

PLACA: a white box for plate reconstruction and best-fit pole determination[☆]

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Abstract

PLACA was developed as a general purpose computer program for the earth scientist that has to manipulate the rigid plate tectonics theory, from the representation of plate reconstructions to the determination of best-fit poles using magnetic anomalies, fracture zones or volcanic alignments. In the “forward” mode PLACA has the features of most available demonstration software plus the ability of simulating mid-oceanic ridges (MOR) as dynamic segments that move with a fraction of the relative motion between two plates. The movement can be illustrated by the generation of flow lines, plate trajectories and/or pseudo-magnetic anomalies on the ocean floor. The evolution of simple triple junctions of the R–R–R type can also be studied. In the “modifying” mode, best-fit poles can be computed either visually or by a systematic search routine. Five methods are available to evaluate the residuals between predicted and observed reconstructed points. Once the best-fit pole is obtained, several statistical tests can be done to evaluate the confidence on the fit. Surprisingly, the use of high-resolution geophysical data that are now available in the oceanic domain doesn’t always imply that the reconstruction poles are better constrained, as shown by an application example. Other examples presented document a discussion on the precision of plate reconstructions and suggest a few words of caution for the general user of PLACA.

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1. Introduction

The classical plate tectonics paradigm is based on three simple assumptions: (i) the external earth layer, the lithosphere, is solid and rigid and can move over a low-viscosity asthenosphere for geological times; (ii) the lithosphere is divided into a small number of domains,

the tectonic plates, and the deformation is concentrated at the plate boundaries; (iii) the movement of the tectonic plates over the spherical globe is described by rotations about Euler poles. The consequences of this approach have been explored in depth by the Earth Sciences and its simplicity captivated also the layman.

If plate rigidity seems to sustain a close inspection in most cases, the number of identified tectonic plates is increasing. The reason is the high-resolution geophysical data (gravity, magnetic, seismic, multibeam bathymetry) that has been recently collected on the oceanic domains. The interpretation of these data has shown that in some cases the large plates are formed by smaller plates that

[☆] Code on server at <http://www.ifremer.fr/drogm/Logiciel/index.htm>.

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weakly interact between each other and behave rigidly for long time periods (e.g. the Indo-Australian plate, Royer and Gordon, 1997; Royer et al., 1997). Does this mean that the closer we look, the smaller will be the blocks that make our tectonic plates? Or else, have we reached a limit where the resolution of our data reveals that intraplate deformation is widespread? How can we proceed under these circumstances?

The purpose of this paper is to present a computer program for plate tectonic modelling that can be used by earth scientists to address a wide number of problems. Graphical programs that are able to manipulate geographical features on the sphere using Euler rotations have been publicly available for quite a long time (for example Saunders et al. (1983) or Dagger (1989) and the references in the work of Schettino, 1998). These first public domain applications allowed for the simple forward modelling of plate motions, through reconstruction poles that were given beforehand or interactively during runtime. Other computer programs have been recently presented by Schettino (1998) and Torsvik and Smethurst (1999) (the GMAP package; <http://www.ngu.no/dragon>) to solve more complex problems involving paleogeographic reconstructions that are based on the analysis of paleomagnetic data and the construction of Apparent Polar Wander (APW) paths.

In comparison to GMAP, PLACA is not very user-friendly, as it is directed to the professional earth scientist, even if it can still be used for demonstration purposes. PLACA does not process APW paths on its current version, but in its “forward” mode it extends the capabilities of previous programs to the simulation of ridges and RRR triple junctions, to the generation of flow lines, pseudo-magnetic anomalies and plate trajectories. In the “modifying” mode PLACA allows the user to obtain best-fit poles from the analysis of fracture zones and magnetic anomalies. The visual fit method is performed directly on the screen through the selection of points to be superposed. Furthermore, PLACA reads and writes files that can be directly input to the GMT mapping routines (Wessel and Smith, 1991; GMT homepage. <http://gmt.soest.hawaii.edu>), making it an ideal companion for most of the problems involving plate kinematics.

PLACA cannot be confused with other computer programs developed for plate tectonic modelling. These were described for the first time by Ross and Scotese (1988) (see also: Schettino, 1999; Schettino and Scotese, 2001; http://earth.agu.org/eos_elec/010181e.html) and they are based on the definition of a rotation model. In this instance, relative positions of plates are not described with respect to a common reference frame, but are included in a tree structure whose root node is oriented independently according to paleomagnetic data or hot-spot tracks.

2. Plates and poles

The computer program PLACA, which means “Plate” in Portuguese and Spanish, was originally developed to make a practical illustration of plate tectonics at global scale. In PLACA each plate to be drawn is identified by the following attributes: name, sequential number, colour and a set of files containing geographic locations of plate polygons. The format of these files is plain GMT “psxy” text files, that is, sequences of (longitude, latitude) pairs divided by a line separator with the character “>”. To reduce the size and detail of the input files, they can be optionally truncated and/or decimated.

Relative positions of each plate in the geologic past must be defined in terms of total reconstruction poles (TRP) relative to a common fixed plate or reference frame and defined for a sequence of reconstruction ages.

If only stage poles are available, or the reconstruction poles do not have a common fixed reference, then they must be processed by the user before they can be input to PLACA. The mathematics of finite rotations is discussed in several books (e.g., Cox and Hart, 1986) and summarised in the work of Greiner (1999). The latter reference also provides programs that perform the basic operations required on Euler poles. We will mention though that the paradigm of rigid plate tectonics is only valid on an ideal spherical earth and so all geodetic coordinates are first transformed to geocentric and then to Cartesian coordinates inside PLACA. The pole coordinates are always considered to be geocentric coordinates.

3. General operation within PLACA

PLACA has two operation modes: (i) the forward modelling mode (or mode “t”), where the poles are kept constant; (ii) the modifying mode (or mode “m”) where poles can be changed by the user. Each simulation, in both modes, is described to PLACA by a set of parameters that are entered as a “parameter file” called *placa.in*. Most of these parameters have default values attributed by PLACA, and many of them can be changed during the simulation. When PLACA starts successfully, a graphic window opens on the screen and commands are communicated to PLACA through the mouse buttons or the keyboard. The ? key lists a simple description of the commands available. Some options require a dialogue to be performed either on the graphic window or on the text window used to start PLACA.

PLACA can display the geographic features using any of the following five projections: Plate Carree, Mercator, Stereographic, Orthographic and Hammer. Using the mouse or single letter commands the user can zoom-in

and out or move around the Globe. Oblique projections can also be used. Geographic features can be digitised directly from the screen using the mouse and their coordinates saved as a GMT “psxy” file that can be later included in other simulations.

We used PLACA and a simplified version of the contours of the plates and blocks involved to reproduce the closure of the North Atlantic Ocean as proposed by Olivet (1996) on his Fig. 12. The drawings presented in Fig. 1 show the two forms of output available, either the generation of a PostScript file from the data displayed on the screen (top panel), or the output of files in GMT psxy format that can be further processed by GMT commands (bottom panel). The top panel also

displays the relative velocity between Iberia and the Eurasia-Sud-Occ plate at the Nord-Gascogne basin. The Eurasia South Occidental block was introduced by Olivet (1996) to accommodate the intra-plate deformation required by the fit proposed. The user controls the size of the arrows and the velocity values are written on the screen.

4. Dynamic points and auxiliary segments

As a first extension to the basic abilities in mode “t”, PLACA was modified to compute the location and to plot one type of plate boundary, the mid-ocean ridges

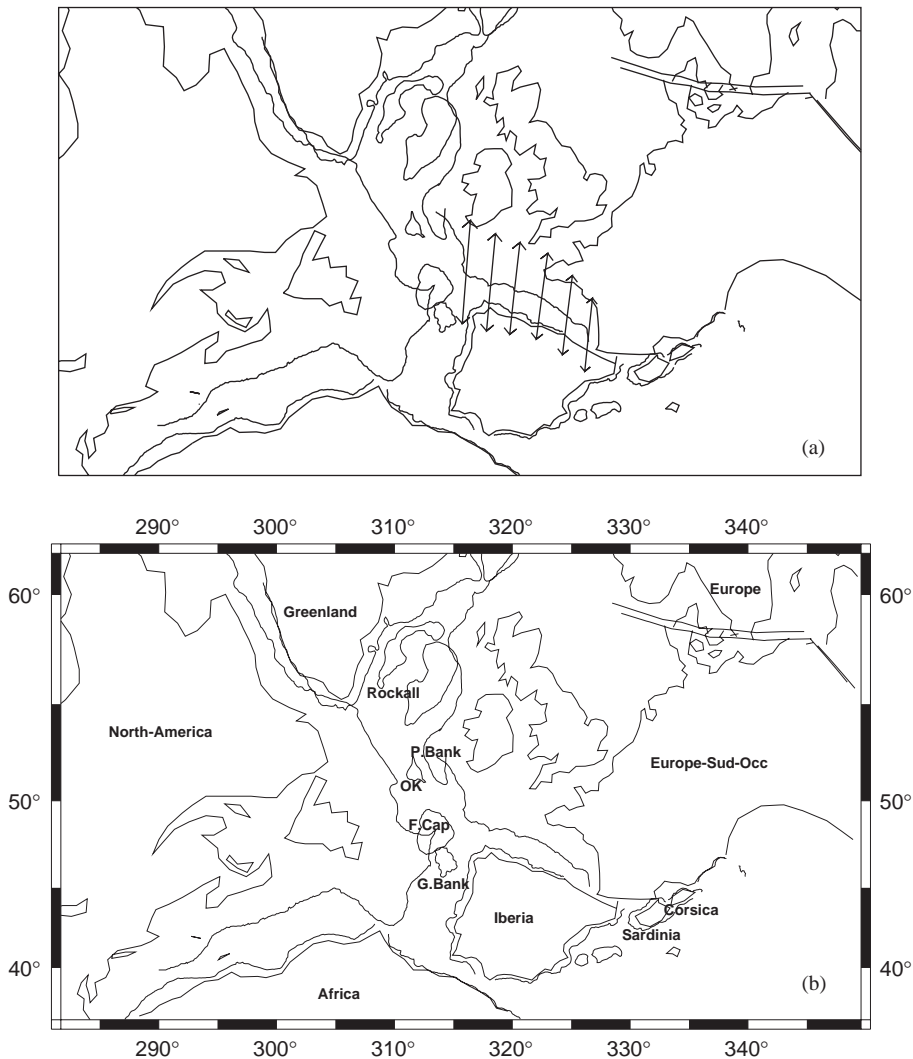


Fig. 1. Reproduction of plate reconstruction provided by Olivet (1996) on his Fig. 12 as produced by PLACA. (a) Hardcopy from a PostScript file that reproduces screen display. (b) GMT reproduction of output files generated by PLACA in psxy format. Legend: OK—Orphan Knoll, P.Bank—Porcupine Bank, G.Bank—Galicia Bank, F.Cap—Flemish Cap.

(MOR), generally referred as “dynamic points” (DP). These points are particular in the sense that they belong simultaneously to 2 plates and move apart with a velocity that is half or a fraction of the relative motion between the two plates. This means that a properly designed experiment can use DP to simulate the effects symmetric/asymmetric ridge spreading, and even stretching or compression. Another ability of the DP is that they may generate “auxiliary” points or segments on both plates when they move apart. These may represent pseudo-magnetic anomalies, the traces of pseudo-fracture zones, flow lines or trajectories of plates depending on the definition of DP velocity factors.

The India–Eurasia collision zone provides a good geodynamic framework to illustrate the use of PLACA in simulations of compression and strike-slip movements. This example was constructed from a schematic drawing of the continental blocks provided by Olivet and Mattauer (pers. comm., 1999). The reconstruction poles used in this simulation are only indicative of the relative plate motion and were obtained using PLACA in the “m” mode. Fig. 2 shows the 20 Ma frame of a “movie” that could be produced by telling PLACA to plot the plates from 40 Ma to the present with a 2 Ma time interval.

In the plot of Fig. 3, which illustrates the opening of the South Atlantic Ocean, “dynamic points” represent mid-ocean ridges that move with half of the relative velocity between the Africa and South America plates.

The user can also simulate the effects of asymmetric spreading. According to the type of points selected by the user, PLACA can produce synthetic magnetic anomalies (top panel), fracture zone trajectories (bottom panel), or a combination of these features (isochrons). The MOR points used in this example are a very crude approximation of the real structure and so the results shown are only an indication of the abilities of PLACA. For a given time interval where the relative motion between two plates is assumed to be constant, the DPs identified as ridges will draw small-circles about a stage pole. These flow-lines can be associated to symmetric or asymmetric spreading.

5. Evolution of RRR triple junctions

The evolution of ridge–ridge–ridge (RRR) triple junctions (TJ) can be represented in PLACA using an approach similar to the one proposed by Cronin (1992) and named TJ1 model. When one location of the TJ is known, its next position (either forward or backward in time) is obtained by the following strategy. All 3 segments in the TJ are initially moved like ordinary ridges. This will result in 3 new segments that will not intersect in a single point, but will have multiple intersections. Taking the 3 new intersections defined by each pair of segments (P_{12} , P_{13} and P_{23}), the next TJ coordinates are computed by the average of these points weighted by the relative velocities normal to each

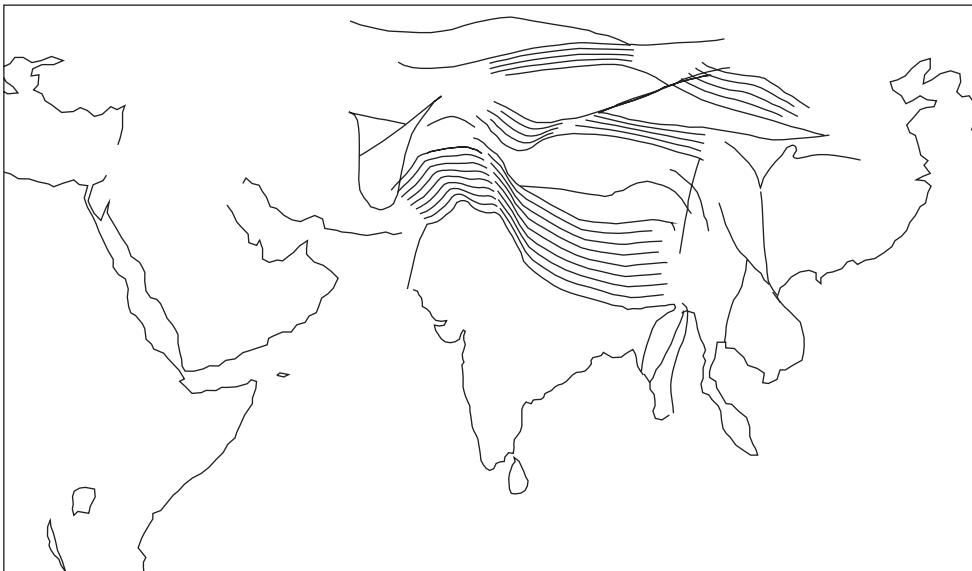


Fig. 2. Screen copy (as PostScript file) of a movie frame taken at 20 Ma using a simple model for India–Eurasia collision. “Dynamic points” defined between rigid blocks pretend to illustrate the compression in deformation fronts. Besides main plates, 6 continental blocks are used in simulation.

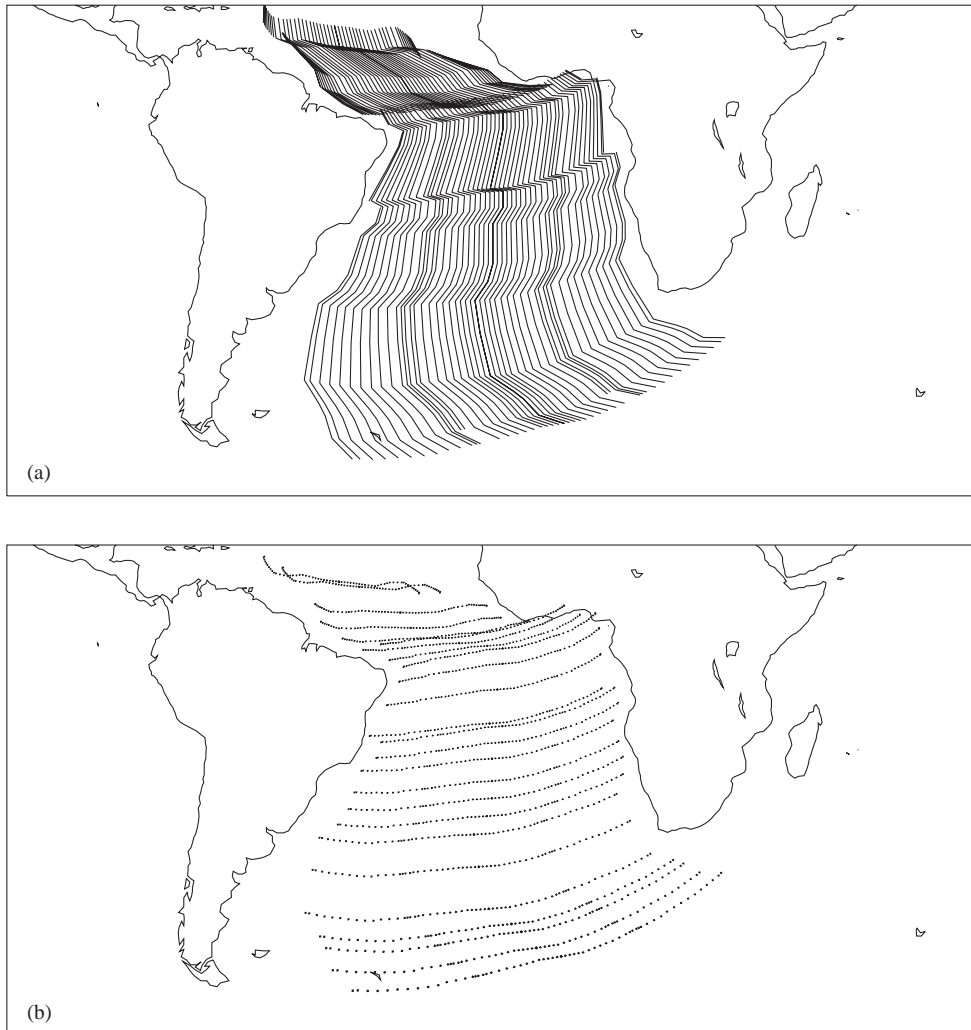


Fig. 3. Two different applications of “dynamic points” (DP) illustrated by opening of Central and Southern Atlantic Ocean. (a) DP represent mid-ocean ridges and generate pseudo-magnetic anomalies every 5 Ma. (b) DP represent fracture zones that leave its trace on each plate every 4 Ma. On both figures direction of movement and changes in velocity are clearly displayed. Poles used are from Cox, Hart (1986) and Srivastava et al. (1990).

segment. Fast segments have more weight in the computation and fracture zones are given a fixed weight of 0.1. During the evolution of a TJ, ridge segments can decrease/increase in length and rotate. Large accumulated rotations will imply the deletion of the segment and a definition of a new TJ. Very small segments are also deleted and very large segments resulting from the TJ evolution are split. Other developing rules and strategies could be designed to accommodate different TJ types or spreading environments.

The example shown in Fig. 4 represents a simulation of the possible evolution of the Azores Triple Junction that results from the poles compiled by one of us for

Eurasia and Africa in relation to North America. The trace for the Mid-Atlantic Ridge (MAR) and the Gloria Fracture Zone (GFZ) are taken from Bird (2003; Plate boundary model PB2002. <ftp://element.ess.ucla.edu/PB2002/>). The Pico Fracture Zone (PFZ) is taken from a simple interpretation of the bathymetry. The Azores Ridge (AR) is much less constrained and was estimated to lie between the main islands, crossing the S. Jorge Island.

We assume that the evolution of the TJ is controlled by the relative motion between Eurasia, Africa and N. America along the current plate boundaries, from the present to 19.5Ma (anomaly 6). After this time, the

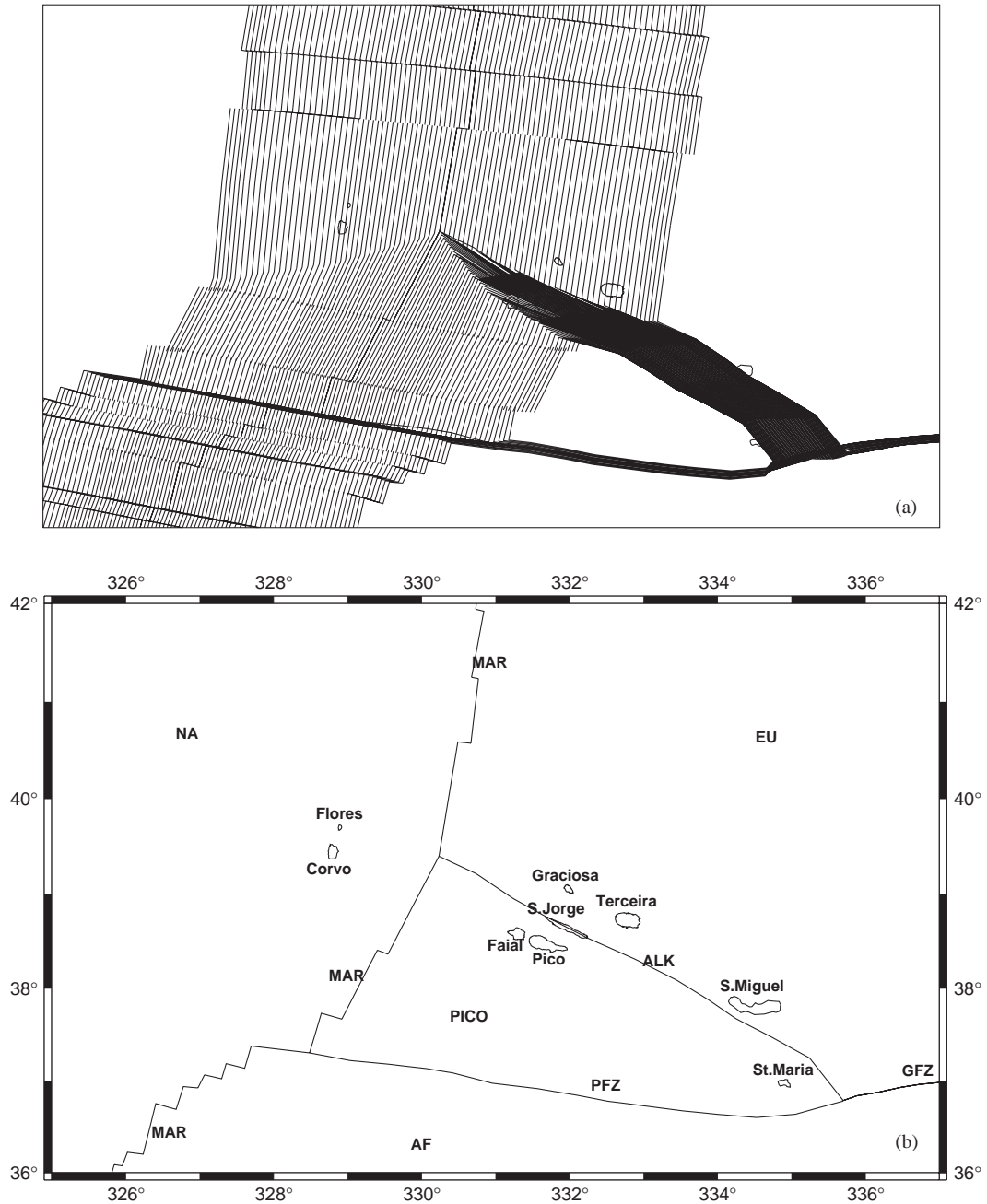


Fig. 4. Possible evolution of Azores Triple Junction (AZT) from 22 Ma till actuality. “Dynamic points” generate pseudo-magnetic anomalies every 0.5 Ma in (a). Main plates and geographical references mentioned in text are shown in (b): NA—North America, EU—Eurasia, AF—Africa, MAR—Middle Atlantic Ridge, AR—Azores Ridge, PFZ—Pico Fracture Zone, GFZ—Gloria Fracture Zone. From 22 to 19.5 Ma active AZT was in South, while PICO block moved with EU plate.

Azores Ridge ceases its role as a plate boundary and the TJ jumps to a point near the PFZ, south of the Azores archipelago. To accommodate this jump, a 4th plate is considered in the modelling, named the Pico plate, that

moves with Africa from anomaly 6 to present, and is attached to Eurasia before that. TJ trajectories on each plate can be inferred from the bends in the pseudo-magnetic anomalies.

6. Determination of best-fit poles

6.1. Parameterisation of fracture zones, magnetic anomalies and perturbing rotation

In the previous sections we presented the passive “tracing” mode of PLACA using a set of plate descriptions and a set of finite rotation poles given beforehand. In the mode “m”, the “modifying” mode, the user can compute the pole that performs the best fit between features on two sets of plates. The quantitative approach to this question was described by Royer and Chang (1991): “The problem is to estimate the unknown rotation A_0 that will bring in coincidence two contours on the sphere, and to define a confidence region for A_0 based on the uncertainties in the points forming the two contours. [...] the contours to be matched are conjugate isochrons from two plates. Isochrons are formed of magnetic lineation segments and fossil transform fault segments [...]”

In PLACA each set of isochrons is assigned to one plate only and it can be further divided into segments, so that the best-fit pole results from the sum of segment contributions composed by independent sets of points. The residuals between predicted and observed point/segment reconstruction can be evaluated by 5 different methods. Once the best-fit pole is obtained, several statistical tests can be performed to evaluate the confidence of the fit. We may stress here that assignment of points to particular segments is in many areas a difficult and subjective task. The consequences of an erroneous segment association on an estimation of the uncertainty of the best-fit pole are difficult to assess and normally ignored in the literature. With PLACA this task can be performed by careful and lengthy trial and error analysis using different segment assignments.

Under “m” mode the velocity factors defined for “dynamic points” gain a different meaning. Each pair of DPs defines a vector in relation to which we must assign a “left” plate and a “right” plate. In mode “m” the DPs are always attached to the left plate and the velocity factor of each segment (used in mode “t” to model ridge evolution) is known an identification tag used to make the separation between different segments. Positive integers represent fracture zones, while negative (or zero) integers are interpreted as magnetic anomaly picks.

To calculate the uncertainty of an estimated rotation, following the work of Chang et al. (1990), in PLACA any rotation A near the best-fit pole A_0 , can be described by the application of a small perturbing rotation $A = \Phi(\vec{u})A_0$. Two possible parameterisations can be considered within PLACA for this rotation, latitude, longitude, omega or the variable exponential $\Phi(\vec{u}) = \exp(M(\vec{u}))$, which represents a rotation around the vector $\vec{\omega} = \vec{u}/\|\vec{u}\|$ and a rotation angle $\rho = \|\vec{u}\|$. The statistical analysis implemented comprises the computa-

tion of the covariance matrix $[C]$ (on the chosen parameterisation), a systematic grid search to obtain the confidence interval for the pole location on the globe and the plot of confidence intervals in the perturbing space.

6.2. The merit function and the computation of uncertainties

If y_i represents the observed point and $y(x_i, \vec{a})$ the desired model location depending on point coordinates x_i and model parameters \vec{a} , the misfit between data and model is defined as $\delta_i = \sigma_i^{-1} \|y_i - y(x_i, \vec{a})\|_M$, where $\|\cdot\|_M$ represents one of the 5 methods to measure misfits allowed by PLACA and σ_i represents the a priori uncertainty (1-sigma) on data location.

The first three methods to measure the misfit (0), (1) and (2) are based on the principle of homologue points, that is, points that should be the nearest possible after reconstruction. The homologue points are selected according to a distance criterion. Only the nearest point of the same type and segment are selected as homologue. The number of degrees of freedom that have statistical significance with this method is the number of one-to-one connections established minus 3, the number of parameters defining the sought pole. The 3 methods differ only on the way distances are evaluated. Method (0) means that direct distance over the sphere is computed. Method (1) measures the distance parallel to the expected motion at ridges or normal to the motion at fracture zones. When oblique spreading ridges are present Method (2) combines the previous two: plain distance for magnetic anomalies and distance normal to motion at fracture zones.

The widespread method of pole determination by the criteria of Hellinger (1981) is implemented under PLACA as Method (3). This criterion is based upon the concept of best great circle to describe the alignment of points belonging to the same segment from two different plates. The difference to the homologue approach is that points very far away can be correctly fitted to a great circle. In this method the unknowns to be determined are the best-fit pole (3 parameters) plus the $2N$ parameters defining the N best great circles, one for each segment. This means that the total number of degrees of freedom is, for M points and N segments, $Ndf = M - 2 * N - 3$.

Once the best great circles are computed for each configuration, the errors are simply the distance from each point to its great circle segment, without any consideration to homologous points. Also, the great circles that are computed for fracture zones, which in theory should be oriented along small circles around the rotation pole, can have any orientation, depending only on the distribution of points used in the reconstitution. This feature suggested a small refinement to Hellinger

method, evaluating the errors for the fracture zones according to the predicted small circles parallel to relative plate motion (Method (4)). Being more close to the physical model of plate tectonics, this correction does not overcome the other limitations of the Hellinger method.

The contribution of all misfits is accumulated for a given pole solution as an L1-norm (sum of absolute values of errors) or L2-norm (sum of the squares of errors). The merit function defined by the L2-norm is also designed as χ^2 and can be used to define confidence intervals near the best-fit pole, under some regularity conditions (see Press et al., 1992). PLACA uses a systematic search routine to output the merit function χ^2 on 3 planes. These outputs can then be processed and plotted by GMT.

Using the value of the merit function, the user can evaluate the quality of the current fit or start a systematic search around the current pole. In this approach, a small volume of the parameter space is explored and its radius can be interactively reduced until there is no more improvement on the fit. This step-by-step procedure can be also automated through a specific PLACA command. The convergence criteria are given by user-defined parameters.

6.3. The “visual” fit method of Olivet (1978) and Bonnin (1978)

This method is based on the existence on each plate of unambiguous homologous points, defined by geological criteria that must have coincided in the moment of their formation. These can be the intersection of a magnetic anomaly with a fracture zone, the termination of volcano alignments, the bending point of fracture zones due to the change of relative movement, or other features. Any other additional constraint can then be used, geological, contoured anomalies, etc. The visual fit is obtained by the application of two simple rotations: the first one puts the homologous points in coincidence using a pole defined by the great circle that joins the 2 points on the sphere; the second rotation has its pole on the homologous point and the rotation angle is visually defined by the fit of the desired features. Within PLACA this method can be applied interactively on the screen. The first rotation (keyboard command “t”) is defined by two mouse clicks on the homologous points, and the second rotation is defined by three clicks, the first on the homologous point, that becomes the Euler pole, and the other two to define the rotation angle. In addition, relative poles (to be added to the current pole) or total reconstruction poles can be also given numerically on the keyboard. The current pole is always displayed and the new poles can be saved into PLACA and then later to a file. The “visual” method for best-fit determination is the only one that can take into consideration field

observations like lineaments, volcanic outcrops, continental structures, sedimentary basins, evaporites distribution, contoured magnetic anomalies, etc.

7. Examples of best-fit pole determination

7.1. The relative position of India and Africa at anomaly 5

We illustrate the use of PLACA in determining best-fit poles by applying it to the data published by Royer et al. (1997) concerning the reconstruction of the India and Africa plates at anomaly 5 (11 Ma). The 1–sigma error attributed to magnetic anomaly and fracture zone crossings is 5 km, close to the average of the variable error defined by the authors. Fig. 5 shows the results obtained from the direct application of Hellinger (1981) method to the data of Royer et al. (1997). The segmentation of the data and their contribution to the overall misfit can be directly appreciated on the screen. With high-resolution data, as the one in the example, only automatic merit functions can make the difference between two apparently equivalent visual fits.

The confidence regions of the Euler pole between India and Africa at anomaly 5 are represented in Fig. 6 using the exponential parameterisation ($x/y/z$) for the perturbing rotation. The solution obtained by PLACA and its precision are very close to the ones published by Royer et al. (1997). Different methods used to evaluate the merit function generate solutions that are inside the confidence region obtained from the Hellinger method. However, it is clear that this method needs both magnetic anomalies and fracture zones to give meaningful solutions. We verify also that the systematic search takes into consideration some of the non-linearity of the “best-fitting” problem and shows a volume for 95% confidence that is at least two times larger than the one obtained by the covariance matrix approach.

7.2. “Absolute” movements

To determine the best-fit pole for one plate from the alignment of volcanoes (i.e. the determination of the so-called absolute pole in the plume reference frame) we can use the method (4) described above. Even in the absence of the second plate, if we translate the volcanic alignments into PLACA as fracture zones, a best-fit pole can be obtained and its uncertainty estimated since the merit function includes the distance of each volcanic cone to the respective small circle.

A few years ago, Wessel and Kroenke (1997) presented an age-independent method, “hotspotting”, to refine absolute plate motions and relocate extinct hotspots. Using this essentially geometric technique, they proposed a new stage pole (25°N, 27°W) for the

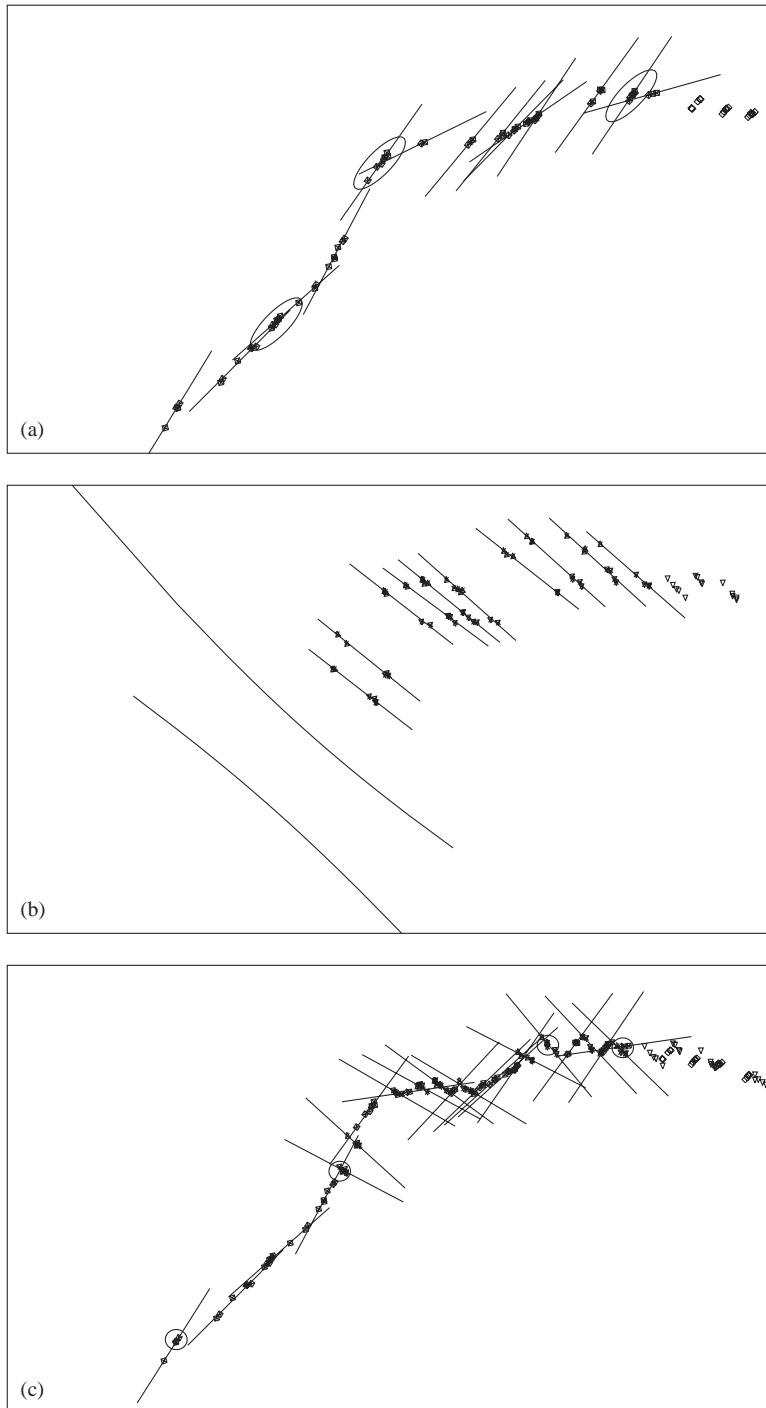


Fig. 5. Results of "best fitting" pole between India and Africa at anomaly 5 (11 Ma), using method of Hellinger (1981) for magnetic anomaly and fracture zone data of Royer et al. (1997). In this method best pole is computed at same time as great circles that join magnetic anomaly and fracture zone crossings from both plates for each segment defined. (a) Data, great circles and confidence regions (95%) for each point in the moving plate (India in the example) when only magnetic anomalies are used. The uncertainty of location along anomaly direction is very large. Confidence region of reconstructed points is estimated by rotating that point with a pole that follows border of confidence region for best-fit pole. (b) Same results as above when only fracture zone crossings are used. The method of Hellinger makes the FZ migrate from each other to reduce the misfits. As a consequence pole obtained is obviously wrong and uncertainty areas are so large that they cannot fit in area of the plot. (c) Same results as above when both magnetic anomalies and fracture zones are used. Confidence regions for reconstructed points are clearly smaller than ones in (a).

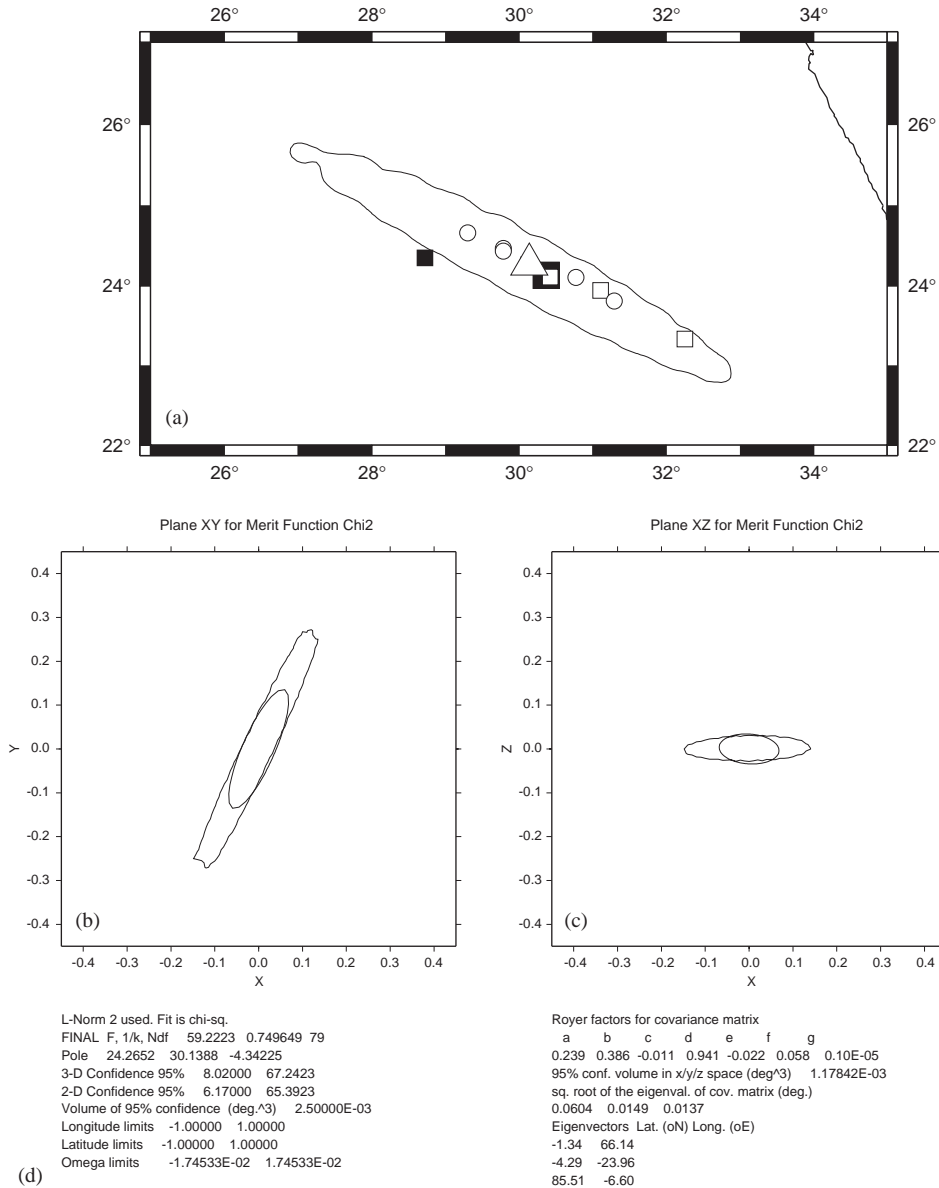


Fig. 6. Statistical analysis and confidence regions for Africa–India pole obtained previously. All drawings were produced by GMT (Wessel and Smith, 1991; GMT homepage. <http://gmt.soest.hawaii.edu>) using output files generated by PLACA. (a) 95% confidence region plotted over sphere for Hellinger method that produced pole represented by large triangle. Large dark square is solution by Royer et al. (1997); small dark square is solution obtained when only magnetic anomalies are used. Same solution for fracture zones is outside drawing limits. White boxes are solutions produced by different ways of computing merit function, using L-2 norm (see text for explanation). White circles are same for L-1 norm. (b) and (c) plots of 95% confidence region in perturbing rotation domain parameterised by an exponential rotation. Irregular shapes result from systematic search while ellipses result from covariance matrix computed by PLACA. (d) Example of output written to text window and to file when final systematic search is executed. Meaning of some parameters is found in Royer and Chang (1991).

most recent hotspot tracks to take into account of the recent bend of the Hawaiian chain and to relocate the present Louis hotspot to the Hollister Ridge, in contradiction to available geochemical data and most Pacific alignments of age < 5 Ma. Aslanian et al. (1998) show

that, in order to fit those alignments and the bend of the Hawaiian chain (if it is significant and not a local structure), the pole must be located at 57°N, 260°E, that locates the Louisville hotspot near a 0.5 Ma old volcano known to have a Louisville isotopic signature.

Fig. 7 illustrates how to use this option: first we digitised directly on the screen a set of volcanic alignments (Fig. 7a); Fig. 7b shows the volcanic alignments used in the best-fit pole determination and the final small circles drawn after the Wessel and Kroenke (1997) pole and the pole calculated with PLACA (57.13°N, 266.97°E); Fig. 7c shows the 95% confidence region produced from a systematic search for the PLACA pole and the location of the other poles. Note that the Wessel and Kroenke (1997) pole is far away from this confidence region and could not be plotted in this geographic box.

8. The meaning of precision in plate reconstructions

The example presented in Section 7.1 showed that using the same source data, magnetic anomaly and fracture zone crossings, but applying different methods and/or error estimates to the data, we may obtain best-fit poles and confidence regions that are not coherent at the 95% confidence level. This variability cannot be truly assessed by the propagation of a priori or a posteriori errors in the data (assumed as random) to the final best-fit pole. When more high-resolution geophysical data become available, the uncertainties in the estimated best rotation can be no longer considered as an exclusive function of data uncertainties. Since model uncertainties are much more difficult to evaluate, PLACA, providing a number of tools to obtain the best-fit pole, can be used to evaluate the consequences of these hidden uncertainties.

To illustrate this point we performed the following exercise. One of us used bathymetric, magnetic and gravity data from in the Equatorial Indian Ocean (Sandwell and Smith, 1997; Smith and Sandwell, 1997; Predicted Topography. http://www.ngdc.noaa.gov/mgg/announcements/announce_predict.html) to draw a few ship tracks similar to the ones that are currently used to obtain the magnetic anomaly and fracture zone crossings data. The actual ridge and fracture zones were irregularly sampled by this method, and the points obtained, were attributed either to the African or the Indian plates. Then, a simple rotation was applied to one of the data sets. The error in sampling using large-scale maps is estimated to be 3 km. The purpose of the exercise was to recover the original rotation, using the best-fitting procedures of PLACA.

The results are shown in Fig. 8. An apparently well-constrained solution is obtained, as shown by the size of the 95% confidence regions plotted. However, different methods and L-norms used to evaluate the merit function give, by systematic search, best-fit poles that are at the border, or even clearly outside the confidence region computed for the Hellinger criteria. Moreover, the original rotation pole used to build the exercise is

also outside this confidence region, for an estimated 2.5 km a priori error. It is clear that the statistical model that describes the data can fail in an unpredictable way and our best-fit solution, even if coherent and well constrained, can be wrong at the 95% confidence level. It is worth noting that this exercise was simplistic, without any intraplate deformation considered.

In reality, the geophysical data has not such a high level of precision as in the previous exercise, they suffer from geographical location errors but also from non-quantifiable uncertainties as the definition of anomalies and segments, heterogeneity, etc. Even in the ideal case presented by Sloan and Patriat (1992) (high-resolution magnetic survey, homologous anomalies, short and young segments without intraplate deformation), the fit between anomalies is difficult to attain. Fig. 9 shows that the misfits still persist. These errors may result from an unknown factor in the data and/or from geological causes such as deformation and asymmetric spreading occurring at the moment of crust emplacement at the ridge. We may question then if it makes sense to try to eliminate completely these errors (smaller segments for example)? What is the contribution of data noise to the fit of Klitgord and Schouten (1986) (Fig. 9), which was based on a global study? Are we at risk of interpreting noise as signal in fitting magnetic anomalies?

The quantitative approach developed in PLACA for determining best-fit reconstruction poles from isochron data follows the usual procedures found in the literature (e.g. Klitgord and Schouten, 1986; Royer and Chang, 1991; Royer and Gordon, 1997; Royer et al., 1997; Sloan and Patriat, 1992; Srivastava et al., 1990) where only two or three plates are studied together in a small area. One way to avoid the pitfalls discussed in the previous paragraphs might be the inclusion of the studied area in a consistent rotation model (at regional or global scale), which would take into account the whole dataset and not only a few isochron segments (like the approach followed by DeMets et al. (1990) for the determination of the current plate motions).

9. A few words of caution

During the last two decades we have seen an enormous improvement of the quality, coverage and resolution of geophysical data. This data availability has allowed many earth scientists to perform plate reconstructions at a scale and detail never attained before. However, one must bear in mind that the plate tectonics paradigm is based on strict geometrical foundations. This means that “high-resolution” reconstitution poles, obtained from very detailed studies on a small region of a plate boundary, must be validated by examining its consequences in all parts of the plate. If this test is not performed, then the validity of the poles obtained will be

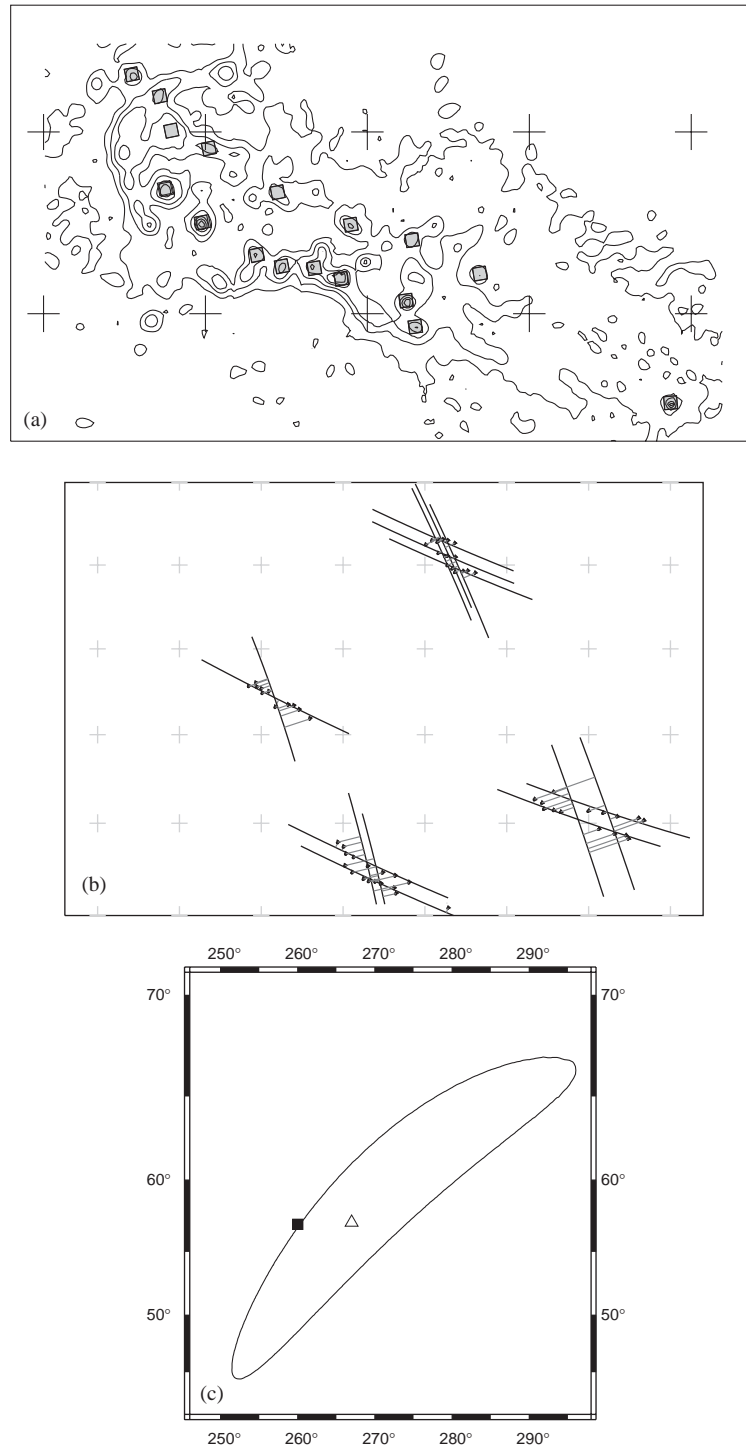


Fig. 7. “Absolute” movements with PLACA. (a) Simplified bathymetric map (Smith and Sandwell, 1997) used to digitise on-screen recent volcanic alignments in Cook-Australes seamounts (boxes in the plot). (b) Some of small circles, volcanic alignments and misfits that result from use of method (4) (see text for explanation) to obtain location of most recent hotspot pole. (c) 95% confidence region for pole obtained (triangle) and comparison with pole obtained by Aslanian et al. (1998) from a visual fit. Note that Wessel and Kroenke (1997) pole is far away from this confidence region and could not be plotted in this geographic box.

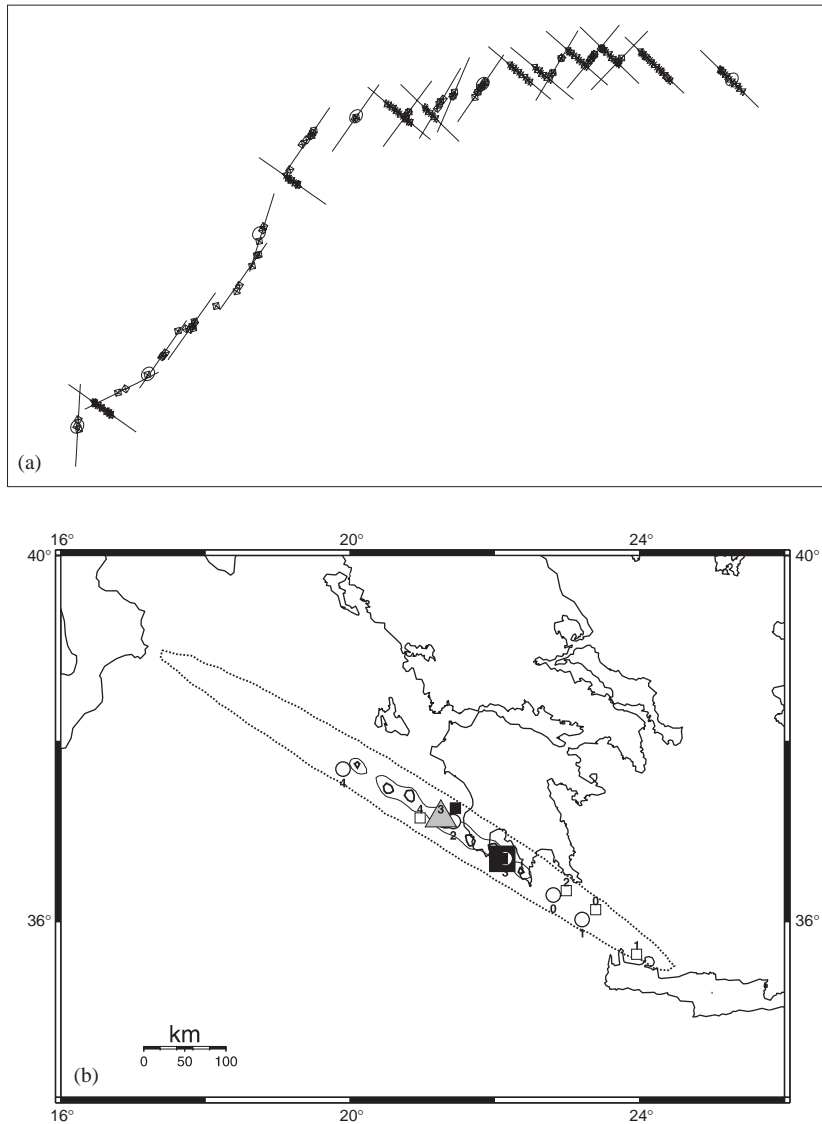


Fig. 8. Application of PLACA best-fitting techniques to a synthetic example generated from actual ridge and fracture zones at Equatorial Indian Ocean. (a) Plot of reconstructed 169 points divided into 25 segments. Ellipses represent a posteriori uncertainty for reconstructed points. (b) Uncertainties on determination of Africa–India pole obtained by Hellinger method (large triangle). Three 95% confidence regions are plotted over sphere, corresponding (from inside to outside) to a priori data uncertainties of 2.5 km (thick irregular blobs), 3 km (thin line) and 5 km (thick dotted line). Large dark square is original pole of rotation used to build exercise. Small dark square is solution obtained when only magnetic anomalies are used. Same solution for fracture zones is outside drawing limits. White boxes are solutions produced by different ways of computing merit function, using L-2 norm (see text for explanation). White circles are same for L-1 norm.

strictly local and they should not be attributed to the whole plate.

Fig. 10 presents two solutions for the reconstruction of Iberia at anomaly C21. Two segments of magnetic anomalies in the Iberia and North America plates are identified, separated by one fracture Zone. The two segments cannot be fitted simultaneously and two

extreme solutions are presented. The choice between these two solutions cannot be done looking at the ridge data only. It must be founded on geologic criteria taking into consideration the consequences on the plate boundaries, far away from the ridge, such as in the Pyrenees, where extreme points are separated by 120 km. Furthermore, the uncertainty in Iberia position is

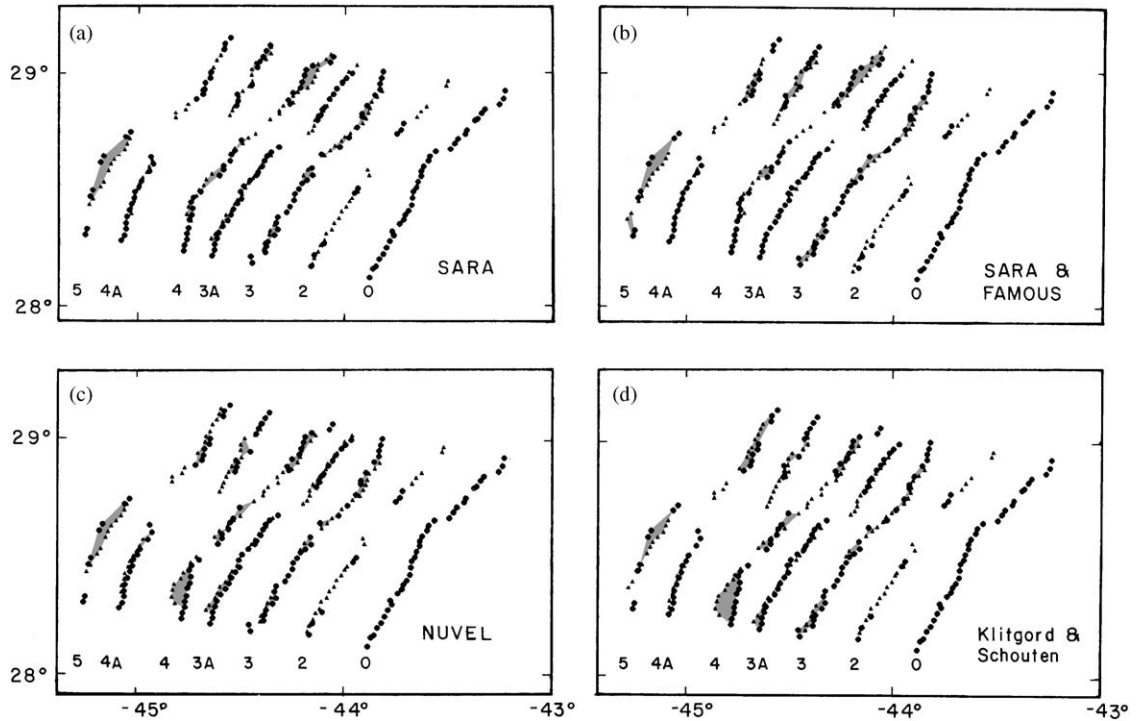


Fig. 9. Illustration of lack of precision on superposition of magnetic anomalies using an example taken from SARA zone, between Atlantis and Kane Fracture zones (adapted from Sloan and Patriat, 1992). Magnetic anomalies of eastern flank (triangles) are superposed to analogous anomalies on western flank (circles). Western flank is fixed and a different set of rotation poles are presented: (a) pole computed using magnetic data in SARA region (Sloan and Patriat, 1992); (b) pole computed from a combination of SARA and FAMOUS magnetic data (Sloan and Patriat, 1992); (c) pole estimated from NUVEL-1 model (DeMets et al., 1990) for anomaly C2A; (d) pole estimated from pole of Klitgord and Schouten (1986) for C5 anomaly.

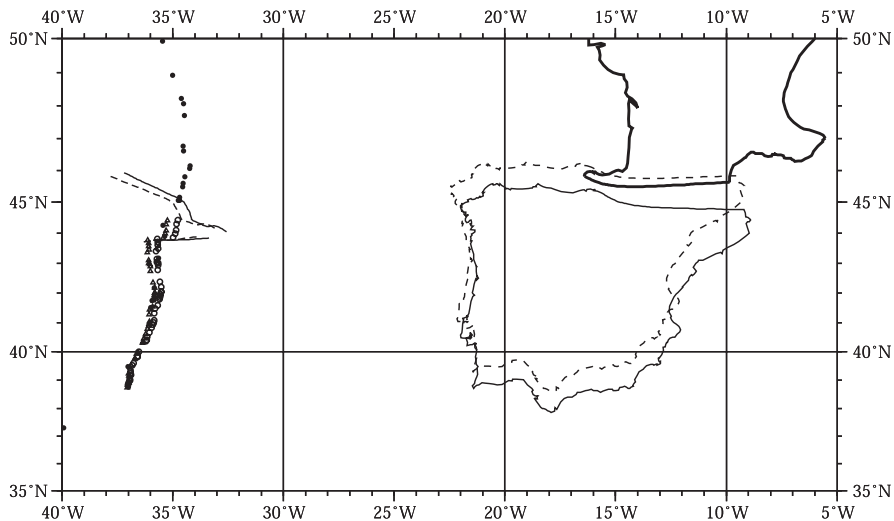


Fig. 10. Two possible solutions for Iberia plate at anomaly C21 obtained by a visual fit are presented. Dark dots represent anomaly C21 on North America plate. Thick contour is Europe (considered fixed). Thin contour and open dots represent Iberia and C21 anomaly rotated with pole (77.99°N , 115.07°E , -11.42°) while dashed contour and triangles were rotated using pole (63.23°N , 131.88°E , -10.55°). Given that no single fit can be obtained with whole data set, two reconstructions shown present two extreme approaches, one fits best southern anomaly segment while other fits best small northern segment.

limited in the N–S direction due to the existence of one recognised fracture zone, south of King's trough. Both sides of this feature should coincide in any reconstitution. However, for anomalies older than C21, as C30 and C32, the position of Iberia is no longer constrained by a fracture zone. The exclusive use of magnetic anomalies to obtain the best-fit is then a very poorly defined problem and one should use other criteria, such as the consistence of the solution at regional and global scales.

It is then clear that the best-fit solution we should look for is not always the geometrical one, evaluated from the data acquired near the ridge. Sometimes, the best solution is the one that takes into account of the geological constraints offered by the whole plate configuration and the one that presents the best coherency in time. For example, in Fig. 9, the best-fit pole of Sloan and Patriat (1992) introduces a jerk in the movement between C5 and today which consequences must be verified in the field.

Geological data on key deformed areas taken separately are not very helpful for best-fit pole determination. However, taken as whole, considering different plate boundaries, they provide useful constraints on the pole determination because they can locally quantify the age and direction of relative movements.

10. Conclusions

PLACA is a general-purpose computer program that can be used to address a number of questions raised today by the plate tectonics paradigm. It can be used as a tool for demonstration purposes but also to test geodynamical models that can be described by a set of total reconstruction poles or instantaneous angular velocities. PLACA provides several methods for determining best-fit poles from magnetic anomalies and/or fracture zone data. Confidence regions can be estimated for the poles obtained, but the examples presented show that these regions are underestimated due to the bias introduced by the limits in the physical models adopted. The visual fit method of Olivet (1978) and Bonnin (1978) is implemented by a two-step interactive procedure. Simple tests performed using PLACA and recent high-resolution geophysical data suggest that the precision on plate reconstruction is no longer controlled by the random errors in the observations, but that it depends on the failure of the rigid plate model and on the complex geological processes that affect the MOR, their magnetic anomalies and the fracture zones. This intrinsic source of uncertainty must be taken into consideration at all times as well as the large-scale implications of fits obtained using data on a small region of a plate. The mathematical procedures implemented in

PLACA for best-fit pole determination are very useful in many circumstances, however the estimates of the best-fit pole uncertainty can be very optimistic. We feel that in most cases the mathematical solution must be confronted with the geological constraints brought by the direction of alignments and a coherency on the evolution over time.

PLACA was built in Fortran code, under the UNIX operating system. It has been fully tested on Sun and PC-Linux platforms. PLACA is distributed freely (PLACA distribution site. <http://www.ifremer.fr/drogm/Logiciel/index.htm>) with a detailed manual and several worked examples.

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