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Plate tectonic modelling: virtual reality with GMAP☆

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Abstract

Palaeogeographic reconstructions have been an integral part of global tectonic research since the advent of the plate tectonic paradigm, and GMAP is a state of the art computer program which performs all processing and plotting tasks associated with the generation of palaeogeographic reconstructions and plate tectonic modelling. GMAP is menu-driven and easy to use; the user is never far removed from the basic data from which palaeogeographic reconstructions are derived, and therefore has a sense of total control over the program's performance. GMAP can generate reconstructions based on known Euler rotation data poles or palaeomagnetic poles. The user is also free simply to move continents around on the screen, according to less tangible constraints. GMAP is supplied with a full range of continental outlines. It is also possible to import new continents via simple ASCII files. GMAP is in use at leading institutions world-wide, and has been the work-horse of the EUROPEAN GEOTRAVERSE and EUROPROBE projects. © 1999 Elsevier Science Ltd. All rights reserved.

Keywords: Plate tectonics; Palaeogeography; GMAP; Software package

1. Introduction

The display of plate reconstructions through geologic time augmented with biogeographic, geologic and palaeogeographic information, is a useful tool to understand local and regional geologic relationships as well as the fundamental driving forces of the Earth's core and mantle. The present earth's surface is divided into a dozen or so tectonic plates; the two most important plate boundaries which also have an effective bearing on the plate tectonic driving forces are (1) divergent boundaries where new crust is generated and subsequently cooled as the plates pull away from each other and (2) convergent boundaries where crust is destroyed as one plate is subducted beneath another. It may appear difficult to describe precisely or adequately grasp these acting forces, but most would argue that relatively shallow forces driving the lithospheric plates are coupled with forces originating much deeper in the Earth (Forsyth and Uyeda, 1975; Gurnis and Torsvik, 1994). Lithospheric cooling is important, but subduction, the sinking of a cold denser oceanic slab, which thus pulls the rest of the plate along with it (slab pull), is now generally considered to be the most important force in running the plate tectonic machinery.

In order to undertake global tectonic modelling, the GMAP software system package was originally developed by THT at the University of Bergen (1982) and later upgraded together with the second author from 1989 and onwards. The incipient development of GMAP was motivated from THT's interest in spherical geometry and his father who financed the very first personal computer on which GMAP was developed. The latest version of GMAP described here is a 32-bit edition, developed with using Microsoft Visual Basic 5 and Fortran Powerstation programming tools to run under Windows 95 and Windows NT operating systems. GMAP is available in two editions, Standard or

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☆ GMAP Standard is available as a freeware on http://www.ngu.no/geophysics

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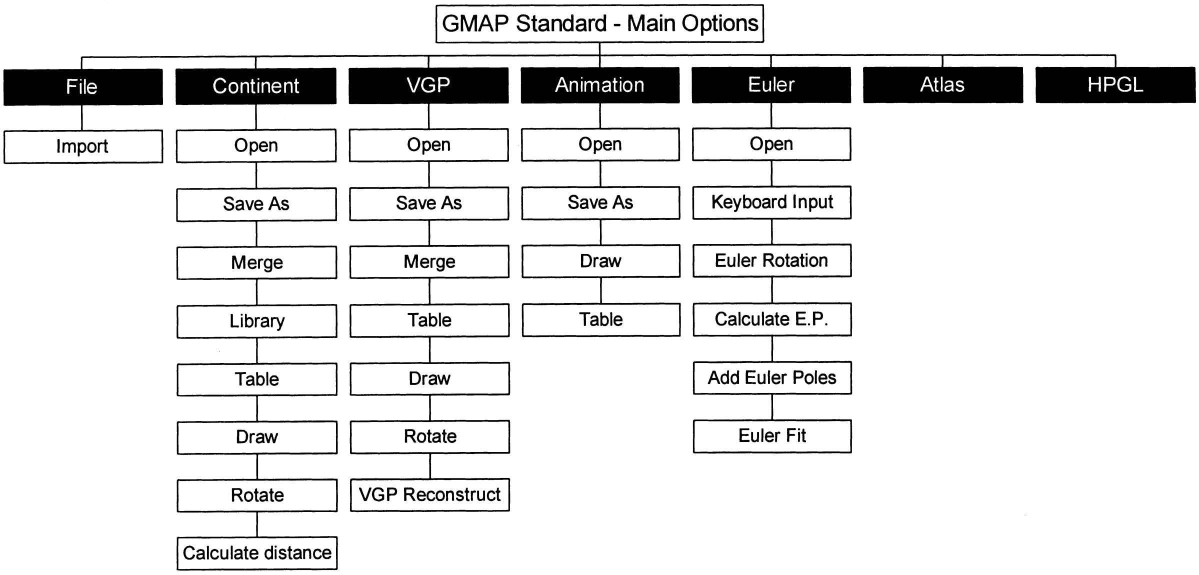


Fig. 1. Chart of some main options in main menu (filled boxes) and some important suboptions.

Professional. GMAP Standard is available as a freeware (http://www.ngu.no/geophysics). A comprehensive manual and a report demonstrating GMAP capabilities are presented in Torsvik and Smethurst (1998) and Torsvik and Eide (1998). These reports can be purchased from the Geological Survey of Norway at printing costs (contact http://www.ngu.no).

2. Main features in GMAP

Some of the important options in GMAP Standard as discussed in the text are shown in Fig. 1. In addition, there are numerous other options such as choice of map projection, projection centre, map scale and zoom centre coordinate. GMAP uses three types of data files containing continent outlines, palaeomagnetic pole positions and palaeogeographic animation files:

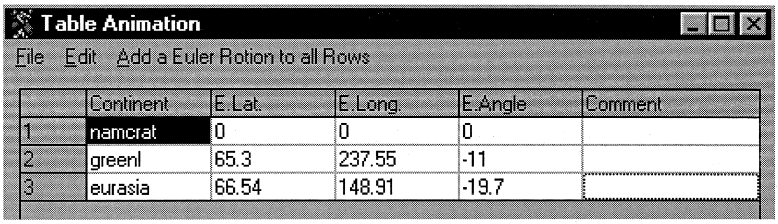
1. GMAP is supplied with a range of continental outlines. These outlines may be edited, split or combined, and then permanently saved. It is also possible to import new continents via simple ASCII files or to import continents from the PALAEOMAP project of Chris Scotese and coworkers.
2. GMAP is also supplied with example files of palaeomagnetic poles and calculated apparent polar wander paths (APWPs) (stored in VGP files). GMAP also interacts with the Global Palaeomagnetic Data Base (Lock and McElhinny, 1991) via the Geological Survey of Norway's DRAGON web-site (http://dragon.ngu.no/palmag/paleomag.htm). At this web-site the content of the result table from a paleopole query can be transferred to the user's own computer in the form of an ASCII text file. This is done via a link placed at the top of the paleopole query's result table. The file can then be downloaded to a local computer and opened directly by GMAP.
3. Animation files are files containing a list of continent names and Euler rotation poles (latitude, longitude and rotation angle, see examples below).

3. Reconstruction methods

GMAP can produce plate reconstructions based on palaeomagnetic poles or known Euler rotation poles and angles. The user is also free to move continents around on the screen, according to less tangible constraints.

3.1. Known Euler poles

Movements of a plate on the Earth's surface are described by a rotation angle around an Euler pole. Euler poles and rotation angles that bring to fit continents into their former relative positions are regularly published in the literature. Relative or absolute Eeuler poles can be derived from sea floor magnetic anomalies



	Continent	E.Lat.	E.Long.	E.Angle	Comment
1	namcrat	0	0	0	
2	greenl	65.3	237.55	-11	
3	eurasia	66.54	148.91	-19.7	

Fig. 2. Option ANIMATION TABLE. Greenland (continent file = greenl) rotated to North America (continent file = namcrat) after Roest and Srivastava (1989). Eurasia to North America after Srivastava and Roest (1989). Resulting figure produced in option 'Animation Draw' is displayed in Fig. 3a.

(since c. 175 Ma, i.e. the oldest preserved oceanic crust), hot-spot tracks (reliable to ~130 Ma), the matching of continental margins, palaeomagnetic data or a combination of these.

Our first example considers a relative reconstruction of the North Atlantic at ca. 84 Ma (Late Cretaceous times) which accounts for sea-floor spreading (ca. 95 to 46 Ma) in the Labrador Sea (between North America and Greenland — now part of the same plate) and Tertiary (< 56 Ma) spreading in the East North Atlantic (between Greenland and Eurasia). This task can be approached in several ways using GMAP, but the simplest procedure is to construct an animation file (Fig. 2) as follows:

1. From the FILE menu select ANIMATION TABLE and then NEW.
2. Enter continent names and Euler rotation poles (Fig. 2).
3. Select EXIT from the FILE menu and select ANIMATION DRAW.
4. Save animation file for later use.

Above, we outlined the procedure to produce a reconstruction leaving North America in its present geographic position, however we know that the landmasses shown in Fig. 3a have moved in both latitude and longitude since 84 Ma. We could use Late Cretaceous palaeomagnetic data for North America to restore the landmasses to their original latitudes and orientations or alternatively, we could use a hot-spot reference scheme. From early Cretaceous times (130 Ma) we can use hot-spots from the Atlantic and the Indian Ocean (e.g. Müller et al., 1993) combined with information from sea floor magnetic anomalies to produce total reconstructions. The underlying assumption, however, is that hot-spots are stationary or move at insignificant speeds relative to plate-tectonic speeds. If so, hot-spot references and their corresponding reconstructions offer a unique contribution to palaeoreconstructions because they give palaeologitudinal control on plate positions, in contrast to reconstructions based on palaeomagnetic data alone. It should be noted though, that the 'stationary' character of hot-spots is disputed (e.g. Tarduno and Cotrell, 1997).

Combining relative fits with hot-spot frames is easily done with GMAP. From the previous example we already have an animation file which contains the relative fits with North America fixed in its present position. We can then look up the hot-spot frame for North America (e.g. Müller et al., 1993); the Euler rotation pole is simply entered in option 'Apply an Euler rotation to all Rows' (Fig. 4). This will calculate determine and insert appropriate new Euler poles for Greenland and Eurasia.

3.2. Palaeomagnetic poles

To generate a reconstruction using palaeomagnetic poles requires an additional numerical procedure, easily accommodated in GMAP. For an out-and-out understanding of the palaeomagnetic method and palaeomagnetic poles we refer to Cox and Hart (1986), Butler (1992) and Van der Voo (1993), but a few basic principles are outlined next.

Under ideal circumstances, when rocks are formed, they acquire a remanent (permanent) magnetization parallel to the Earth's magnetic field at that location. The inclination of the Earth's field varies with latitude and is the main feature of interest in palaeomagnetic reconstructions. At the north magnetic pole the inclination of the field is +90 (straight down), at the equator the field inclination is zero (horizontal) pointing north and at the magnetic south magnetic pole the inclination is –90 (straight up).

Ideally, as a time average, a palaeomagnetic pole for a newly formed rock (calculated from declination and inclination of the remanent magnetization carried by the rock and the geographic site location of the site) will correspond with the geographic north or south pole. If a continent later moves (continental drift), the palaeomagnetic pole moves with the continent. To perform a reconstruction with palaeomagnetic poles we therefore have to undertake the following exercise: (1) calculate the Euler pole and rotation angle that translates the palaeomagnetic pole back to the geographic

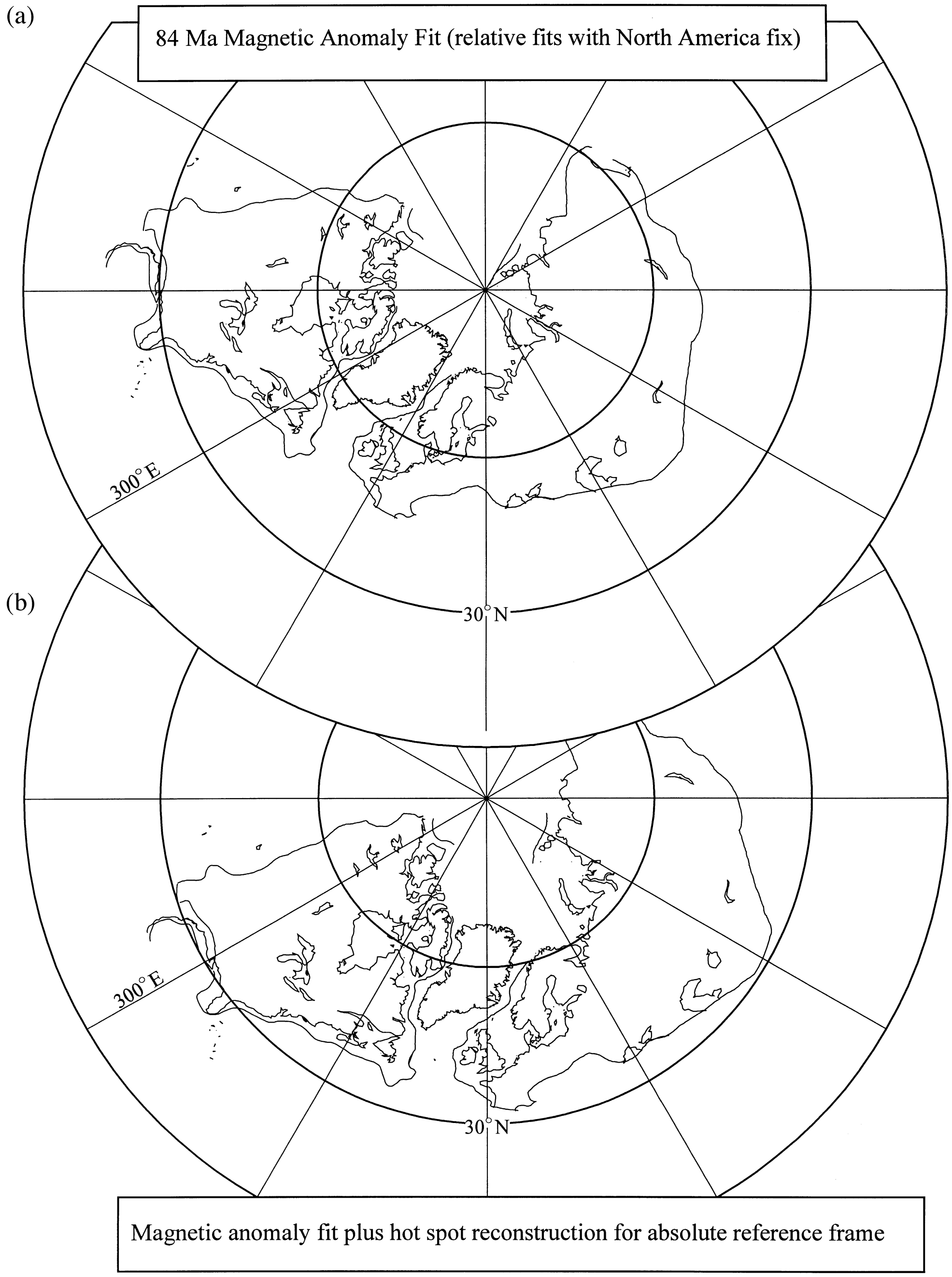
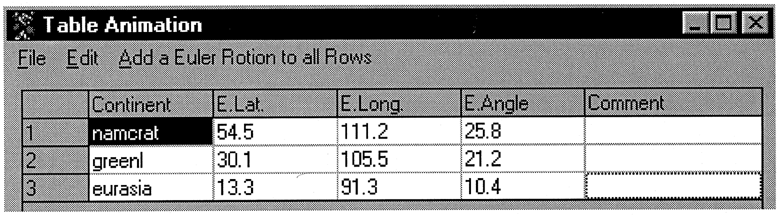


Fig. 3. (a) 84 Ma magnetic anomaly fit (relative fits with North America fix). Euler data: Eurasia–North America (66.54°, 148.91°, rotation angle = −19.7°) Greenland–North America (65.3°, −122.45°, rotation angle = −11°). (b) Magnetic anomaly fit plus hot spot reconstruction for absolute reference frame: As in (a) but added with joint Euler rotation of 54.5°, 111.2° and rotation angle = 25.81°.

north or south pole, and (2) apply the same rotation to the continent outline.

As an example, we use an early Triassic (ca. 243 Ma) palaeomagnetic pole (latitude = 52.9°S and longitude = 344.4°E) for the Eurasian plate. In this example 'OPEN' continent 'EURASIA' from the main menu (Fig. 1), then engage option 'VGP reconstruct' and enter the palaeomagnetic pole position −52.9 (south latitude) and 344.4 (east longitude) and select South Pole (Fig. 5). GMAP will automatically calcu-

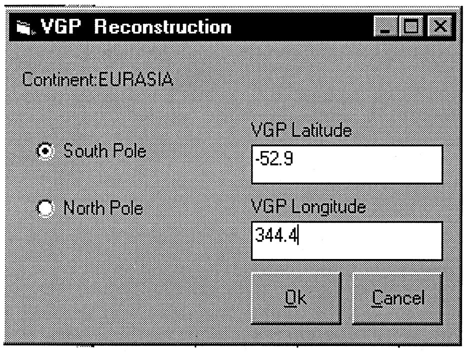


	Continent	E.Lat.	E.Long.	E.Angle	Comment
1	namcrat	54.5	111.2	25.8	
2	greenl	30.1	105.5	21.2	
3	eurasia	13.3	91.3	10.4	

Fig. 4. Option ANIMATION TABLE. Relative fits of Greenland, North America and Eurasia as Fig. 2, but we have now added common Euler pole of 54.5°N, 111.2°E, rotated through angle of 25.8° (with the use of option 'Add a Euler Rotation to all Rows'). Resulting figure produced in option 'ANIMATION DRAW' is illustrated in Fig. 3b.

late the Euler pole required to rotate the palaeomagnetic pole to the present south geographic pole (in our example Euler pole latitude = 0°, longitude = 74°E and rotation angle = 37.1°); then GMAP will apply rotation to the continent 'Eurasia' and the result will be as shown in Fig. 6.

Palaeomagnetic data can only constrain latitude (based on remanent magnetization inclination) and the amount of angular rotation (based on remanent magnetization declination), hence palaeolongitudinal position remains unknown, and one must draw upon other data to restore 'EURASIA' to its original longitudinal position in relation to other continents. There is also uncertainty regarding the polarity of ancient remanent magnetizations. If the paleomagnetic record for a continent is broken for significant lengths of time we cannot know in old rocks whether a palaeomagnetic pole is a SOUTH or NORTH pole. In our case, we assumed that the pole was a SOUTH pole, but if we used a NORTH pole, 'EURASIA' would be plotted in the southern hemisphere and geographically inverted. Hence, the choices produce reconstructions which will place the continent in an opposite hemisphere and geographically inverted (i.e. rotated 180°). This does not present a large problem during the Mesozoic and most of the Palaeozoic (the polarity choice for APWP is reasonably well known), but for Precambrian and the early Palaeozoic this may present serious problems in palaeomagnetic reconstructions.



Continent:EURASIA

● South Pole

○ North Pole

VGP Latitude: -52.9

VGP Longitude: 344.4

Fig. 5. Example of use of option 'VGP Reconstruct' engaged from main menu (Fig. 1). In this example we have 'OPENED' continent 'EURASIA' from main menu and entered latitude and longitude for early Triassic palaeomagnetic pole. Click 'OK' and EURASIA will be reconstructed as in Fig. 6.

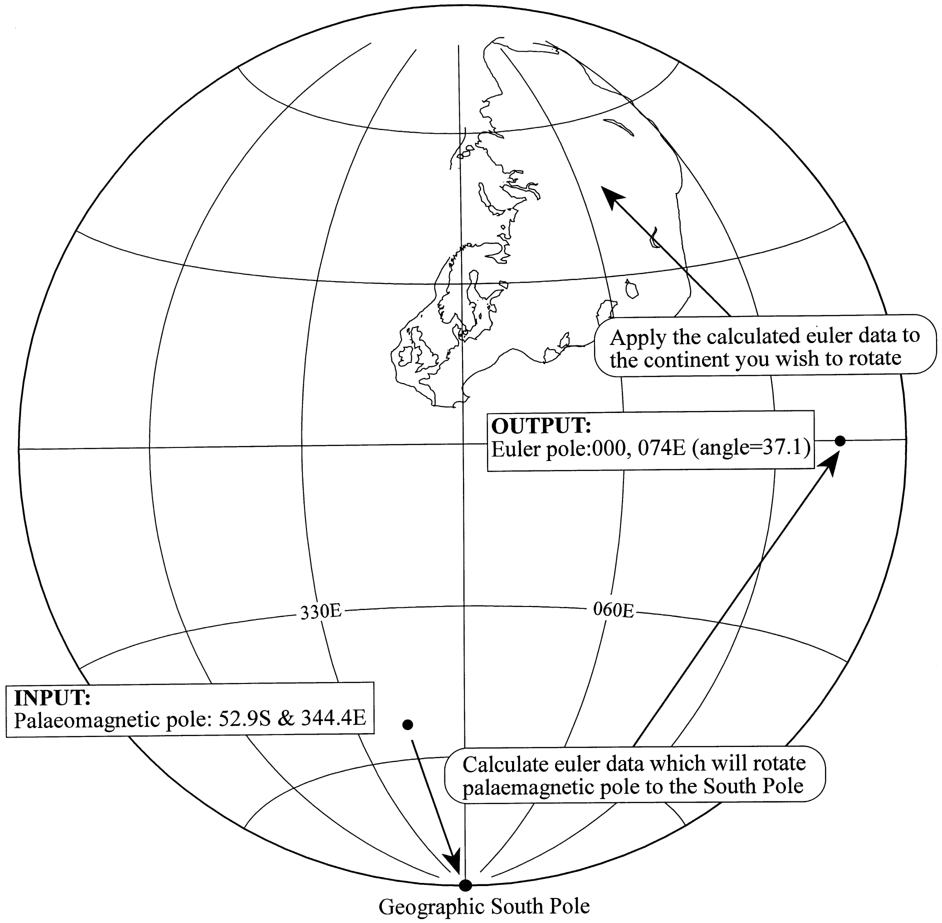
4. Putting it all together

Information useful for global reconstructions include geometric matching of continental borders (the classic paper is Bullard et al., 1965), crustal province matching, palaeontology and palaeoclimatic, palaeomagnetic, sea-floor spreading (magnetic anomalies/fractures), petrotectonic and hot-spot track data.

An ATLAS of reconstructions (from Torsvik and Eide, 1998) is included in GMAP and is designated for educational purposes for both students and professionals. Each reconstruction is supplied as a vector file in Windows metafile format (<AGE>.WMF) that allows the operator to import the file into a drawing package for modifications. In Fig. 7 we selected four palaeogeographic 'snap-shots' assembled on different geological and geophysical grounds (after Torsvik et al., 1996; Eide and Torsvik, 1996; Torsvik and Eide, 1998 and references cited therein). These are all produced with GMAP.

Our first example is a reconstruction for the Early Ordovician (Fig. 7a) based on palaeomagnetic data augmented with platform trilobite and petrotectonic information. At this time, the paleo-plates Laurentia, Siberia and the North China Block occupied equatorial latitudes and they were all dominated by warm-water carbonates. Baltica faced the Avalonia–European Massifs–Northwest Gondwana conglomerate in high southerly latitudes (>60°S). Arenig–Llanvirn platform trilobites show the existence of a separation between the low-latitude continents Laurentia, Siberia and the North China Block, the intermediate-latitude Baltica, and the high-latitude areas of NW Gondwana/Avalonia/European massifs.

During the Palaeozoic all continents converged to form the supercontinent Pangea by Permian or earliest Mesozoic times and the Caledonian and Hercynian deformation areas are shaded in Fig. 7b. This reconstruc-



INPUT:
Palaeomagnetic pole: 52.9S & 344.4E

Calculate euler data which will rotate palaemagnetic pole to the South Pole

OUTPUT:
Euler pole:000, 074E (angle=37.1)

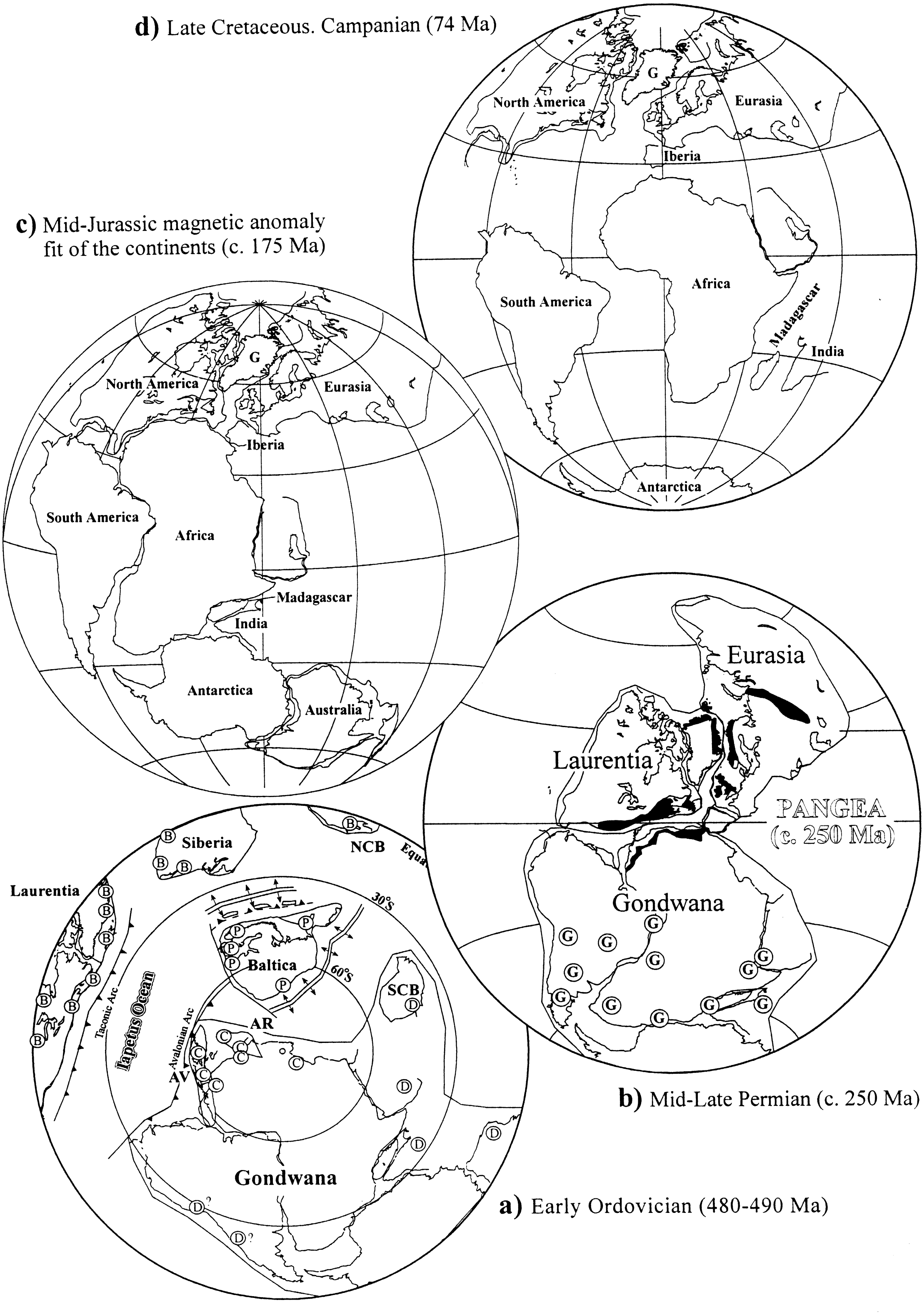
Apply the calculated euler data to the continent you wish to rotate

Fig. 6. Example of early Triassic reconstruction of Eurasia using palaeomagnetic pole of 52.9°S and 344.4°E. See text for details.

tion, palaeomagnetically controlled in latitude but with relative fits after Lottes and Rowley (1990), shows that the supercontinent Pangea was centered on the equator during mid-late Permian times. The southern parts of Laurentia and Eurasia straddled the equator while the Gondwanan part of Pangea stretched to high southerly latitudes. The latter is readily noticed in the stratigraphic record by the presence of glaciogenic deposits in southern Gondwana.

The next example (Fig. 7c), Mid-Jurassic times, demonstrate GMAP's capabilities to use finite rotation poles derived from sea floor magnetic anomalies (or backward extrapolated to account for predrift extension; rotation poles after Royer et al. (1992) and also listed in Torsvik and Eide (1998)). This reconstruction is only a relative reconstruction and Europe remains in its present position on the globe. The oldest identified magnetic anomaly is of mid-Jurassic age (ca. 166 Ma, Central Atlantic), but the break-up of Pangea is likely to have started at ca. 175 Ma. From this time period and onward, we can use magnetic anomalies extensively for relative plate fits, while we can use palaeomagnetic data for the latitudinal positions of the continents. The Mid-Jurassic is associated with two major global events that led to the break-up of Pangea, (1) initiation of NW-SE directed sea-floor spreading in the central Atlantic and (2) rifting of the south-Gondwana elements (Antarctica–Australia–Madagascar–India) from Pangea (Gondwana dispersal).

The final example (Fig. 7d) demonstrates a combination a hot-spot frame and magnetic anomalies for a Late Cretaceous reconstruction (ca. 74 Ma). In the Atlantic region, spreading in the South Atlantic (ca. 133 Ma) and the Labrador Sea (ca. 95 Ma) followed sea-floor spreading in the Central Atlantic. In the Indian Ocean, Greater India separated from Africa/ Madagascar at around 85 Ma. In contrast to the



d) Late Cretaceous. Campanian (74 Ma)

c) Mid-Jurassic magnetic anomaly fit of the continents (c. 175 Ma)

b) Mid-Late Permian (c. 250 Ma)

a) Early Ordovician (480-490 Ma)

Fig. 7. Examples of GMAP capabilities, as described in text.

'palaeomagnetic' reconstructions shown in Fig. 7a–b we have now included palaeolongitudes since we are using a hot-spot reference frame.

5. Conclusion

Palaeogeographic reconstructions have been an integral part of global tectonic research since the advent of the plate tectonic paradigm and in this account we have described some of the options available in GMAP Standard; this freeware edition has all the fundamental options required to undertake palaeogeographic reconstructions, including hard-copy options and the possibility to export reconstructions to ordinary drawing packages (via the use of HPGL vector files). Figs. 3, 6 and 7 were made with GMAP, then exported as HPGL vector files, and in our case, 'improved' and labelled with Corel Draw. However, any drawing package with HPGL import capabilities can be used.

GMAP Standard should prove useful for both academic research and educational purposes. GMAP Professional is essentially used by very advanced users; this edition includes extended animation, palaeomagnetic and Euler-rotation (including all magnetic anomaly fits) libraries in addition to a built-in, statistically robust, method for fitting smooth curves to palaeomagnetic pole positions. This edition also estimates plate-speeds (Gurnis and Torsvik, 1994; Torsvik et al., 1992, 1996), angular rotations and rates of APW (Torsvik et al., 1998).

Acknowledgements

This paper is dedicated to Alf Ernst Torsvik (1936–1998) (COSE DELLA VITA). It was composed in a period of emotional distress for THT, and may not have dawned without the constrained inspiration from Liz, Vala, Yanni and Sir Phillip.

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