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Plate tectonic reconstructions with continuously closing plates

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ABSTRACT

We present a new algorithm for modeling a self-consistent set of global plate polygons. Each plate polygon is composed of a finite list of plate margins, all with different Euler poles. We introduce a "continuously closed plate" (CCP), such that, as each margin moves independently, the plate polygon remains closed geometrically as a function of time. This method solves emerging needs in computational geodynamics to combine kinematic with dynamic models. Because they have polygons that are too widely spaced in time and have inconsistent motions between margins and plates, traditional global plate tectonic reconstructions have become inadequate for geodynamics. The CCP algorithm has been incorporated into the GPlates open-source paleogeographic system. The algorithm is a set of procedures and data structures that operate on collections of reconstructed geometric data to form closed plate polygons; the main data structures used for each plate polygon are based on a nested hierarchy of topological elements. Reconstructions with CCPs can be created, edited, visualized, and exported with GPlates. The native storage of the dynamic reconstructions is the GPlates Markup Language, GPML, which uses an XML-based file format called GML. We demonstrate the utility of the CCP method by creating a global reconstruction with continuously closing plates from 140 Ma to the present using data from existing, traditional reconstructions.

<H1>1. Introduction

Plate tectonic reconstructions are widely used in the earth sciences, including having applications in hydrocarbon exploration, regional geology, paleobiology, and as input constraints for climate and geodynamic computations. It is the wide use of plate reconstructions in geodynamics that motivates us, including the prediction of present day mantle structure, models of plate motion, and the interpretation of the drift of hotspots, true polar wander (TPW), sea level and stratigraphic signals, and the transport of geochemical domains within the mantle. By focusing on how they have been applied previously, we will identify how we can overcome previous limitations in a new generation of software and global plate reconstructions.

Their first geodynamic application was for the interpretation of variables like present-day mantle structure, the gravity field, and the distribution of hotspots through a comparison of a single reconstruction to such variables (Chase, 1979; Anderson, 1982; Chase and Sprowl, 1983; Richards and Engebretson, 1992). From these correlations, a central paradigm of geodynamics emerged: High seismic velocity regions of the mantle are downwellings controlled by the history of subduction, that these mantle downwellings push hot mantle into upwellings that are responsible for low seismic velocities, geoid highs, and hotspot locations. For these applications, only subduction zone locations were required. Building on these well-known correlations, a more advanced use of reconstructions was as constraints on mantle flow models. Early models assumed that slabs were inserted at subduction zones and descended vertically in the mantle at a constant rate (Ricard et al., 1993). These led to the use of time-dependent reconstructions with closed plate polygons as velocity boundary conditions on the full solution of mantle convection within a spherical shell (Bunge et al., 1998; McNamara and Zhong, 2005). In these cases, the application had been for the prediction of present mantle seismic structure or the geoid, that is, a time-dependent model being tested against a single instant of earth history. Approximate matches could be found between the distribution of cold downwellings and high seismic shear velocity in the lower mantle (Bunge et al., 1998)

and between thermo-chemical upwellings and low shear velocity in the lowermost mantle (McNamara and Zhong, 2005).

Time-dependent models need to be compared against constraints over geological time, such as models that addressed variations in continental flooding (as a proxy for dynamic topography) (Gurnis, 1993; Lithgow-Bertelloni and Gurnis, 1997) and changes in plate motion (Lithgow Bertelloni et al., 1993; Lithgow-Bertelloni and Richards, 1995, 1998; Conrad and Lithgow-Bertelloni, 2004). A critical issue for the reconstructions is how the plate margins are represented, especially for flow models used to predict global plate motions. A characteristic that is especially important for flow models, but that has yet to be fully achieved in global plate motion with commensurate mantle flow, is the mechanical continuity between slabs (the principal driving force of plate motions) and the subducting plate (Zhong et al., 1998; Stadler et al., 2010). Trenches slowly migrate and the coherence must be maintained in the time domain. This places design requirements on paleogeographic models: The motion of the margin must be self-consistent with the overriding plate and the migration must be sufficiently small between successive reconstructions so that mechanical coupling remains intact. It is possible that the lack of success of time-dependent plate models (Richards and Lithgow-Bertelloni, 1996) has been due to inadequate models of plate boundaries.

Models linked more closely to geology have been attempted with both regional and global models, including those linked to onshore continental stratigraphy and the evolution of geochemical domains in the mantle (Gurnis et al., 1998, 2000) or those linked to hotspot tracks on oceanic plates (Steinberger and O'Connell, 1998; O'Neill et al., 2005). The implications of these studies were wide ranging, including the conclusion that mantle flow causes significant vertical motions within continental interiors (Gurnis et al., 1998) and that the best fits of plate motion occur when hotspots slowly drift in response to mantle flow (Steinberger and O'Connell, 1998; O'Neill et al., 2005). For those applications, predictions of geodynamic models (such as topography, stress, and temperature) need to be mapped from the frame of reference in which mantle flow is computed to plate frames. This would be true for both intraplate, such as the eruption of

hotspots from plumes (e.g., Steinberger and O'Connell, 1998) or the prediction of stratigraphy (e.g., Gurnis et al., 2000), and interplate signals, such as the sampling of mantle chemistry at mid-ocean ridges (e.g., Gurnis et al., 1998). This places strict requirements on paleogeographic software systems because the data must be assigned to the moving plates.

Various reconstructions have been used in geodynamic models. The continental flooding models (Gurnis, 1993) used continental outlines, areas of marine flooding, and trench locations from the *Paleomap Paleogeographic Atlas* (Scotese and Golonka, 1992). The trench locations were used to position the descent of slabs into the mantle while continental outlines were used for the prediction of flooding from the modeled dynamic topography; the maps of flooding were used to test the models. The principal limitations of these models were that the reconstructions lacked closed plate polygons and the data used for geodynamic model validation (continental environments) were not rotated with the plate but rather drawn statically on continents at specific times.

Most of the plate motion studies above used the data set assembled by Lithgow-Bertelloni and Richards (1998) from several sources with 11 reconstructions for the Cenozoic and Mesozoic (back to 119 Ma) with an average duration of 11 Myr. For the Cenozoic they used the plate boundaries and poles of rotation from Gordan and Jurdy (1986), while the Mesozoic plate boundaries were mostly from Scotese (1990), except for oceanic plates in the Pacific domain. The Pacific Mesozoic poles were from Engebretson et al. (1992). For mid-ocean ridges, partial workarounds have been used to reconstruct plate boundaries at smaller time intervals which were necessary for geodynamic models (e.g., Conrad and Gurnis, 2003; Xu et al., 2006).

Global plate tectonic reconstructions have become inadequate for geodynamic models (especially time-dependent models with variable viscosity), either as information to be assimilated into a model or as the basis to map a geodynamic prediction back for comparison with the geological record. Specifically, the reconstructions described above have polygons representing the plates that are too widely spaced in time. Margin

migration rates can reach tens of centimeters per year in retreating trenches, so that trench locations jump thousands of kilometers when the interval between reconstructions is 10 Myr or more. With plate thicknesses <~100 km, mechanical coherence cannot be maintained and substantially smaller intervals between reconstructions are required. Plate margin evolution can be inconsistent with plate motions and this leads to unrealistic geodynamic predictions. Because the geological record can be poorly constrained, the position of a trench can be less well known compared to a ridge, even during the Cenozoic (some plates, such as the Philippine plate has been completely surrounded by convergent boundaries), and so large swaths of the surface are ambiguously defined. Consequently, alternative reconstructions are needed to assess uncertainty, especially in areas where constraints are sparse. It is essential that we address the extent to which predicted mantle structure is uncertain because of uncertain reconstructions, in addition to uncertainties in the flow model. Unfortunately, alternative reconstructions (or modifications to existing reconstructions) are difficult to incorporate with current systems (essentially because of the need to recompute plate closure) and so alternative reconstructions have not been widely used for geodynamic studies.

We have attempted to overcome these limitations with reconstructions by first developing new concepts for reconstructions, incorporating them into a new software system, and then using the procedures to develop a new set of global plate reconstructions. We use GPlates,[1] a new software system for interactive plate tectonic reconstructions linked to geodynamic models and GIS databases (Boyden et al., 2011). The program incorporates evolving closed plate polygons to represent tectonic plates and incorporates both a data representation of closed plate polygons as well as onscreen capabilities allowing the user to interactively create polygons with geological data. The program also incorporates utilities to read in files from geodynamic models and prepare data files that control geodynamic simulations. In this paper, we describe the continuously closed plate algorithm, provide a brief overview of the GPlates system,

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[1] http://www.gplates.org/.

describe the CCP algorithm as implemented within GPlates, and illustrate the construction of a global reconstruction with continuously closing plates with data from existing traditional reconstructions. We conclude with some preliminary examples of using the new reconstructions in geodynamic models as illustrations.

2. Continuously closing plates

A continuously closing plate is constructed with the rules of plate tectonics (e.g., Cox and Hart, 1986) in which a plate is represented at any moment in time by a closed polygon. The difficulty in creating such polygons is that the different segments of its boundary continuously change. Each segment potentially has a different Euler pole. Consider a plate P_1 (Fig. 1A) that is bounded by a finite set of plate boundaries. Each of those plate boundaries has their own Euler pole, ω_1^M, ω_2^M, ω_3^M, ω_4^M …, ω_n^M (where superscript M denotes a plate margin while the subscripts refer to which margin 1, 2, 3,…n). These Euler poles may only exist for a finite period of time and some boundaries may disappear while others appear. The time intervals over which each plate boundary Euler poles are valid are potentially different for each segment. A plate P_1 may only have a constant set of data for a restricted period of time when the Euler pole data remain constant. Consequently, a CCP for P_1 over a longer time interval of time must be composed of a finite set of "uniform margin Euler pole" subsets.

Let us focus on a CCP subset when the margin Euler poles are constant (Fig. 1B). The margins that compose P_1 must intersect so that a uniquely defined polygon can be constructed. Since the Euler poles of two intersecting margins are different, their point of intersection continuously changes with time. If their intersection changes with time, then the plate boundary length will change with time. The geometry of the extended plate boundary (Fig. 1B) must be defined using constraints that are reasonable for both the regional geological constraints and the rules of plate tectonics.

Subduction plate boundaries move with the Euler pole of the overriding plate. For example, imagine that margin, M_1, with Euler pole ω_1^M moves with plate P_3 (i.e., ω_1^M

$= \omega_3^P$). This could be the case of the Peru-Chile trench moving with the stable interior of South America. This is not an exact assumption, as there is some internal, compressional deformation in the Andes. Alternatively, imagine that the margin M_2, with Euler pole ω_2^M, of the ocean–ocean subduction type, such as the Marianas. The ω_2^M is that of a small microplate that moves with the Marianas fore-arc with Euler pole ω_2^P. The entire boundary that makes up the small plate must be composed of the trench, the fracture zones and spreading centers with the back-arc, and zones of distributed deformation. In order to have continuously closing plates, such small fore-arc plates cannot be ignored.

All plate boundaries must be incorporated into the definition of plate P_1 so that the region within the boundary moves according to ω_1^P. Besides subduction boundaries, we include mostly strike slip (M_3) that may have a small component of tension and compression, ridges (M_4), and ocean–ocean transform faults (M_5) (Fig. 1). For complete coverage of the surface of the earth with no gaps or overlaps, the plate margins and data that define them between adjacent plate boundaries at all times must be identical such as M_1 between P_1 and P_3 (Fig. 1A).

Since the geometry between any two plates is entirely defined by relative motion between those plates, one might conclude that global coverage does not depend on the absolute frame of reference. A global model composed of continuously closing plate polygons is independent of the global frame of reference only if the margin Euler poles all share the same trunk in the reconstruction tree. Many traditional Cenozoic reconstructions have this characteristic, but other reconstructions including those that merge the Pacific with the rest of the world before the middle Mesozoic, when the Pacific was entirely surrounded by subduction zones, do not (e.g., Wessel and Kroenke, 2008; Torsvik et al., 2008).

<H1>3. GPlates

GPlates is a computer program that allows for interactive plate tectonic reconstructions that are needed by a diverse range of disciplines with utility far beyond geodynamics (Boyden et al., 2011). GPlates open-source software is written in C++,

utilizing several open-source development libraries including Qt, OpenGL, GDAL, and CGAL. GPlates uses the CMake build system to allow for easy compilation on most platforms, including various types of Linux, Windows 7/XP/Vista, and Mac OSX.

GPlates has all of the traditional functionality of plate reconstruction software, with a few advanced tools to create and edit data, and export the data to geodynamic models. At the core of GPlates is a geometry-reconstruction engine that calculates the modeled position and motion of tectonic plates on the surface of the Earth (Boyden et al., 2011). GPlates provides a graphical display of the positions and motions of tectonic plates, enabling the user to visualize this process on a virtual globe and in projected map view (Fig. 2). GPlates can display the position of the plates at a single geological time, or animate the motion of the plates over a period of time. GPlates also displays various geological objects on top of the tectonic plates, and the user is able to query and manipulate the properties of these objects.

GPlates uses an extensible markup language (XML)-based data model called GML, the Geography Markup Language (Lake et al., 2004). This is an XML-based file format defined by the Open Geospatial Consortium (OGC) and is on its way to becoming an ISO standard. GML defines building blocks common to many applications in the geosciences, including geometric primitives like points and lines, as well as temporal primitives like time windows and time instants. GML also has more complicated data items like time scales and coordinate reference systems.

In the spirit of XML, we have extended GML into a plate tectonic-specific language called GPML, the GPlates Markup Language (Boyden et al., 2011). GPML is an application schema of GML that combines the basic GML building blocks into more complex data elements for modeling geological and geophysical data, with emphasis on tectonic reconstructions. We have reflected GML's feature-property paradigm both in our data model, the GPlates Geological Information Model (GPGIM), and in the underlying structures of the C++ code. In this way we have good coupling among the real-world geophysical entities, the abstract data model, and the specific implementation of the

model in the program. Briefly, the feature-property model is a way to store information in a hierarchical fashion. Any geological or geophysical entity that exists in the system is modeled as a feature object. A feature has properties, like position, name, or lifetime, which determine its specific behavior and use. Each property has a value that may be a simple data element (like integer, or string), or the value may itself be a subproperty with its own value. In this way a nested hierarchical complex of data may be formed (Lake, et al., 2004, Chapter 9). Although GPML is the native file format, GPlates is backward compatible with older plate tectonic reconstruction software and is able to read PLATES 4 data and rotation files (Gahagan, 1998), as well as both read and write ESRI Shapefiles.

GPlates is able to read and display global or regional time-dependent raster images or grids (Fig. 2). Typical grids have data with oceanic age, spreading rates, or dynamic topography, and these images are used to help build or refine reconstructions. In addition to the main reconstruction engine, GPlates has a number of tools available to create and manipulate data. GPlates is able to query and manipulate the finite rotations, and the rotation hierarchy, used to reconstruct geologic data. The Total Reconstruction Poles dialog provides several alternative views of the rotation data including Tables of relative and equivalent finite rotations, a tree-like representation of the hierarchy, and the circuit between any two plates. GPlates also has tools to change existing feature data by editing a feature's properties, or by moving, adding, or deleting its geographic coordinates. There are tools to create new geologic features with standard geometries like points and lines, as well as features having complex topological structures like continuously closing plates.

<H1>4. Closing plates with GPlates

The continuously closing plate algorithm is a set of procedures and data structures that operate on collections of reconstructed geometric data to form closed plate polygons. The main data structures used to create a polygon for each plate are based on a nested hierarchy of topological elements defined by our GPML schema (Fig. 3A). The top level feature element is the Topological Closed Plate Boundary. This element represents the full tectonic plate, with all its geophysical properties defined by subelements. The main

feature property used by the CCP algorithm is the boundary property, <gpml:boundary>. The value of this property is a specialized type of Topological Polygon. This is not a traditional static polygon with a fixed list of vertices, rather it is a list of gpml elements, called "sections," that contain references to other geologic features that exist in the data collections. These sections are the individual plate boundary margins that make up the closed boundary of the plate. To represent the full history of a real-world plate we have created many short-lived instances of "logical plate polygons" that model the plate. For example, over the full scope of an example global plate reconstruction (see next section), we have created about 50 distinct instances of the North American plate, each with a life of about one to ten million years.

A plate's boundary may be composed of two types of topological sections: point sections and line sections. Each of these section types has a link back to a source geologic feature. The links of the boundary sections are used to obtain the geographic coordinates of the reconstructed feature data and assemble them into the closed plate polygon. Point sections are references to geologic data with point-like geometry. While we have not yet found the need to use point data in generating actual reconstructions so far, the CCP algorithm does allow them for completeness. The simplest, minimal case for a continuously closing plate is a topological boundary with a list of three point sections. As the points are reconstructed the plate polygon boundary is formed from those three vertices.

Line sections are references to geologic data with line-like geometry. Line sections also have a property allowing for the coordinates of the line data to be used in the reverse order. The CCP algorithm makes no assumptions about the orientation of polygons with respect to closure in a clockwise or counterclockwise sense. When two plates share a line, and they are closed in the same sense (i.e., both clockwise), one plate uses the line data's coordinates in the reverse sense of its neighbor plate. The next simplest case for a closed plate is a topological boundary with a list of only one line section. As the line is reconstructed the plate polygon boundary is formed from its vertices, possibly in reverse order.

Line sections also have two optional properties that define the relationships between a line section and its neighbors on the boundary sections list. Each line may have a start intersection, used to define the relationship with the previous section on the list, and it may have an end intersection, used to define the relationship with the next section on the list. If the line does not intersect with its neighbors, then these properties are not needed. In practice we have constructed nearly all plate boundary sections so that they do intersect. In addition to the reverse setting, the intersection properties further control how the source geometric line data are to be used when forming the plate polygon boundary. If a line intersects with its neighbors, then only a subset of its vertices is used for the boundary. The dynamically computed intersection points and all the vertices of the line between them determine the subset, possibly in reverse order. GPlates uses proximity tests on the end points of the segment that results from intersections to determine when to reverse the component vertices of that segment. Each subsegment is tested with its neighbors during the intersection process. Whichever end is closer to the neighbor determines if the segment should be reversed or not.

As we have discussed, when line data are reconstructed at different times, the actual intersection point will change, and so we have not represented the relationship as a static point, or a list of points. Rather, we represent each line section's possible intersections by referencing the neighboring features, not the coordinates of intersections. In this way we can keep track of how the lines intersect independently of their actual vertices or intersection points, all of which may change on each reconstruction. This is one of the key features of the CCP algorithm: we have modeled the continuously closing plate boundary as a set of intersection relationships.

Now we come to a more realistic case of a closed plate: a topological boundary with a list of several line sections, where each line section has both a start intersection (with its previous neighbor) and an end intersection (with its next neighbor). Fig. 3A shows a sample GPML file with these topological elements isolated. Lines 13 to 19 hold the start intersection, including the target feature's unique id (GPlates-1383d4e01), the geometric

property to reference (gpml:centerLineOf), and what type of geometry to expect (gml:LineString). Lines 20 to 26 hold similar information for the end intersection. We have made use of many of the geometric primitives defined by the GML standard for our referencing mechanisms.

As the source lines are reconstructed, the plate polygon boundary is formed from processing the neighbor relationships, computing the intersection points, and splicing out those vertices that fall between the intersection points.

During each reconstruction, GPlates performs a few steps to execute the continuously closing plate algorithm (Fig. 3B). First, all regular features (points, lines, static polygons, etc.) are reconstructed from present day positions to new positions at the current reconstruction age. These new positions are called "Reconstructed Feature Geometries" and are stored in an internal data structure called "the Reconstruction." This is an abstract representation of the model, and is used by other parts of the program to access the current state of features (locations, properties, etc.).

A topological feature (continuously closing plate, deforming zone, etc.) is resolved by processing its list of topological boundary sections into a closed polygon. Each topology feature has a list of the component features that make up its boundary. Each section on the list holds a reference to a regular feature, and that reference is used to "look up" the new reconstructed position of the section. The reconstructed coordinates of the current section are fetched from the reconstruction.

Next, the intersection relationships are processed. The coordinates for the previous and next neighbors are also fetched from the reconstruction, and these are tested against the coordinates for the current working section. If there are intersections, GPlates splices out the proper subset of coordinates and appends them (possibly in reverse order) to the closed plate polygon. If the current section does not intersect, then GPlates uses all of its reconstructed vertices for the polygon. If the current section only intersects on one end, then GPlates performs a "rubber banding" of the current section's free end to the

nonintersecting neighbor, simply closing the gap with a single line. A similar reversal test is performed on nonintersecting sections to ensure proper ordering around the final boundary.

During the lifetime of the plate polygon, if boundary sections move away from one another, so that they no longer intersect, GPlates will simply use all the vertices of the features. In this way we ensure that the polygon is truly closed. If boundary sections move such that they "slide past" one another, then GPlates will continue to obey the relationship originally set up. Strange or inverted plate polygons may result, and this is a good indication that a new instance of the plate polygon is required. GPlates does not detect nor correct such polygons. A malformed polygon is actually a good visual indicator that the source feature data are probably no longer valid for that polygon, and new relationships, or a new lifetime of the polygon, should be defined.

If a particular feature referenced by the topological boundary section is not found in any feature collection, then GPlates will issue a warning message, but continue to close the plate polygon without the feature. The intersection relations are still followed, now with the new neighbors in the list. Again, this might result in odd polygons, and require adjustments to the lifetime or boundary list of the plate, or loading a file with the referenced feature.

A sample plate polygon from our example global reconstruction shows how the resolved set of vertices can change at different reconstruction times (Fig. 4). As the boundary lines move relative to one another the intersection points are recomputed dynamically. Some vertices from the source lines will be added to the polygon's resolved set, while others may be lost, depending on the relative motion of the neighboring boundaries.

<H1>5. Testing the CCP algorithm: A global reconstruction

Using the algorithms just described, we created continuously closing plates from 140 Ma to the present (Fig. 5; Animations 1–3) using data from existing, traditional reconstructions. This reconstruction was generated to demonstrate the CCP algorithm, to exercise and debug the GPlates software, and to provide a data set of existing geological reconstructions in a format that can be used directly in geodynamic models and related applications. The geological detail and reasoning of these existing reconstructions are beyond the scope of this paper, but the details, including references to the existing reconstructions can be found online.[2]

These are global reconstructions in which the total rotation poles are attached to a moving hotspot reference frame (O'Neill et al., 2005). However, a user can change that frame of reference by adding a single rotation to the entire reconstruction tree without upsetting plate closure and global coverage. Because of the limited life of plate polygons composing CCPs, there are 59 "Plates" that are identifiable units connected to the rotation tree. However, there are also 697 "Logical plate polygons." These are closures that were manually created through the GPlates GUI and embody the rules of continuous closure. The life span of a polygon is between 1 and ~25 Myr. For example, the Australian and Pacific plates are the most complex with 59 and 61 closures, respectively, and with polygons lasting on average ~2–3 Myr. At times, the Pacific plate polygons can be composed of up to 32 plate boundary segments, many with different Euler poles.

All of the rotation poles that were used for the plate boundaries either came directly from published poles, specifically the EarthByte Global Rotation Model (Müller et al., 2008a), or were derived from these poles. There are a few exceptions, but in general poles used for the trenches assumed the poles of the overriding plate; sometimes the overriding plate is only a microplate (Section 2). The poles for oceanic ridges and rifting margins were determined assuming symmetrical spreading. Although trench asymmetry does not influence the rules of plate closure, such asymmetry was tracked using GPML. Finally, the CCPs are generally self-consistent with the paleo-age grids of Müller et al.

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[2] http://www.gps.caltech.edu/~gurnis/GPlates/gplates.html.

(2008b), except for a few exceptions in the Late Mesozoic. The maps of the CCPs are plotted along with the paleo-age grids (Fig. 5 and Animations 1–3).

In the global plate reconstruction, at times, plate boundaries will change configuration or abruptly jump (Animations 1–3). Sometimes these discontinuities in time are well constrained by geological data, while at other times they could represent either misinterpretations or an incomplete geological record. So, for example, at the Bouvet Triple junction between the South American, African, and Antarctic plates in the South Atlantic, there are ridge jumps at 95 Ma to capture the Malvinas-Africa motion, another at 83.5 Ma to represent the spreading in the Agulhas Basin, and a westward ridge jump at ~64 Ma to represent the present-day location of spreading (LaBrecque and Hayes, 1979; Marks and Stock, 2001) (see Animation 1). In other cases, entirely new subduction zones and spreading centers will appear where there were none before (Animation 3, 56 Ma) (e.g., Stern and Bloomer, 1992).

The line data for the plate boundaries came from several sources. We used the EarthByte Global Coastline File (Müller et al. 2008) for those subduction zones that we attached to continental crust or currently existing island arcs. Oceanic ridges generated by magnetic isochrons were based on Müller et al. (2008). Finally, some relic trenches were digitized from their present day locations on the free air gravity map of Sandwell and Smith (1997).

The reconstruction is available[3] dynamically as a GPML file, which can be read in, manipulated, and output in other formats (including as static polygons) with GPlates. The data are also available as 140 sets of static polygons.

<H1>6. Discussion and conclusions

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[3] http://www.gps.caltech.edu/~gurnis/GPlates/gplates.html

The GPlates reconstructions can be used directly in geodynamic models that require continuously closing plates, including global flow models of the lower mantle (such as models of thermo-chemical plumes), global plate motion models with plate and slab strength, models of regional-global coupling), and adjoint models of convection incorporating tomography and vertical motion constraints.

Example applications illustrate the utility of the CCPs within the interactive environment of GPlates. The consistency between plate motions and margins was critical in adjoint (inverse) models of mantle convection (Liu et al., 2008; Spasojevic et al., 2009). The reconstructions were used in adjoint models initiated with seismic tomography and allowed the recovery of flat lying Farallon slab by fitting model vertical motion predictions against a variety of stratigraphic data. The convection models used a stress guide formulation so that the strong slab remained attached to the Farallon oceanic plate from about 100 to ~20 Ma, despite the large translation of North America to the west. These models would have been impossible with the traditional approach with static polygons that are too widely spaced in time. DiCaprio et al. (2011) have used the reconstructions in coupled regional-global forward models of the Australian region since 140 Ma. With these models, they found solutions that matched both the distinctive stratigraphic history of Australia from the Cretaceous and the present location of slabs in the mantle. In a related study, they shortened the time between generating alternative reconstruction and diagnosing the outcomes of the dynamic models so as to reach conclusions on the Cretaceous paleogeography of the continent (Matthews et al., 2011).

A limitation for the current implementation of the CCPs is the lack of internal plate deformation. In the case of the Cenozoic extension of the western United States, we required that the Euler pole of the plate margin move with respect to the continental interior. However, plate deformation is a natural extension of our CCP algorithm: A deforming plate region will still be encompassed by a continuously closing topological polygon. This means that data structures that represent the plate deformation, such as a time-dependent Lagrangian mesh, can be made to exactly fit within the confines of a CCP. The next generation of our CCP and GPlates will have this feature in which such

zones of deformation either are entirely within a rigid plate or define a zone between several plates.

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Captions.

Fig. 1. Schematic of the generic features that are incorporated into the continuously closed plate (CCP) algorithm. The ω^P are the Euler poles for the plate interiors while ω^M are those for the plate margins.

Fig. 2. Main window of GPlates showing our global reconstruction at 26 Ma. Plate polygons are outlined in black. The Australian plate is selected, and outlined in gray, with its vertices highlighted as gray dots. Some of its 19 component boundary sections are shown in the Topology Section table below the globe. Present-day coastlines are shown in aqua, other line data are shown in blue and gray. Background raster image is a paleoage grid in which gray areas denote nonoceanic crust.

Fig. 3. Details associated with the CCP algorithm as implemented within GPlates. (A) Sample GPML file that illustrates how several Line features (lines 12, 19, and 26) are contained within a TopologicalClosedPlateBoundary. (B) Processing sequence associated with reconstructing and resolving a previously created TopologicalClosedPlateBoundary.

Fig. 4. Philippine Sea Plate from five intersecting boundary lines at two times. Plate polygon is outlined in gray, with gray dots showing polygon's vertices. Boundary line data are colored (with their individual lengths extended so as to ensure closure) at (A) 45 Ma and (B) 41 Ma.

Fig. 5. Hammer projection centered at 180°W with closed plate polygons overlying paleoage grids (Müller et al., 2008). (A) 140 Ma; (B) 80 Ma; (C) 50 Ma; (D) present. Plotted using the GMT package (Wessel and Smith, 1998). GPlates has output feature data files in xy format for both closed plate polygons as well as oceanic trenches with subduction polarity indicated. Plotted in red are the data in the EarthByte Global Coastline File. Plate motions with respect to the moving hotspot model of O'Neill et al. (2005).

Animation 1. Orthographic projection of the north Atlantic from 140 Ma to the present using GPlates.

Animation 2. Orthographic projection of the south Atlantic from 140 Ma to the present using GPlates.

Animation 3. Orthographic projection of the western Pacific from 140 Ma to the present using GPlates.

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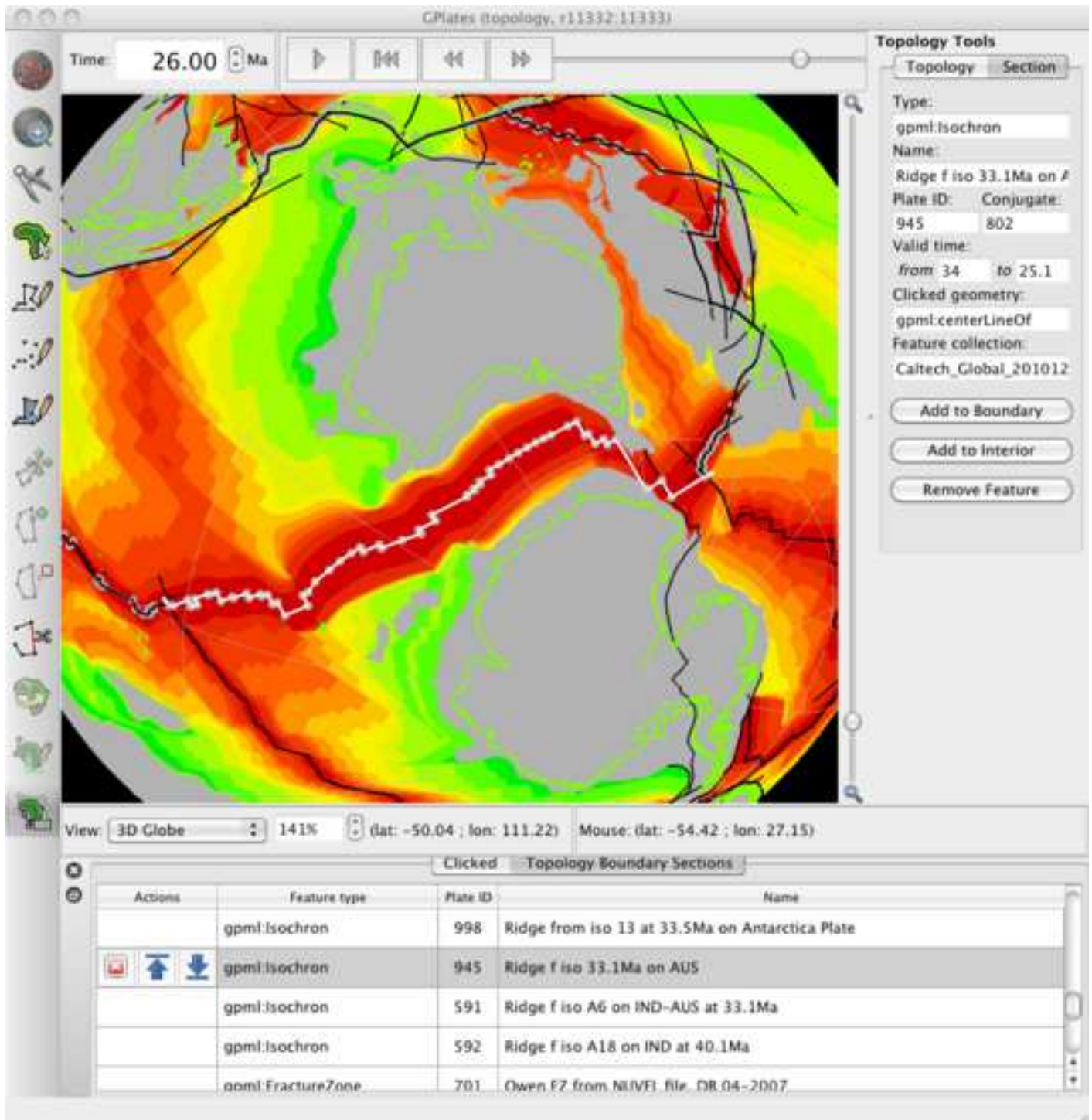
- Formulation of the continuously closing plates (CCP) algorithm for plate reconstructions.
- Implemented the CCP algorithm into the GPlates open source software
- Developed a new global plate reconstruction from 140 Ma to the present using method.
- The method allows a new generation of geodynamic models to be formulated.
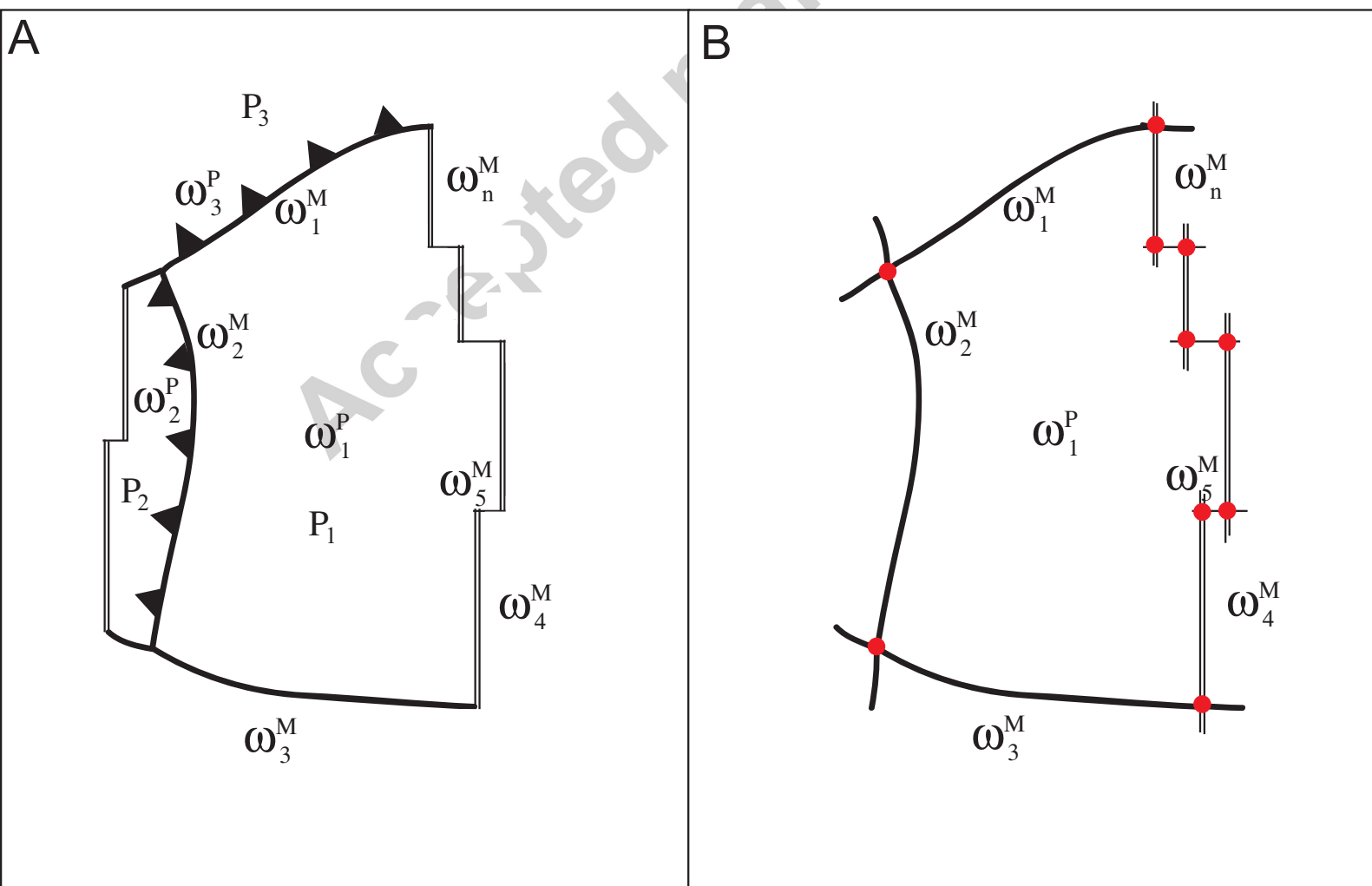
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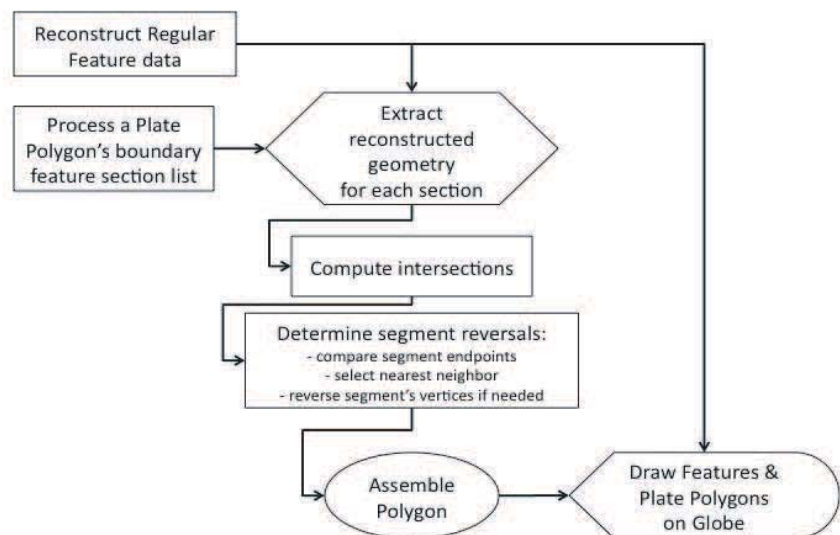
B

A

B

A. 140 Ma

C. 50 Ma

B. 80 Ma

D. 0 Ma

20 cm/yr

Ma

0   50   100   150   200