknown length of the extinct older Palau-Kyushu remnant arc and the more recent Izu-Bonin arc has been subducted during the course of the Philippine Sea subduction history beneath southern Japan. This implies that it is possible to virtually, if not entirely, remove the record of intervening oceanic arcs that might once have been interposed between, for example, Japan and the Pacific-derived plates, such as Izanagi or Phoenix. Hence, inferences derived from the record preserved in Japan may or may not reflect the history of these extrapolated plates.

The third comparison presents the case of extrapolation in a completely closed Atlantic-type margin setting. This is extrapolation by guess. The Tasman Sea was used to test the rigor of extrapolation of the age distribution in former ocean basins that have subsequently closed and been incorporated into orogenic collages. The spreading history and age distribution within these reconstructed basins are obtained on the basis of inferences derived from the timing of rifting, onset of subduction, and final collision.

Following this reasoning, the age distribution of the Tasman Sea has been extrapolated. Even though the extrapolation uses the actual eastern Australian margin continent-ocean boundary as the template

for the geometry of the isochrons and the average early opening rotation of the Lord Howe Rise relative to Australia as the extrapolation rotation, there is a virtually complete misfit between the extrapolated and modeled ages. This reflects the fact that the opening history of the Tasman Sea was complex and that the mid-Tasman Ridge became extinct at 52 Ma (Gaina et al. 1998), none of which is inferable from the stratigraphic history of the eastern Australian or western Lord Howe passive margin. The lack of correlation between extrapolated and model age distributions in this example reinforces the underlying theme that extrapolation of age distributions does not provide a rigorous basis for testing important hypotheses that depend on accurate knowledge of the age distribution of oceanic lithosphere on a global basis.

Stated another way, extrapolation of histories constitutes an entirely underconstrained inverse problem. In cases of mode 2 and mode 3 extrapolation, the solution space is so large that it is likely that virtually any result is possible. Thus, it is highly probable that global kinematic histories can be derived that result in models that have decreasing, constant, increasing, or otherwise time-varying rates of production and mean age of the oceanic lithosphere as a function of time and obey all of the rules of plate tectonics. Since ridges can become extinct or be newly created, as can trenches, and since plates can therefore be added and subtracted as a function of time, it is possible, by construction, to arrive at virtually any outcome. The models presented by Müller et al. (2008), as is also true of those of Kominz (1984), are nonunique and represent but a few of the virtually infinite array of models that equally obey the simple rules but complex outcomes of plate tectonics. This suggests that observations of preserved plates and models of Earth behavior derived therefrom provide the only rigorous basis for proceeding (Rowley 2002; D. Rowley, unpub. manuscript) and that extrapolation should be understood as resulting in highly uncertain and unverifiable results that cannot provide the basis for rigorous analysis of these types of important problems.

Conclusions

Three case examples from the Pacific realm are analyzed in regard to extrapolation of the age distribution beyond the age extent of a preserved ridge system or, in the more extreme case of extrapolation, without any observational constraints of entirely closed ocean basins. These three cases demonstrate that the actual history of plate boundary evolution is

far more complex than can be incorporated in simple modes of extrapolation. The net result is that, as with many instances of extrapolation, the outcome is entirely predicated on the model assumptions and not on data. Therefore, any solution should be viewed as one among a nearly infinite array and hence not a unique result or one that provides statistically significant bounds on possible solutions. The consequence is that conclusions derived from such solutions do not provide a basis for rigorously determining the history of global ridge production, mean age, or mean ocean depth as a function of time. This result is, at one level, obvious, but the persistent use of extrapolated age distributions and conclu-

sions derived therefrom implies that it is not actually widely appreciated.

ACKNOWLEDGMENTS

I would like to thank my colleagues in the Canadian Institute for Advanced Research–Earth System Evolution Program for support and discussions. In particular I want to thank A. Forte for comments and discussion. I also want to thank M. Foote and B. Buffett for discussions and for reviewing a draft of this manuscript. Comments by D. Sahagian and an anonymous reviewer are also gratefully acknowledged.

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