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PMTec: A new MATLAB toolbox for absolute plate motion reconstructions from paleomagnetism

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ABSTRACT

Established on Euler rotations (rotation poles and angles), quantitative representation of plate motion history has been one of the focus fields in geoscience since the beginning of the age of plate tectonics. Here we present a new MATLAB based toolbox PMTec primarily developed for (1) construction of apparent polar wander paths (APWP, in the form of running means and spherical splines) from paleomagnetic data and (2) absolute plate motion calculations through APWP geometric parameterizations. We choose to build the graphical users interface of PMTec using MATLAB considering its powerful mapping toolbox for geospatial data visualization and its rising popularity in the geoscience community. Theoretical background, functioning modules, and data and file management in PMTec are formulated in this paper. The computational and graphical capabilities of PMTec are demonstrated using published data to provide an overview about its operation procedure and potential applications. The PMTec package and associated tutorials are available for download from the website: http://www.ualberta.ca/~vadim/software.htm. PMTec is a freeware for plate tectonic research and education purposes and allowed to be redistributed among users.

1. Introduction

Numerical characterization of plate motions on the Earth's surface is one of the longstanding interests and challenges in the geoscience community which underpins the advancement of plate tectonic paradigm. Theoretically, any displacement on the spherical Earth can be represented as a rotation around an Euler pole by a certain amount of angle (e.g. Cox and Hart, 1986; Schettino, 2014). Using powerful computational facilities, Bullard et al. (1965) first implement an iterative algorithm to match the conjugate coastlines bounding the Atlantic Ocean. In the studies of relative plate motions, marine geophysical observations including magnetic lineations and fracture zones are widely used to calculate Euler rotations during the studied period (e.g. Schettino and Turco, 2009). For absolute plate motions, Euler rotations are usually derived based on the geometric characterization of seamount trails, surface expression of hot spots (Morgan, 1971; Wessel and Kroenke, 1997), or on the combination of relative plate motions models and geometries of hot spots tracks (e.g. Müller et al., 1993). Note that the formulation of any reliable plate kinematic model should have high-fidelity paleomagnetic constraints. Since the revelation of the compelling evidence that hot spots are not fixed in the mantle (Tarduno, 2007), refined rotation models have been presented mainly through implementing modelling of hot spot motions (e.g. O′Neill et al., 2005; Doubrovine et al., 2012). By integrating plate motion models and true polar wander estimates, paleomagnetic data can also be used to define Euler rotations (e.g. Steinberger and Torsvik, 2008; Mitchell et al., 2012). The outcome reconstructions, however, are associated with large uncertainties because of various underlying assumptions such as long-term stability of deep mantle structures (e.g. Torsvik et al., 2014).

Inspired by the reconstruction of the eruption site of ~250 Ma Siberia Traps using paleomagnetic Euler pole analysis (Smirnov and Tarduno, 2010), Wu and Kravchinsky (2014) formulate and demonstrate the methodology of absolute plate motion reconstructions by geometrically parameterizing apparent polar wander paths (APWP), which has the potential to extend absolute plate reconstructions back through deep time using high-quality paleomagnetic data. One primary motivation here, therefore, is to present a software implementing the methodology of Wu and Kravchinsky (2014) to calculate absolute plate motions from paleomagnetic data. Notably, there is a new reconstruction method gaining popularity in recent years: using sinking slabs and deep mantle structures resolved from global mantle tomography models to correct for existing plate reconstructions primarily defined in the paleomagnetic reference frame (e.g. van der Meer et al., 2010, 2012; Torsvik et al., 2014). This method usually starts with reconstructions presented in the paleomagnetic reference frame,

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and ends up with modifying the input finite rotations using ancient subduction zones inferred from users' selected seismic tomography models. Note that outcome reconstructions should not depend on which of the different methodologies is employed, unless one or more of them is constructed on erroneous premises. In practice, we need to find the most sensible reconstructions that can explain as many observations as possible, which is not straightforward because of the large uncertainties from various methods. Here we incorporates a whole mantle P-wave tomographic model of Obayashi et al. (2006) with a decent resolution of mantle dynamic features so users can fit the seismically derived reconstructions with paleomagnetic observations within uncertainties (and verse versa). Assuming that slabs (i.e. ancient subduction zones) are sinking vertically and well preserved for hundreds of million years, we have an option to match our reconstructions with slabs visible in tomographic maps. The adjustment is usually achieved by rotating the reconstructions around an Euler pole to minimize the fitting discrepancies (Schettino, 2014). Such analysis should be done with cautions as there is no unambiguous interpretation on all the tomographic features. In addition, the paper also aims to promote our APWP construction module for the calculation of APWPs (in the forms of running means and spherical splines) and the correlated kinematic proxy parameters, the standard methods in the community to present and analyze paleomagnetic data for tectonic plate reconstructions.

Lots of plate reconstruction softwares have been published in the past decades, such as GMAP (Torsvik and Smethurst, 1999), PaleoMac (Cogné, 2003), PLACA (Matias et al., 2005) and GPlates (Boyden et al., 2011) which can be used for reconstruction data processing and visualization. As a complement to the field, here we present a new MATLAB toolbox PMTec to perform absolute plate reconstructions from paleomagnetism. The mounting popularity of MATLAB in academia and industry provides an ideal platform to promote the use of PMTec both for plate tectonic research and educational demonstration purposes. In this paper, we introduce the theoretical background, the component functioning modules, and data and file management for PMTec. To provide an overview of its usage, the main computation and visualization capabilities of PMTec are demonstrated with published data. The PMTec package together with tutorial document and data can be downloaded from http://www.ualberta.ca/~vadim/software.htm.

2. Methodology

2.1. Construction of apparent polar wander paths

High-quality paleomagnetic poles are essential for the construction of reliable APWPs. Van der Voo (1990) proposes seven reliability criteria for paleo-poles quality assessment: for each criterion a given pole passes, it receives one point which is added up to obtain the quality factor Q ranging from 0 to 7. The higher the value of Q is, the more reliable the pole would be. Schettino (2014) reviews alternative paleo-poles evaluation methods, such as using errors of paleo-poles. For users of PMTec, all paleomagnetic data are recommended to be evaluated using the selection criteria of Van der Voo (1990). For most of continental plates, paleomagnetic poles with variable qualities tend to have an uneven temporary distribution along the trend lines. Applying up-to-date Euler plate rotation models to transfer coeval poles across continents is one common solution (e.g. Torsvik et al., 2012). For earlier times with no preservation of marine geophysical data, however, techniques other than using plate circuits are needed to determine the overall patterns of APWPs by averaging out random noises caused by inadequate quality and quantity of available paleomagnetic data. In PMTec, we present two most commonly implemented methods for APWP constructions: running average means and spherical smoothing splines.

Running means are calculated from selected subsets of paleomagnetic data falling within the specified window of time intervals. Elliptical errors of input paleo-poles defined by semi-axes dm and dp need to be converted into circular ones A_{95} using the approximation formula $A_{95} = \sqrt{dm \times dp}$ suggested by Khramov (1987). Mean pole position with uncertainty in each time window are computed using the method of McFadden and McElhinny (1995). Error cannot be presented if there is only one paleo-pole in a time interval. Practically, there might be some blank intervals (especially for earlier ages before Middle Paleozoic) when reliable paleo-poles are sparse. Running means paths can be jerky with abrupt cusps and anomalously high migration velocities which can be caused by the combined uncertainties in age progression and paleo-pole positions. In such situation, spherical splines have proved to be able to retrieve the main features of apparent polar trajectory by averaging our random noises (Jupp and Kent, 1987). However, no errors are estimated from spline calculations.

In PMTec we implement a spherical splines algorithm originally presented by Jupp and Kent (1987) that has been widely used for constructing APWPs. One merit of this technique is that spline paths are anchored to the most reliable paleo-poles with higher weights (qualities) (e.g. Jupp and Kent, 1987; Torsvik et al., 2012). Weighting scheme for the algorithm evolves with time, primarily based on A_{95} (Torsvik and Smethurst, 1999), quality factor Q (e.g. Torsvik et al., 2001) or $7/Q$ (Torsvik et al., 2012). In PMTec, we use $7/Q$ for paleo-poles weighting. Different smoothing parameters S should be tested until visually satisfying paths are obtained. Generally speaking, smaller S produces less smoothed curve which sticks to input data points while larger S yields smoother curve that does not necessarily approach every poles.

2.2. Absolute plate motion reconstructions from APWPs

In plate tectonics, Euler rotations (a.k.a. rotation poles and angles), are well-established parameters to describe motion trajectory of the studied plate geometry in a designated reference frame (e.g. spin axis of the Earth) (Cox and Hart, 1986; Schettino, 2014). Before these parameters, the type of rotations at hands (finite or stage) have to be distinguished: finite rotations (or total rotations) rotate plates to and from their present locations while stage rotations describe plate motions during certain time intervals (Cox and Hart, 1986; Schettino, 2014). Plate reconstruction softwares such as GMAP (Torsvik and Smethurst, 1999) and GPlates (Boyden et al., 2011) use finite rotations which are derived from marine magnetic lineations and sea-floor fracture zones, geometries of hot spot tracks or paleomagnetic data. However, to provide paleolongitudinal constrains in the geographic reference frame, Wu and Kravchinsky (2014) recently formulate the methodology of deriving paleomagnetic Euler rotations (stage rotations) by fitting APWP tracks either with great circle or small circle modelling. In PMTec, we allow the conversion between finite and stage rotations by implementing the formulas summarized by Doubrovine et al. (2012). Moreover, PMTec also supports the use of finite rotations for plate reconstructions and kinematics calculations. Note that PMTec follows the protocol that positive signs are assigned to rotation angles of counterclockwise rotations for reconstruction purpose. Conversely, performing forward motions would require negative signs for the same rotations.

From stage rotations PMTec constructs a series of rotation matrices to perform rotations on the spherical Earth. During each rotation stages, paleolatitude corrections need to be applied to the calculations to ensure the paleo-colatitudinal consistency between reconstructions (strictly along circular segments centering the reconstruction poles) and corresponding paleomagnetic predictions. To this end, Wu and Kravchinsky (2014) suggest to use paleo-colatitudes defined in the geographic referenceframe to shift the positions of reconstructions along the great circle arcs (i.e. paleo-meridians) connecting paleo-poles (representing the spin axis) and reconstructions. The shifted reconstructions must preserve the spherical distances of paleo-colatitudes between reconstructions and the corresponding paleo-poles. Errors both for paleomagnetic Euler poles and resulting reconstructions are approximated by covariance matrix ellipses encircling 95% of bootstrapped data points which are assumed to follow Fisherian distribution. Readers are referred to Wu and Kravchinsky (2014) for detailed description of the methodology. The reliability of outcome reconstructions primarily depends on the quality of input APWPs and the rationality of APWP tracks fitting. Note that there might be undetectable plate motions during intervals when no apparent polar wandering is recorded.

3. PMTec toolbox presentation

3.1. Overview of PMTec

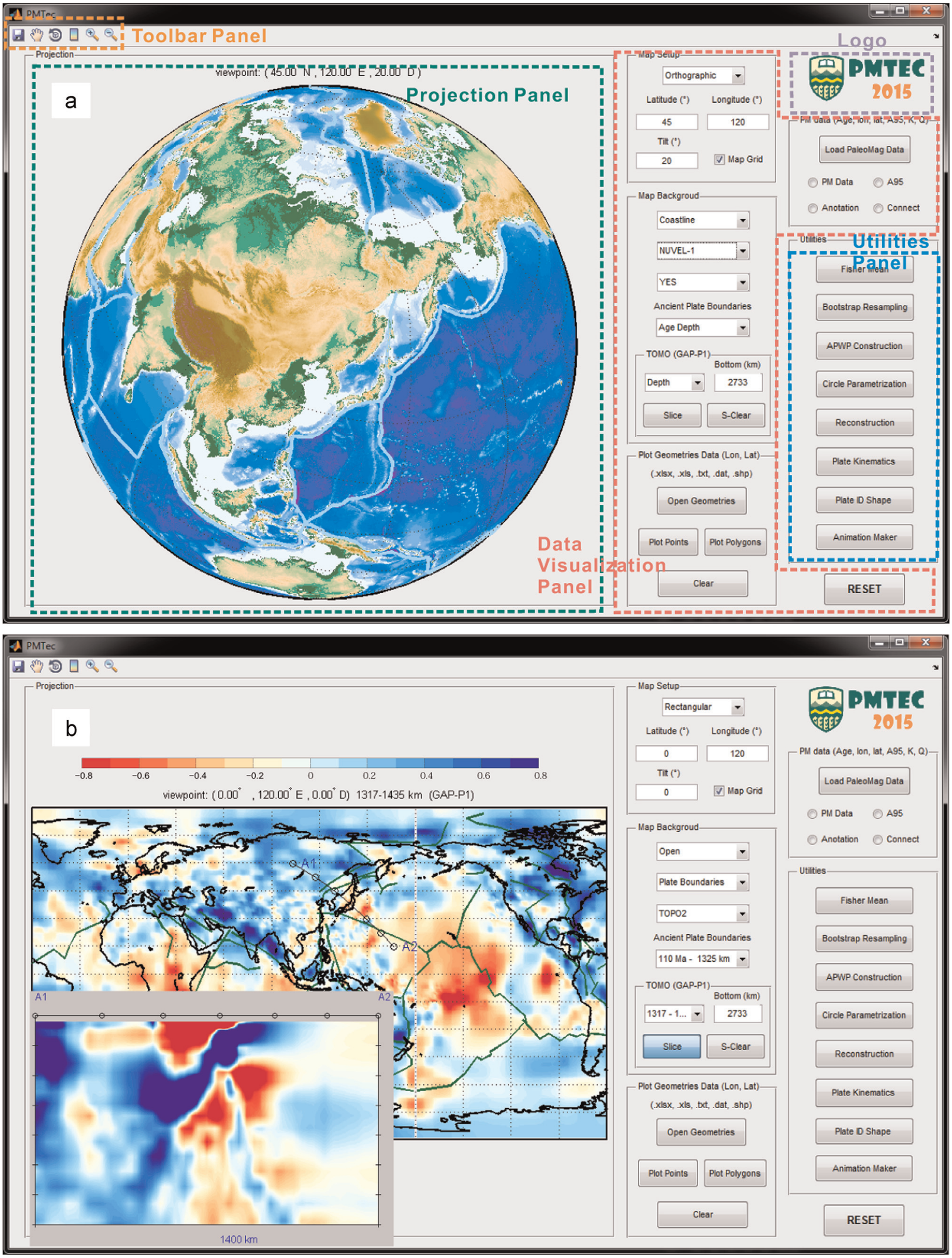
PMTec is developed and optimized on PC but can also be run on Mac and Linux systems. Table 1 lists the major functioning PMTec modules with brief descriptions. The main interface of PMTec is comprised of five panels (Fig. 1a): logo panel, projection panel, toolbar panel, data visualization panel and utilities panel. The projection panel interactively displays the imported paleomagnetic and geometry data with or without the plotting of background data on the specified map projection. Using the toolbar panel, users can manually adjust viewpoint, add/remove colorbar and save figures as editable *.pdf files. In the utilities panel (Fig. 1a), eight functioning modules can be called (1) to construct APWPs and derive paleomagnetic Euler rotations (stage rotations) from paleomagnetic data, (2) to perform absolute plate reconstructions using stage rotations or finite rotations, and (3) to visualize and export results in the format of MATLAB structure data. Detailed descriptions about each utility module will be made in the following subsections.

In the data visualization panel, users can select a series of popular mapping projections with desired viewpoint: mollweide, orthographic, robinson, mercator, sinusoidal and rectangular. For reference, present-day coastline, plate boundaries (DeMets et al., 1990; Bird, 2003), 2-min gridded global relief TOPO2 data (Hastings et al., 1999) and a whole mantle P-wave tomography (Obayashi et al., 2006) can be plotted in addition to input geometry or paleomagnetic data. Given the considerable amount of time to plot all the data from TOPO2, PMTec provides a lower resolution rendering by reducing the original dataset with a factor of four (Fig. 1a). To facilitate the effort of linking surface plate tectonics with mantle dynamic features (e.g. van der Meer et al., 2010, 2012; Torsvik et al., 2014), PMTec includes a set of ancient plate boundaries primarily defined in the subduction frame of van der Meer et al. (2010, 2012) (Fig. 1b). To allow for adjustabilities for these boundaries and reconstructions, PMTec also includes a whole mantle P-wave tomography model GAP-P1 (Obayashi et al., 2006) in the form of percentage velocity perturbations with respect to PREM (Dziewonski and Anderson, 1981). Derived from 7.4 million first arrivals reported to the International Seismological Centre (Obayashi et al., 2006), model GAP-P1 is recommended in PMTec because of its good resolution for large scale mantle features. Fig. 1b, for instance, shows the tomographic depth slice of 1317–1435 km (mid-mantle) where Neo-Tethys and Farallon slabs are clearly resolved under present-day southern Eurasia and east North America. From selected profiles PMTec is able to plot velocity perturbations in vertical cross-sections down to specified levels. (Fig. 1b). Fig. 1b inset, for instance, outlines the subduction zone in northwestern Pacific along profile A1–A2.

For an effective data and file management, a set of variables (system, input and output) are introduced here. Readers are referred to Table 2 for detailed descriptions of data organization, file format and usage (as input or output data for different modules) of each variable in PMTec. MATLAB structure array is widely used in PMTec because of (1) its capability of accessing string and numerical values simultaneously and (2) the memory efficiency during computation especially in bootstrap error estimates. In Fig. 2, the organizations of three most important structure variables in PMTec are illustrated. As the system variable, ‘StructData’ stores descriptions, references and numerical values of background data, including present-day plate boundaries and GAP-P1 tomography model (Fig. 2a). Additional fields are created in ‘StructData’ for potential data inclusions for future PMTec releases. Variable ‘RecSt’ stores most of numerical values involved in absolute plate motion reconstructions from paleomagnetism, including APWP tracks, Euler rotations, reconstructed plates and corresponding kinematic parameters (Table 2). In PMTec, users need to start with building a ‘RecSt.mat’ file, and proceed to fill in all the designated fields with subsequent computations (Fig. 2b) before transferring part of results to variable ‘PlateRec’ for data visualization (Fig. 2c). Alternatively, ‘PlateRec.mat’ files can be made from known finite rotations and plate geometries for reconstructions.

Table 1
Summary of the main modules of PMTec.

Module name	Development code	Brief description of the primary utilities
PMTec	PMTec	1. Plot the paleomagnetic and plate geometry data with(out) the background of plate boundaries, TOPO2 and the whole mantle P-wave tomography. 2. Call for the affiliated computation and visualization modules.
Fisher mean	PMTec_Fish	1. Calculate the Fisherian statistics for paleomagnetic poles or directional data.
Bootstrap resampling	PMTec_BootRes	1. Perform the bootstrap resampling for paleomagnetic or directional data.
APWP construction	PMTec_APWP	1. Construct APWP in form of running means and spherical spline. 2. Compute the APWP migration velocity, paleolatitude variation and rotation rates for the specified reference site.
Circle parameterization	PMTec_Euler	1. Fit the specified APWP tracks using great circle and small circle modelling.
Reconstruction	PMTec_Reconstr	1. Perform the absolute plate reconstructions using the estimated paleomagnetic Euler rotations. 2. Uncertainty estimation for the paleomagnetic Euler rotations and resulting reconstructions.
Plate kinematics	PMTec_PtKin	1. Calculate kinematic proxy parameters (absolute motion velocity, velocity components along the parallels and meridians, and paleolatitude and paleolongitude variations) for the specified reference site 2. Finite and stage rotation poles conversion. 3. Prepare the animation file ‘PlateRec.mat’ for the animation making.
Plate ID shape	PMTec_PlateID	1. Make shape file that can be used in GPlates.
Animation maker	PMTec_AniMaker	1. Make animation from the selected file(s) ‘PlateRec.mat’ and save the movie in form of *.mov or *.gif.



(a)

viewpoint: (45.00 N , 120.00 E , 20.00 D)

Map Setup: Orthographic

Latitude (°): 45

Longitude (°): 120

Tilt (°): 20

☑ Map Grid

Map Backgroud: Coastline; NUVEL-1; YES

Ancient Plate Boundaries: Age Depth

TOMO (GAP-P1): Depth; Bottom (km): 2733

PM data (Age, lon, lat, A95, K, Q)

Plot Geometries Data (Lon, Lat) (.xlsx, .xls, .txt, .dat, .shp)

(b)

viewpoint: (0.00° , 120.00° E , 0.00° D) 1317-1435 km (GAP-P1)

Map Setup: Rectangular

Latitude (°): 0

Longitude (°): 120

Tilt (°): 0

☑ Map Grid

Map Backgroud: Open; Plate Boundaries; TOPO2

Ancient Plate Boundaries: 110 Ma - 1325 km

TOMO (GAP-P1): 1317 - 1...; Bottom (km): 2733

PM data (Age, lon, lat, A95, K, Q)

Plot Geometries Data (Lon, Lat) (.xlsx, .xls, .txt, .dat, .shp)

Fig. 1. Screen shot of the main interface of PMTec, with the colored dashed boxes highlighting the main functionality panels. (a) Orthographic projection of NUVEL-1 plate boundaries (DeMets et al., 1990) (light blue lines) plotted on TOPO2 data grid with a reduction factor of 4 (Hastings et al., 1999). (b) Rectangular projection of a mid-mantle slice (1317–1435 km) using P-wave tomography model GAP-P1 (Obayashi et al., 2006), where Neo-Tethys and Farallon slabs are clearly resolved underneath present-day southern Eurasia and east coast North America. Also shown in the figure are ancient plate boundaries defined in subduction frame of van der Meer et al. (2010, 2012). Inset figure shows the vertical cross-section for profile A1–A2 from which the Pacific subduction is distinctly outlined. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Table 2
Description of the variables and data files used in PMTec.

Variable (file) name	Data organization	File format	Usage (Input/output)
Input data			
Paleomag (directional) data	(age, lat, lon, A95, K, Q)[a]	*.xlsx; *.xls; *.txt; *.dat	PMTec; PMTec_Fish; PMTec_BootRes; PMTec_APWP; PMTec_Euler; PMTec_Reconstr
Geometry data	(lon, lat)	*.xlsx; *.xls; *.txt; *.dat; *.shp	PMTec; PMTec_PtKin; PMTec_Reconstr; PMTec_PlateID
FitCtrl file	(pole1, pole2, GCdirS, SCdirS)	*.xlsx; *.xls; *.txt; *.dat	PMTec_Euler
PEP file	(lonE, latE, omega, npts, dirS, FC)[b]	*.xlsx; *.xls; *.txt; *.dat	PMTec_Reconstr

RecSt	f1 = [APWP tracks];
	f2 = [APWP tracks_transf];[c]
	f3 = [PEP; PEP_transf];
	f4 = [ref, ref_cor (ref_adj), (ref_cor)];[d]
	f5 = [plate (lon, lat)];
	f6 = [plate_cor (plate_adj)];
	f7 = [(plate_cor)];
	f8 = [age,Velo,LatV,LonV];[e]
	f9-f10: backup storage
		*.mat	PMTec_Reconstr; PMTec_PtKin;
			PMTec_AniMaker

APWPboot (DIRCboot)	f1 = [bootstrap directions (lon, lat)]; f2 = [(lonMean, latMean, A95, K)];	*.mat	PMTec_Reconstr
Finite rotaion file	(age, lon, lat, omega)	*.xlsx; *.xls; *.txt; *.dat	PMTec_Reconstr; PMTec_PtKin;
Stage rotaion file	(age, lon, lat, omega)	*.xlsx; *.xls; *.txt; *.dat	PMTec_PtKin

PlateRec	f1 = [ref];
	f2 = [plate];
	f3 = [age,Velo,LatV,LonV];
		*.mat	PMTec_PtKin; PMTec_AniMaker

Output data			
Fisher mean	(Dm, Im, α95, κ)	*.txt	PMTec_Fish
APWPboot (DIRCboot)	see above	*.mat	PMTec_BootRes

APWP	f1 = Running Mean [age,lon,lat,A95,K,npts];
	f2 = Spline [age,lon,lat];
	f3 = Running Mean [age,Plat,V,Rot,RotV];[f]
	f4 = Spline [age,Plat,V,Rot,RotV];
		*.mat	PMTec_APWP

Euler Single Fit	Fit = (lonGC,latGC,omegaGC,radiusGC, … lonSC,latSC,omegaSC,radiusSC, … npts, GCdirS, SCdirS, Vr, Critical Value)[g]	*.txt	PMTec_Euler

Euler Batch Fit	f1 = GC fit = (lon,lat,omega,npts,dirS,FC);
	f2 = SC fit = (lon,lat,omega,npts,dirS,FC);
	f3 = Fit
		*.mat	PMTec_Euler

RecSt file	see above	*.mat	PMTec_Reconstr intermediate calcs
BootAPWP	[bootstrap APWP; bootstrap APWP_transf]	*.mat	PMTec_Reconstr intermediate calcs
BootEuGC	f1 = GC bootfit = [lon,lat,omega,npts,dirS,FC]; f2 = GC bootfit = [lon,lat,radius,residual][h]	*.mat	PMTec_Reconstr intermediate calcs
BootEuSC	f1 = SC bootfit = [lon,lat,omega,npts,dirS,FC]; f2 = SC bootfit = [lon,lat,radius,residual]	*.mat	PMTec_Reconstr intermediate calcs

StrucEuAPWP	f1 = bootfit = [lon,lat,omega,npts,dirS,FC];
	f2 = [bootstrap APWP (lon, lat)];
	f3 = [bootEuler para; bootEuler para_transf]
		*.mat	PMTec_Reconstr intermediate calcs

BootEuAPWPnew	f1 = [Euler para_transf]; f2 = [APWP_transf]	*.mat	PMTec_Reconstr intermediate calcs

BootEuNewRG	f1 = [bootEuler para];
	f2 = [bootEuler para_transf];
	f3 = [bootEuler para_transf; bootEulerMean; Cov; GCD];[i]
	f4 = Uncertainty ellipses [bootEuler,bootEuler_transf][j]
		*.mat	PMTec_Reconstr

BootRec	f1 = bootstrap ref; f2 = bootstrap ref_transf	*.mat	PMTec_Reconstr intermediate calcs

BootRecRG	f1 = [bootstrap ref];
	f2 = [bootstrap ref_cor];
	f3 = [ref_cor;boot ref_cor Mean;Cov;GCD];
	f4 = Uncertainty ellipses [boot ref, boot ref_cor]
		*.mat	PMTec_Reconstr

Finite rotation file	(age, lon, lat, omega)	*.txt	PMTec_PtKin
Stage rotation file	(age, lon, lat, omega)	*.txt	PMTec_PtKin
PlateRec	see above	*.mat	PMTec_PtKin; PMTec_AniMaker
Shape file	(lon, lat)	*.shp	PMTec_PlateID
Movie	reconstruction animation	*.mov; *.gif	PMTec_AniMaker
Figure	saved figures	*.pdf	PMTec
Background data			
Plate boundaries	NUVEL-1 and PB2003 model	StructData140917.mat	PMTec
TOPO2	2-Minute Gridded Global Relief Data	ETOPO2.raw.bin	PMTec
GAP-P1	P-wave whole mantle tomography	StructData140917.mat	PMTec; PMTec_AniMaker

[a] Q – quality factor.
[b] dirS – sign for the rotation direction for reconstruction (+1 for counterclockwise and −1 for clockwise); FC – fitting code.
[c] APWP tracks_transf – transferred APWP tracks by closing later rotation(s).
[d] ref_cor – paleolatitude corrected reference site; ref_adj – modified reference site using the input finite rotations.

[e] Velo – absolute translation velocity for the reference site (cm/yr); LatV/LonV – velocities for the latitudinal/longitudinal movement (cm/yr).

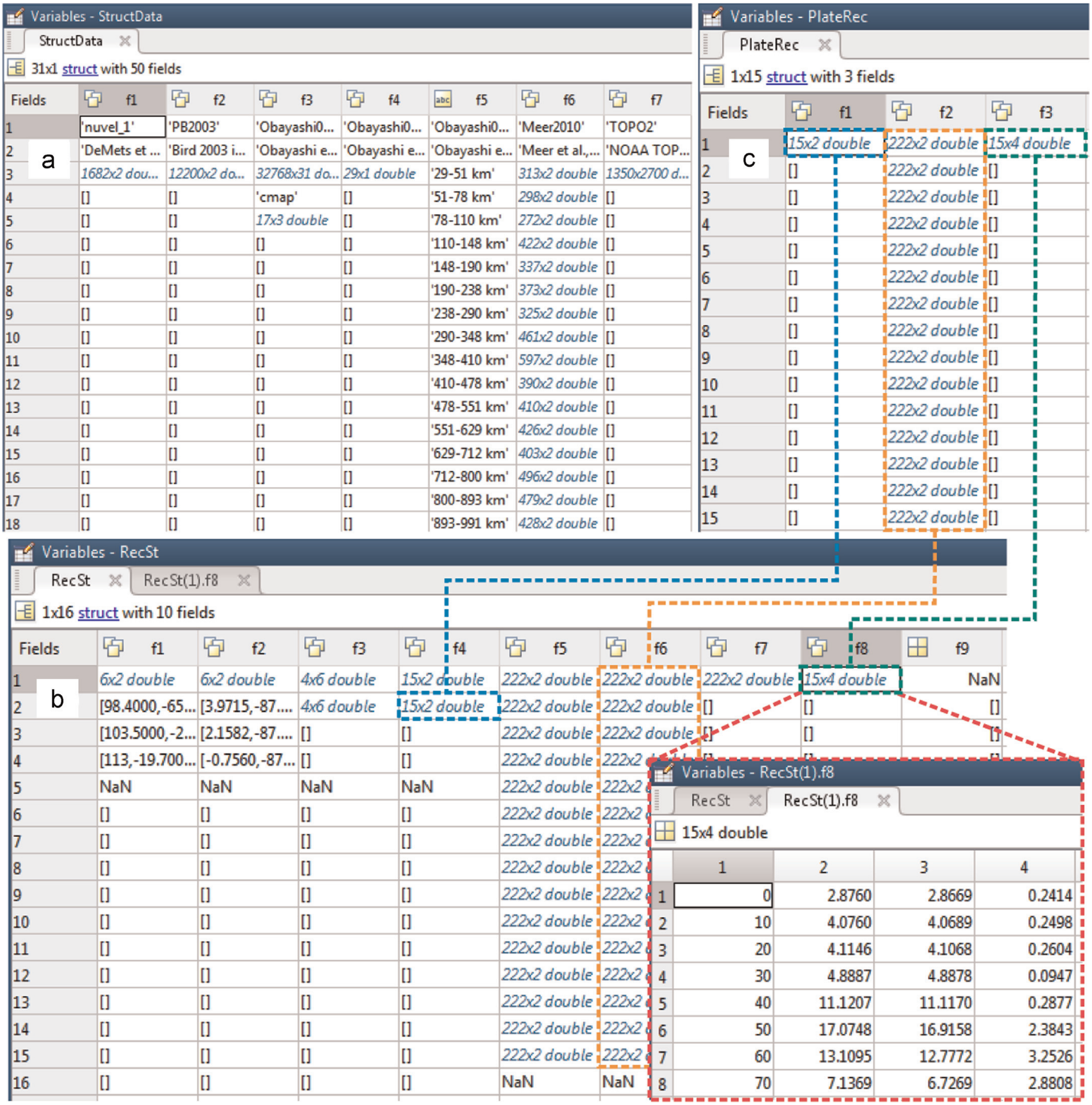
[f] Plat – paleolatitude variation for the reference site; V – migration velocity of the polar wandering (cm/yr); Rot – angular orientation for the reference site; RotV – rate of the angular rotation (°/yr).

[g] V_r – variance ratio; Critical Value – value of $F_{1,npts-3}$ at 0.05 significant level (see the definition in the Supplementary Text of Wu and Kravchinsky (2014)).

[h] residual-angular residuals for the circle fitting (see the definition of Gray et al. (1980)).

[i] bootEulerMean – Fisherian mean for the bootstrapped Euler poles; Cov – the 2 × 2 covariance matrix to represent the uncertainty ellipse at 95% confidence level; GCD – great circle distance between the Euler pole and bootEulerMean.

[j] uncertainty ellipses are in (lon, lat).



31x1 struct with 50 fields

Fields	f1	f2	f3	f4	f5	f6	f7
1	'nuvel_1'	'PB2003'	'Obayashi0...	'Obayashi0...	'Obayashi0...	'Meer2010'	'TOPO2'
2	'DeMets et ...	'Bird 2003 i...	'Obayashi e...	'Obayashi e...	'Obayashi e...	'Meer et al.,...	'NOAA TOP...
3	1682x2 dou...	12200x2 do...	32768x31 do...	29x1 double	'29-51 km'	313x2 double	1350x2700 d...
4	[]	[]	'cmap'	[]	'51-78 km'	298x2 double	[]
5	[]	[]	17x3 double	[]	'78-110 km'	272x2 double	[]
6	[]	[]	[]	[]	'110-148 km'	422x2 double	[]
7	[]	[]	[]	[]	'148-190 km'	337x2 double	[]
8	[]	[]	[]	[]	'190-238 km'	373x2 double	[]
9	[]	[]	[]	[]	'238-290 km'	325x2 double	[]
10	[]	[]	[]	[]	'290-348 km'	461x2 double	[]
11	[]	[]	[]	[]	'348-410 km'	597x2 double	[]
12	[]	[]	[]	[]	'410-478 km'	390x2 double	[]
13	[]	[]	[]	[]	'478-551 km'	410x2 double	[]
14	[]	[]	[]	[]	'551-629 km'	426x2 double	[]
15	[]	[]	[]	[]	'629-712 km'	403x2 double	[]
16	[]	[]	[]	[]	'712-800 km'	496x2 double	[]
17	[]	[]	[]	[]	'800-893 km'	479x2 double	[]
18	[]	[]	[]	[]	'893-991 km'	428x2 double	[]

1x15 struct with 3 fields

Fields	f1	f2	f3
1	15x2 double	222x2 double	15x4 double
2	[]	222x2 double	[]
3	[]	222x2 double	[]
4	[]	222x2 double	[]
5	[]	222x2 double	[]
6	[]	222x2 double	[]
7	[]	222x2 double	[]
8	[]	222x2 double	[]
9	[]	222x2 double	[]
10	[]	222x2 double	[]
11	[]	222x2 double	[]
12	[]	222x2 double	[]
13	[]	222x2 double	[]
14	[]	222x2 double	[]
15	[]	222x2 double	[]

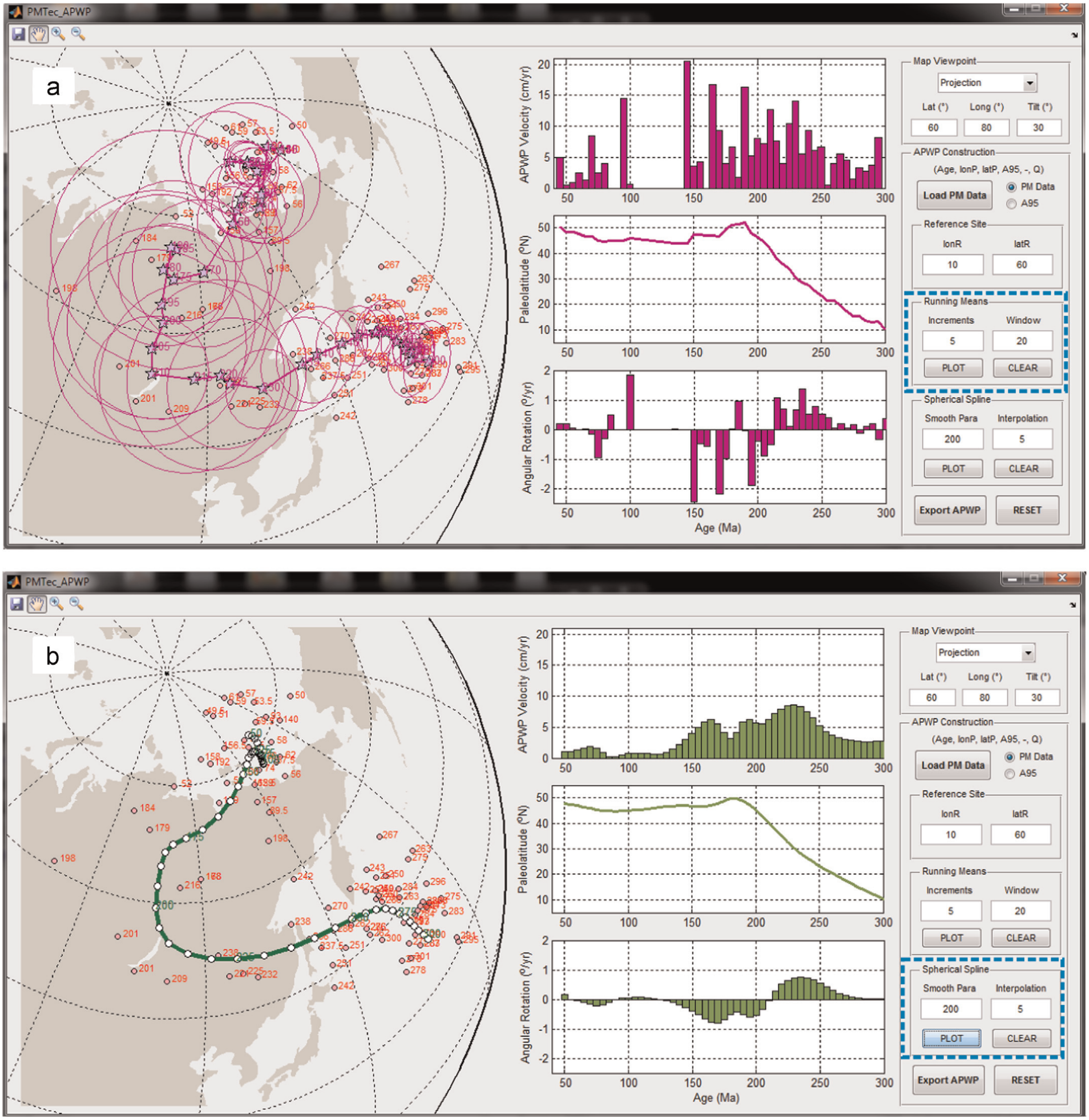
1x16 struct with 10 fields

Fields	f1	f2	f3	f4	f5	f6	f7	f8	f9
1	6x2 double	6x2 double	4x6 double	15x2 double	222x2 double	222x2 double	222x2 double	15x4 double	NaN
2	[98.4000,-65...	[3.9715,-87....	4x6 double	15x2 double	222x2 double	222x2 double	[]	[]	[]
3	[103.5000,-2...	[2.1582,-87....	[]	[]	222x2 double	222x2 double	[]	[]	[]
4	[113,-19.700...	[-0.7560,-87...	[]	[]	222x2 double	222x2			
5	NaN	NaN	NaN	NaN	222x2 double	222x2			
6	[]	[]	[]	[]	222x2 double	222x2			
7	[]	[]	[]	[]	222x2 double	222x2			
8	[]	[]	[]	[]	222x2 double	222x2			
9	[]	[]	[]	[]	222x2 double	222x2			
10	[]	[]	[]	[]	222x2 double	222x2			
11	[]	[]	[]	[]	222x2 double	222x2			
12	[]	[]	[]	[]	222x2 double	222x2			
13	[]	[]	[]	[]	222x2 double	222x2			
14	[]	[]	[]	[]	222x2 double	222x2			
15	[]	[]	[]	[]	222x2 double	222x2			
16	[]	[]	[]	[]	NaN	NaN			

15x4 double

	1	2	3	4
1	0	2.8760	2.8669	0.2414
2	10	4.0760	4.0689	0.2498
3	20	4.1146	4.1068	0.2604
4	30	4.8887	4.8878	0.0947
5	40	11.1207	11.1170	0.2877
6	50	17.0748	16.9158	2.3843
7	60	13.1095	12.7772	3.2526
8	70	7.1369	6.7269	2.8808

Fig. 2. Illustration of three cardinal structure variables for PMTec. (a) Data organization of system variable ‘StructData’. The first two rows of each fields are string values annotating data names and source publications, with numerical values starting from the third row. Fields after ‘f5’ are backup storages preserved for future PMTec releases. (b) Structure of variable ‘RecSt’, which stores APWP tracks, paleomagnetic Euler rotations, reconstructions (reference site and plate geometry) with/without paleolatitude corrections, and plate kinematic parameters. PMTec reads and writes data in file ‘RecSt.mat’ automatically during calculations. The inset figure shows the way to access structure variables, where ‘RecSt(1).f8’ is a MATLAB command to extract the first data row in the field ‘f8’ from variable ‘RecSt’. (c) Structure of variable ‘PlateRec’ for visualizing reconstructions made from stage or finite rotations. The dashed lines and boxes in blue, orange and green show the procedure to construct ‘PlateRec’ from ‘RecSt’. Readers are referred to Table 2 for field descriptions of the structure variables used in PMTec. The demonstration data here are the reconstructions of India since 140 Ma (Wu and Kravchinsky, 2014).



PMTec_APWP (a)

Map Viewpoint: Projection; Lat (°) 60; Long (°) 80; Tilt (°) 30

APWP Construction (Age, lonP, latP, A95, -, Q): ● PM Data ○ A95

Reference Site: lonR 10; latR 60

Running Means: Increments 5; Window 20

Spherical Spline: Smooth Para 200; Interpolation 5

PMTec_APWP (b)

Map Viewpoint: Projection; Lat (°) 60; Long (°) 80; Tilt (°) 30

APWP Construction (Age, lonP, latP, A95, -, Q): ● PM Data ○ A95

Reference Site: lonR 10; latR 60

Running Means: Increments 5; Window 20

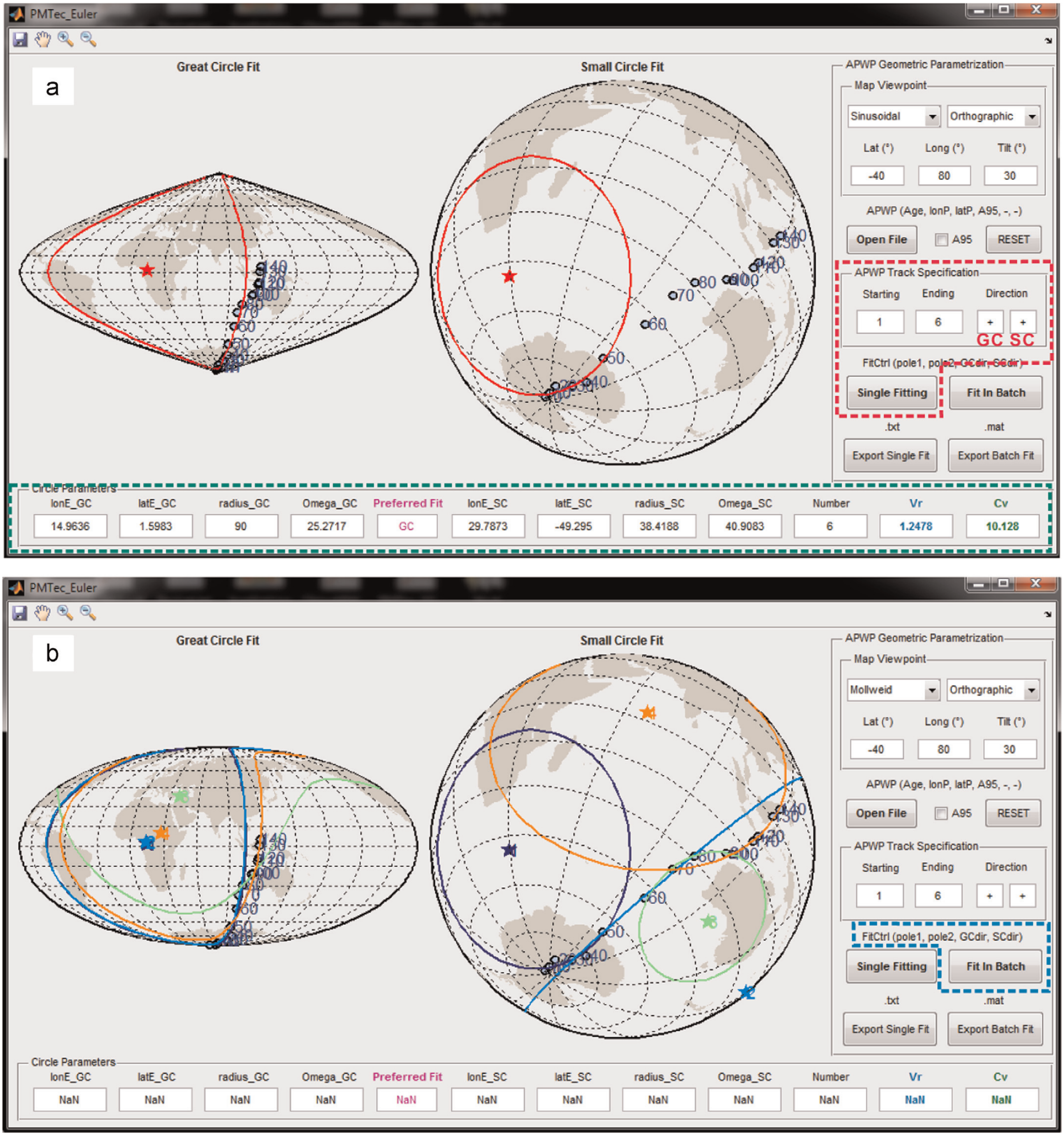
Spherical Spline: Smooth Para 200; Interpolation 5

Fig. 3. Utilities of the PMTec_APWP module. Except for running means (a) and spherical splines (b), kinematic proxies including APWP migration velocities, paleolatitudinal and azimuthal variations for an arbitrary reference site can also be computed in the module. European paleomagnetic poles (pink circles) are from Supplementary Table 1b of Torsvik et al. (2001). Blue dashed boxes mark the governing parameters for APWP calculations. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

3.2. From paleomagnetic poles to APWP

Unlike other paleomagnetic softwares such as PaleoMac (Cogné, 2003) and PmagPy (Tauxe et al., 2010) which are designed to process demagnetization and directional data, PMTec focuses on APWP constructions from available paleo-poles. In PMTec, users can calculate both running means and spherical splines from imported paleo-poles file, which must be prepared in the requested format (Fig. 3a, Table 2). Strict data quality assessment using Voo's scheme (Van der Voo, 1990) beforehand is a must to secure the quality of outcome APWP calculations.

Module PMTec_APWP calculates APWPs and correlated kinematic parameters, including APWP migration velocities, paleolatitude variations and rotation rate for a specified reference site. After loading the data file, users can selectively visualize paleo-poles and their errors (Fig. 3). For reference, all paleo-poles are automatically annotated with their ages specified in the first column of imported data file. For running means, various age increments (or steps) and time average windows can be tested for different smoothness of outcome path. In general, the smaller time



(a)

Map Viewpoint: Sinusoidal, Orthographic

Lat (°)	Long (°)	Tilt (°)
-40	80	30

APWP Track Specification

Starting	Ending	Direction	
1	6	+	+

FitCtrl (pole1, pole2, GCdir, SCdir)

Circle Parameters

lonE_GC	latE_GC	radius_GC	Omega_GC	Preferred Fit	lonE_SC	latE_SC	radius_SC	Omega_SC	Number	Vr	Cv
14.9636	1.5983	90	25.2717	GC	29.7873	-49.295	38.4188	40.9083	6	1.2478	10.128

(b)

Map Viewpoint: Mollweid, Orthographic

Lat (°)	Long (°)	Tilt (°)
-40	80	30

APWP Track Specification

Starting	Ending	Direction	
1	6	+	+

FitCtrl (pole1, pole2, GCdir, SCdir)

Circle Parameters

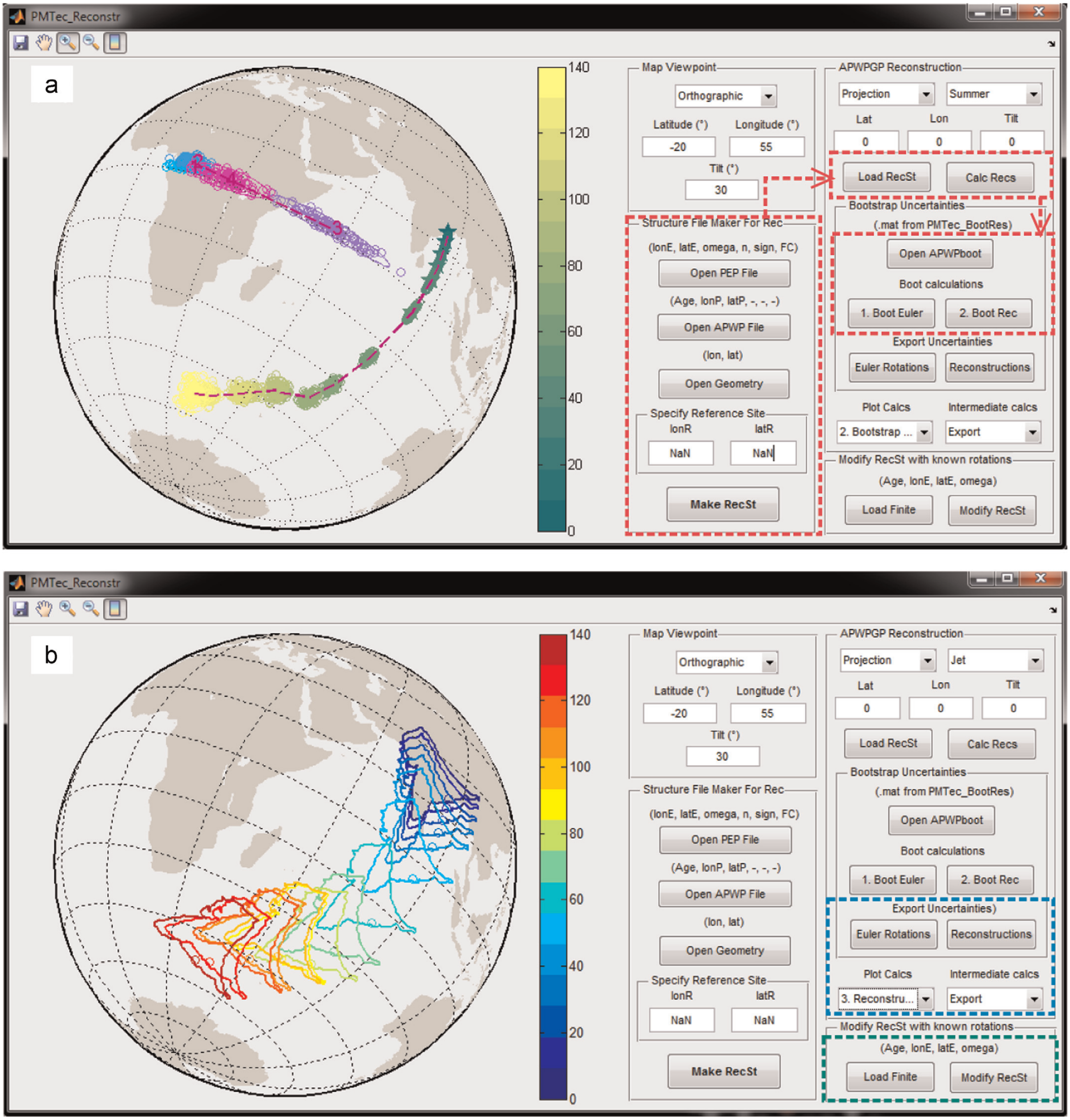
lonE_GC	latE_GC	radius_GC	Omega_GC	Preferred Fit	lonE_SC	latE_SC	radius_SC	Omega_SC	Number	Vr	Cv
NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN

Fig. 4. Euler rotations derivation under the module PMTec_Euler. The demonstration data is Indian APWP of 0–140 Ma presented by Torsvik et al. (2012). (a) Single APWP track fitting by specifying two ending paleo-poles and rotation direction (red dashed box). The text boxes beneath the projection panel (green dashed box) show the calculated circle parameters with the recommended fitting code after comparing variance ratio (V_r) and critical value (C_V) at 95% confidence level (Wu and Kravchinsky, 2014). (b) Concurrent circle fittings to several APWP tracks by loading control files 'FitCtrl' (blue dashed box). Outcome Euler parameters are exported as structure data file (*.mat). See Table 2 for the management of data and files involved in the module. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

windows are, the closer resulting paths are to input data. Similarly, users can specify smoothing parameter and interpolation age to obtain spherical splines with variant smoothness. Larger smoothing parameters tend to smooth outcome curves more. In addition, corresponding time-dependent kinematic proxies can be derived for an arbitrary reference site. All the calculations, i.e. running means, splines and APWP kinematics, are saved and exported as the structure variable 'APWP' with four fields (Table 2).

3.3. From APWP to tectonic plate reconstructions

Assuming that no true polar wander occurred during the studied time intervals, paleomagnetic Euler rotations can be derived by fitting APWP tracks using circle modelling. Paleo-poles at two ends and rotation directions for circle modelling (great circle and small circle) need to be specified for APWP tracks in the module PMTec_Euler (Fig. 4a). PMTec_Euler recommends the preferred fitting code by comparing variance ratio (V_r, significant improvement of small circle over great circle modelling) and critical value (C_V, value of F-distribution probability density function $F_{1,n-3}$, where n is the number of poles along the APWP track) at 95% confidence level (Wu and Kravchinsky, 2014). To accelerate the fitting process, PMTec_Euler allows concurrent circle modelling to several APWP tracks with an input fitting control variable 'FitCtrl'



(a)

Orthographic

Latitude (°): -20

Longitude (°): 55

Tilt (°): 30

lonR: NaN

latR: NaN

Projection: Summer

Lat: 0

Lon: 0

Tilt: 0

Plot Calcs: 2. Bootstrap ...

Intermediate calcs: Export

(b)

Orthographic

Latitude (°): -20

Longitude (°): 55

Tilt (°): 30

lonR: NaN

latR: NaN

Projection: Jet

Lat: 0

Lon: 0

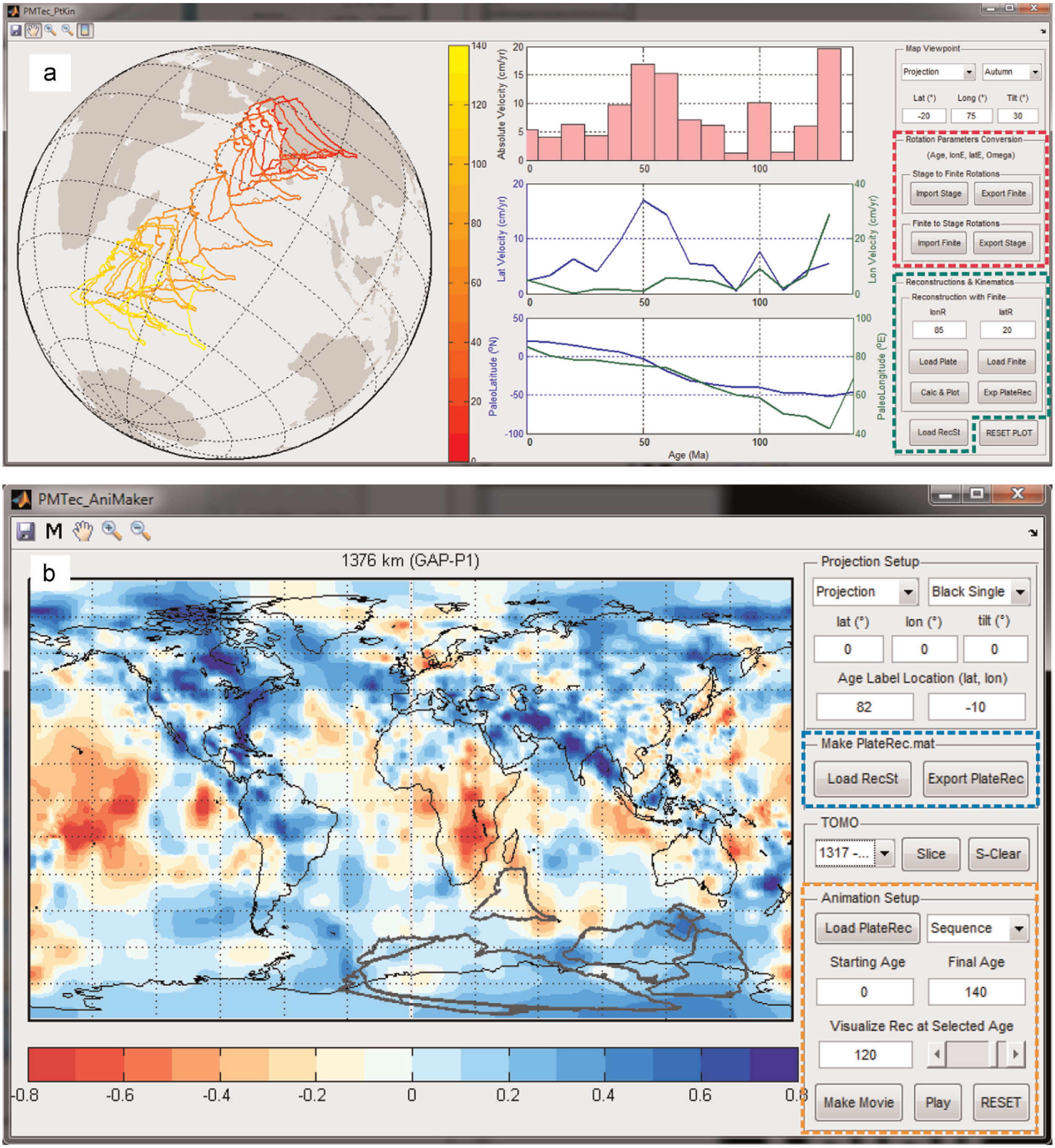
Tilt: 0

Plot Calcs: 3. Reconstru...

Intermediate calcs: Export

Fig. 5. Absolute plate motion reconstructions using the module PMTec_Reconstr. Reconstruction file 'RecSt.mat' needs to be prepared from paleomagnetic Euler rotations, APWP and plate geometry files in the required formats (Table 2). After loading bootstrap APWP file 'APWPboot.mat' produced in PMTec_BootRes, absolute reconstructions and corresponding errors can be computed (arrows among the red dashed boxes show the operation flow chart), visualized and exported (blue dashed box). Reconstruction file 'RecSt.mat' can be modified afterwards using input finite rotations if necessary (green dashed box). (a) Color-coded Euler poles (pentagrams with colormap 'cool') and reconstructions (pentagrams with colormap 'summer') for a reference site calculated from Indian APWP of Torsvik et al. (2012). Also shown are their corresponding error ellipses at 95% confidence level. (b) Restored Indian plate motion trajectory since 140 Ma shown with colormap 'jet'. See Wu and Kravchinsky (2014) for the detailed reconstruction procedure. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

(Fig. 4b, Table 2). The outcomes, i.e. great circle and small circle Euler parameters from batch fittings, are saved and exported in a structure variable (Table 2). Note that the fitting code recommended by PMTec is a statistical determination which is not necessarily the optimal fitting option. The optimal fitting code can only be determined when the resulting reconstructions are consistent with geologic and/or geophysical observations (Wu and Kravchinsky, 2014).



(a)

Projection: Autumn

Lat (°): -20 Long (°): 75 Tilt (°): 30

lonR: 85 latR: 20

(b)

Projection: Black Single

lat (°): 0 lon (°): 0 tilt (°): 0

Age Label Location (lat, lon): 82 -10

TOMO: 1317 -...

Sequence

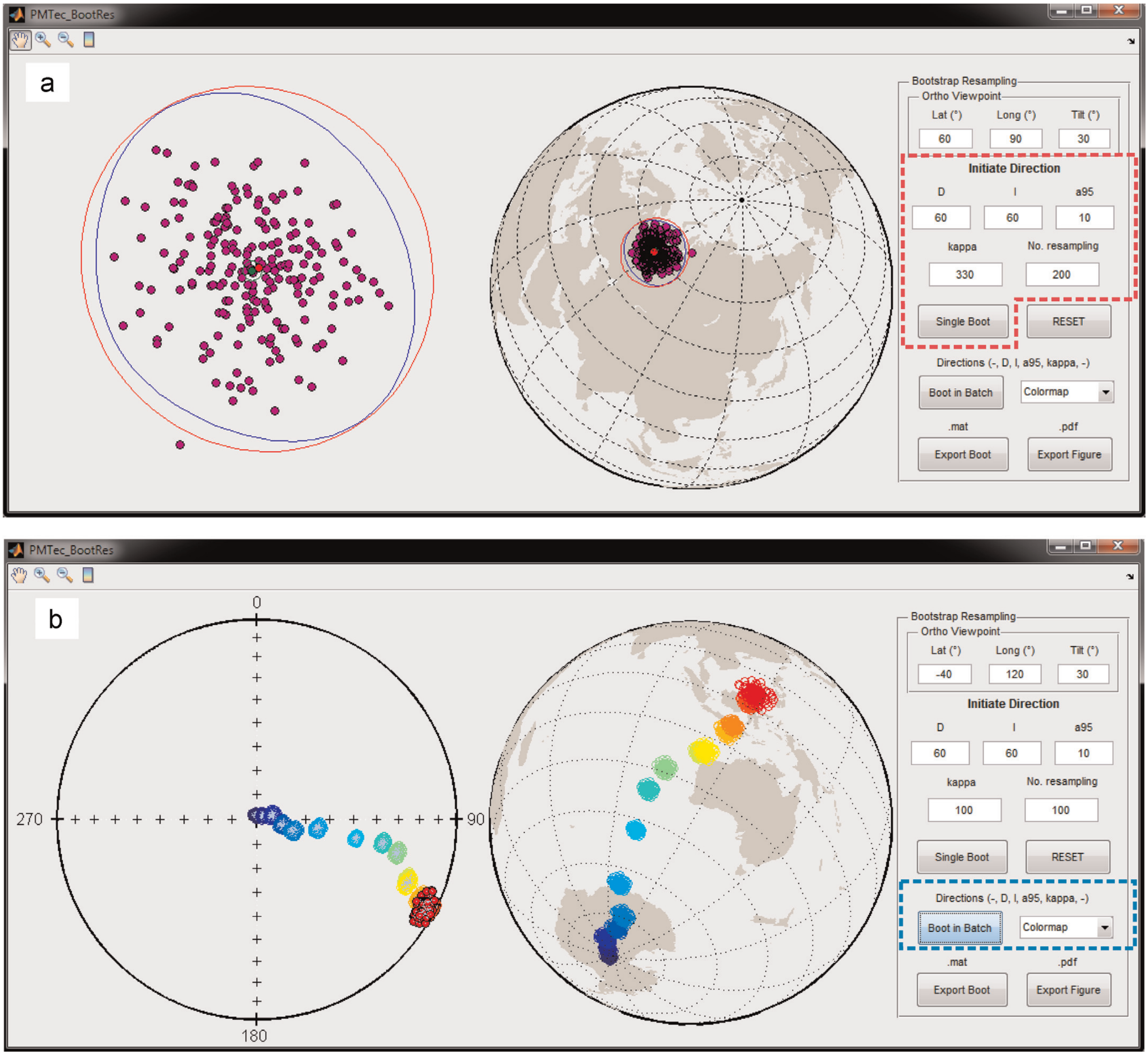
Starting Age: 0 Final Age: 140

Visualize Rec at Selected Age: 120

Fig. 6. (a) Functionality of the module PMTec_PtKin. Absolute motion velocity, component velocities (along parallels and meridians), and paleolatitude-paleolongitude variations for a reference site can be computed using reconstruction file 'RecSt.mat' or any known finite rotations for the input plate geometry (green dashed box). The figure shows kinematics of a reference point in India since 140 Ma determined from finite rotations of Mitchell et al. (2012). PMTec_PtKin allows the mutual conversion between stage rotations and finite rotations (red dashed box). (b) Snapshot of India, Australia and East Antarctica configuration at 120 Ma in the module PMTec_AniMaker. Calculations are made from animation files 'PlateRec.mat' that are produced in PMTec_PtKin using rotations of Mitchell et al. (2012). Animations, forward motions or backward reconstructions, can be made with (or without) plotting the tomography model of Obayashi et al. (2006) and then exported in the format of *.mov or *.gif (orange dashed box). 'PlateRec.mat' can also be prepared directly out of reconstruction file(s)'RecSt.mat' here (blue dashed box). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

PMTec_Reconstr is the core module to perform absolute plate reconstructions from paleomagnetic data. As is discussed in section 3.1, PMTec uses structure variable 'RecSt' to manage and manipulate all the data involved in the reconstruction process and error estimation (Fig. 2b, Table 2). Therefore, users need to start with making a 'RecSt.mat' file out of paleomagnetic Euler rotations, APWP and plate geometry files before calculations. PMTec automatically picks the first data point from geometry data file as the reference site which can be manually changed later. After obtaining reconstructions of all ages, error ellipses both for Euler stage poles and reconstructions can be estimated using an input bootstrap APWP file 'APWPboot.mat' (Table 2) generated in the module PMTec_Fish (Table 1). Fig. 5a illustrates the work flow to fill in the designated fields in 'RecSt' step by step. Bootstrapped Euler rotations and reconstructions as well as their uncertainties are saved in separate structure data files 'BootEuNewRG.mat' and 'BootRecRG.mat'. Intermediate calculations during error estimations are saved in variables 'BootAPWP', 'BootEuGC', 'BootEuSC', 'StrucEuAPWP', 'BootEuAPWPnew' and 'BootRec', which if necessary can be exported using the pop-up menu (Fig. 5b). See Table 2 for the detailed descriptions of these variables. In actual plate reconstructions, users may want to modify their reconstructions to produce more 'sensible' ones. This can be achieved by importing separate finite rotation files. The modified reconstructions are saved in field 'f6' of 'RecSt' with the original calculations being relocated to field 'f7' (Table 2).

Module PMTec_PtKin performs follow-up calculations to reconstruction files 'RecSt.mat' to obtain the kinematics of a



(a)

Bootstrap Resampling
Ortho Viewpoint
Lat (°) 60
Long (°) 90
Tilt (°) 30
Initiate Direction
D 60
I 60
a95 10
kappa 330
No. resampling 200
Directions (-, D, I, a95, kappa, -)
.mat
.pdf

(b)

Bootstrap Resampling
Ortho Viewpoint
Lat (°) -40
Long (°) 120
Tilt (°) 30
Initiate Direction
D 60
I 60
a95 10
kappa 100
No. resampling 100
Directions (-, D, I, a95, kappa, -)
.mat
.pdf

Fig. 7. (a) Representation of a single direction as a bootstrap Fisherian distribution (red dashed box). The original direction and its 95% uncertainty cone are shown as red dot and solid circle. The bootstrap directions are marked as magenta dots with the Fisherian mean (green dot) and error (green circle). Blue circle represents a confidence ellipse enclosing 99% of the bootstrap data. Bootstrap representations are considered reasonable when the 95% error boundary of the original direction (red) and the 99% confidence ellipse (blue) visually share the same tangent plane along the maximum ellipse axis. (b) Bootstrap resampling for Indian paleo-poles of 0–140 Ma (Torsvik et al., 2012) (blue dashed box), where kappa(s) in the input direction file are precision parameters estimated using the method illustrated in (a). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.).

reference site, including absolute motion velocities, velocity components along parallels and meridians, and time variations of its paleolatitude and paleolongitude (Fig. 6a). The outcome results are saved into field 'f8'. Moreover, PMTec_PtKin allows direct kinematic computation from the loaded plate geometry and finite rotations. To facilitate the comparison between rotations (or reconstructions) obtained from different techniques, we can convert between stage and finite rotations in PMTec_PtKin.

3.4. *Miscellaneous features*

PMTec provides two options to prepare animation files 'PlateRec.mat', one of which is through data export from reconstruction files 'RecSt.mat' in the module PMTec_AniMaker (Fig. 6b). PMTec_PtKin also allows an alternative way to produce animation files during the calculation of kinematic parameters from the input plate geometry and finite rotations (Fig. 6a). Before visualization, users must ensure the same dimensions for all input animation files (a.k.a. ages of reconstructions) in which calculations during 'blank' ages with no governing rotations must be filled with a row vector [NaN, NaN] in field 'f2'. PlateRec(rowID).f2 = [NaN, NaN], for instance, is a viable MATLAB command to modify field values in animation files. After specifying visualization sequence, i.e. backward reconstructions or forward plate motions, animation can be produced, played and exported in the format of *.gif or *.mov (Fig. 6b).

To estimate uncertainties for paleomagnetic Euler poles and reconstructions, PMTec_Reconstr needs an input file 'APWPboot.mat' (bootstrapped APWP) which can be generated in the module PMTec_BootRes. Following the methodology proposed by Smirnov and Tarduno (2010) and modified by Wu and Kravchinsky (2014), PMTec represents each paleomagnetic poles (together with errors A_{95}) in terms of discrete Fisherian distributions whose cluttering are determined by precision parameters (kappa). Bootstrap dataset is considered a reasonable representation of the original pole when the confidence ellipse enclosing 99% of the bootstrapped data is approximately tangent to the error of the pole along the maximum axis (Fig. 7a). Users need to determine sensible precision parameters for each poles before implementing bootstrap resampling for further error estimation (Fig. 7b).

Two auxiliary modules are provided in PMTec to assist paleomagnetic data processing for plate reconstructions. PMTec_Fish allows a quick computation of Fisherian statistics from paleo-poles or directional data. PMTec_PlateID can be used to produce and modify shape files using desired plate geometry parameters such as plate ID and valid period useful in GPlates.

4. Discussion and conclusions

Here we use published data to demonstrate some essential capabilities of PMTec for data processing and graphical representation. Fig. 3 illustrates the calculated European APWP in the forms of running means and spherical splines from the paleopoles compiled by Torsvik et al. (2001) (their Supplementary Table 1b). Figs. 4, 5 and 7b use the case study of India (Wu and Kravchinsky, 2014) to demonstrate the general procedure to implement the reconstruction technique. To illustrate the flexibility of PMTec in using finite rotations, Fig. 6 shows reconstructions and corresponding plate kinematics computed from the rotations of Mitchell et al. (2012).

For users' information, we feel obligated to enumerate the potential caveats in interpreting plate reconstructions obtained from PMTec. Firstly, the preferred circle fitting code to a specific APWP track is recommended from mathematic estimates, which does not necessarily lead to the optimal plate reconstructions (Wu and Kravchinsky, 2014). The sensible fitting code can be decided only when the outcome reconstructions are consistent with geologic, marine geophysical and seismic observations. To assist the correlation between plate reconstructions and mantle structures, a well-resolved whole mantle P-wave tomography model is embedded in PMTec. Secondly, there might be plate motions which cannot be resolved from paleomagnetic Euler poles derived from some APWP tracks (Wu and Kravchinsky, 2014). Such 'invisible' plate motions were usually made along paleo-parallels with respect to the Earth's spin axis when there is no recorded paleomagnetic polar wandering. As is discussed in Section 3.3, follow-up corrections can be made in PMTec to the reconstructions using known finite rotations.

To conclude, PMTec is a freeware for plate tectonic research and teaching purposes. The toolbox package, together with the tutorial document and data are available for download from http://www.ualberta.ca/~vadim/software.htm. Users are allowed to redistribute the software for non-commercial purposes. Please be aware that PMTec is originally developed in MATLAB 2013a and tested only in MATLAB 2014a. Problems might occur with MATLAB releases earlier than 2012b when MathWorks started to update syntaxes for some built-in functions. We choose to follow new syntaxes to facilitate the maintenance and update of PMTec. We encourage and welcome any bug reports, comments and suggestions for PMTec which will be considered for enhancement in future releases.

Acknowledgment

PMTec and the demonstration data to replicate our figures are available for download from http://www.ualberta.ca/~vadim/software.htm. Y.J. Gu is thanked for the selection of seismic tomography model. We appreciate the insightful comments from R.D. Müller and A. Schettino which largely improve the manuscript. The project was funded by the Natural Sciences and Engineering Research Council of Canada (NSERC) of V.K. and D.P.

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