The MAGAN Project

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Magan 3.12 User's Manual

by

A. Schettino

e.mail: antonio.schettino@unicam.it

University of Camerino

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Chapter 1

Introduction

1.1 Purpose

The main objective of the *Magan* project is to design and implement a new free software package for the analysis and interpretation of marine magnetic anomalies (Schettino, 2012). The software is available to marine geophysicists with new advanced features with respect to older programs, in an attempt to improve the reliability of anomaly identifications in plate kinematics studies. In particular, the program allows to:

- Load a *time scale* of magnetic polarity inversions;
- Import NGDC ship track data or other magnetic anomaly data;
- Create, load, and save *projects*;
- Manage *ship-track* (*project*) *windows*;
- Set a *background raster image* (e.g., gravity) in a ship-track window;
- Create a *flow line* where the magnetic data can be projected;
- Import *Kp* index data and generate *Kp index windows*;
- Generate magnetic and bathymetric profiles for the projected data;
- Assign and change the ship-track *zero-offset location* in a project window;
- Set *inclination* and *declination* of the reference field at the survey time along the flow line;
- Set the *block wall dip*;
- Load a *rotation model* for the calculation of synthetic *Apparent Plar Wander Paths* (*APWP*);
- Set *default full spreading rate* and *asymmetry*;
- Specify a *crustal thickness* for the magnetized layer along the profile;
- View magnetization models and model/measured profiles in *model profile windows*;
- Set the *magnetization function* along the profile;
- Set the *full spreading rate function* along the profile;
- Set the *spreading asymmetry and obliquity functions* along the profile;
- Specify *ridge-jump* locations;
- *Export* model profiles;
- Save *anomaly crossing points* along the profile;
- Generate *velocity windows*;
- Generate *T-x (age-distance)* and *T*-α *(age-angular distance)* windows;
- Perform a *stage analysis* of age-distance plots.

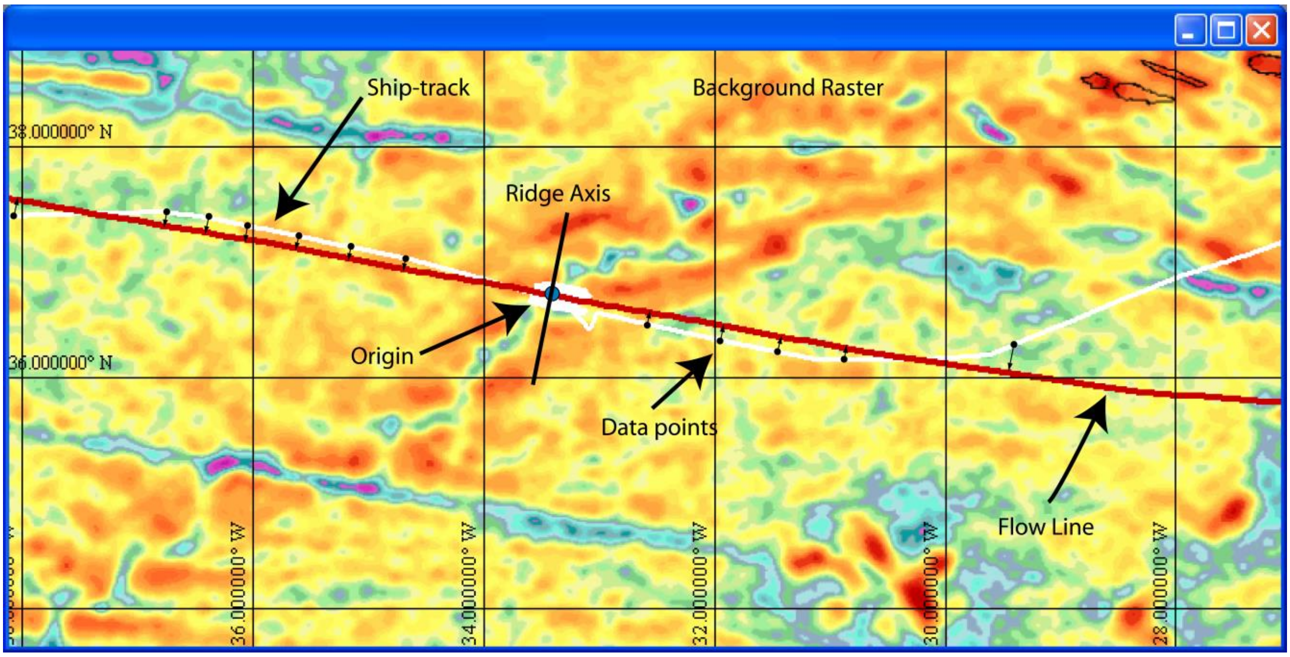

Figure 1. Project Window elements. A flow line (brown line) parallel to existing fracture zones is used to project magnetic anomaly data of a ship-track (white line) in the central Atlantic. The background image shows the gravity anomalies pattern in this zone. Ridge axis orientation is calculated automatically once the user has defined the profile origin.

1.2 General Overview

The program manages two basic kinds of windows: *ship-track* (*project*) windows and *forward modelling* windows. The first kind of windows allows the user to set the general parameters of a project (ship track data, flow line, origin, inclination/declination of the reference field at survey time, block walls dip, background image, basement grid, and optionally a rotation model), and eventually change some default parameters (e.g., full spreading rate, magnetization). The window can show a ship track line on a background bathymetric, gravity or magnetic anomalies image. The user can manually trace and edit a flow line, parallel to fracture zone trends, which will be used later to project ship-track data. Alternatively, the user can ask the program to generate automatically a flow line using an existing rotation model. Figure 1 illustrates the elements of a project window through a real example from the central Atlantic. The user must also select an origin for the reference frame (blue circle), which will be used for calculating the distance from the spreading center.

Forward modelling windows are the primary interactive tool for the analysis of magnetic anomalies. These windows display both the calculated and measured magnetic anomaly profiles along the selected flow line. They also display the magnetization profile. The individual blocks composing this profile are crustal expressions of existing chrons in the selected time scale. The user can locally change the magnetization amplitude or the full-spreading velocity and obliquity of any block. He/she can set a spreading asymmetry simply specifying different velocities for conjugate blocks. Ridge jumps can be introduced clicking on a block and assigning a jump width (in terms of number of blocks) and direction. Once the user has obtained the desired match between theoretical and observed profiles, crossings corresponding to stage boundaries can be exported for future construction of isochrons. Figure 2 illustrates the main features of a forward modelling window.

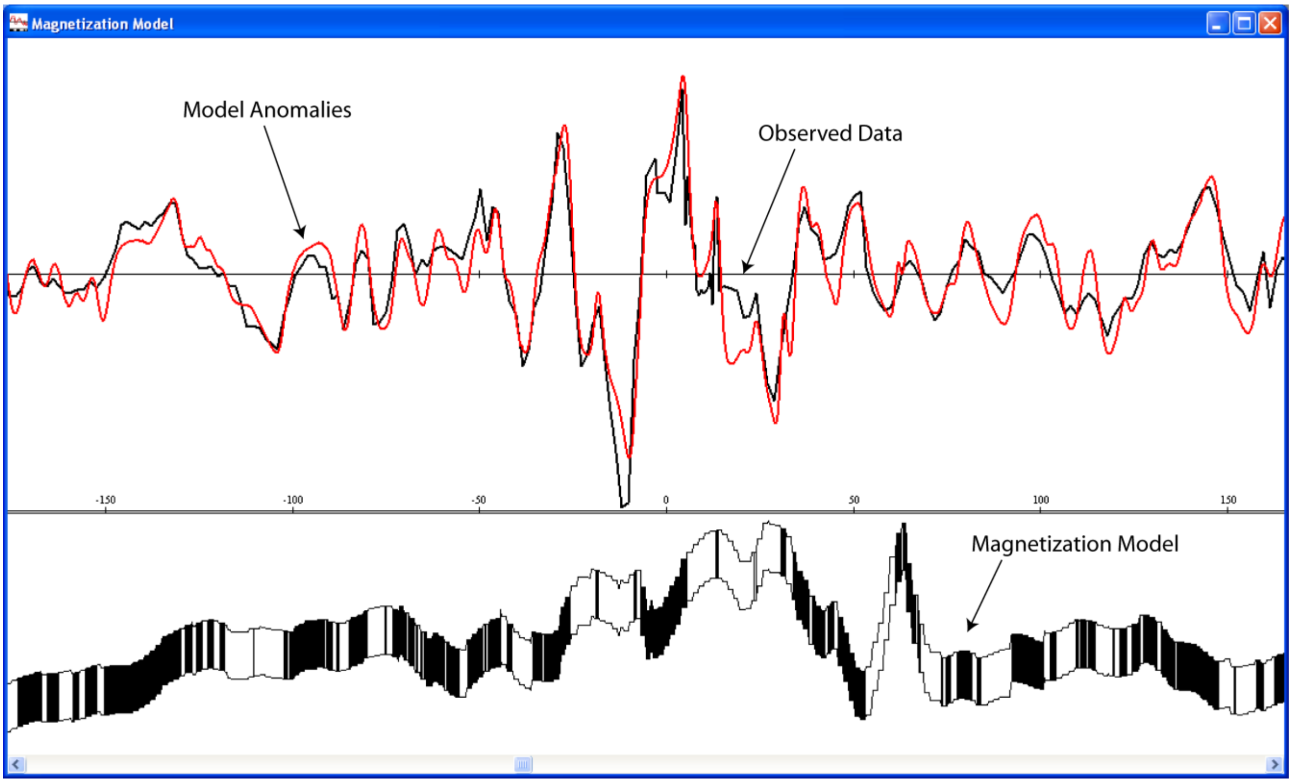

Figure 2. Forward modelling Windows. Individual blocks can be selected to change magnetization amplitude or full spreading velocity. The model is automatically updated when velocity and/or magnetization are changed.

Another important and innovative feature of the program is represented by its capability to calculate the correct anomalous field generated by each block according to the following criteria:

1. The strike of each prism is calculated locally along the user-defined flow line. This means that the spreading direction is not considered as constant for the whole profile. Instead, this quantity is calculated independently for each block in the model;

2. A rotation model supplied by the user is used to generate a synthetic apparent polar wander path (APWP) for each conjugate plate. These data are used in turn to determine inclination and direction of remnant magnetization for each block in the model.

The quality of an interpreted data set can be assessed on the basis of a magnetic disturbance index during the survey. *Magan* can generate a plot of the *Kp* index along any NGDC ship track, allowing an evaluation of the data at local scale (at 3-hours intervals). Once a magnetic profile has been interpreted, two additional plots can be generated, namely a *full spreading rate* curve for the profile (Fig. 3), and a *time-distance* plot showing the mean age at any distance from the spreading center (Fig. 4).

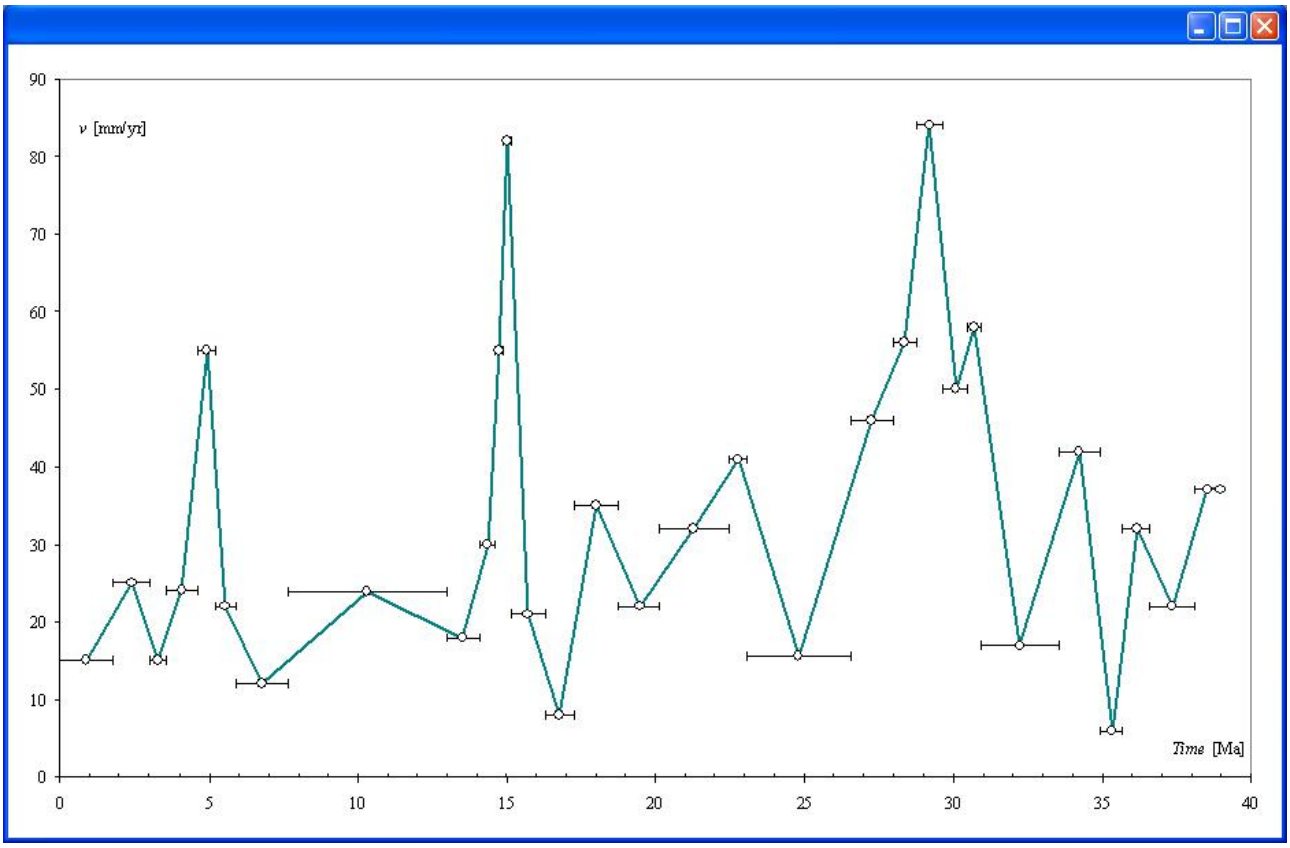

Figure 3. Full Spreading Rates Windows. Each point represents the full spreading rate during a user-defined stage. Error bars represent stage widths.

Finally, it should be noted that this software does not include a module for the computation of finite reconstruction poles and associated statistics, starting from a data set of crossing points. Such a module will be included in the free distribution of PCME (Schettino, 1998), named *PlaKin*, which will be released in August 2014. The following section discusses the importance of flow lines in the forward modelling approach adopted by Magan.

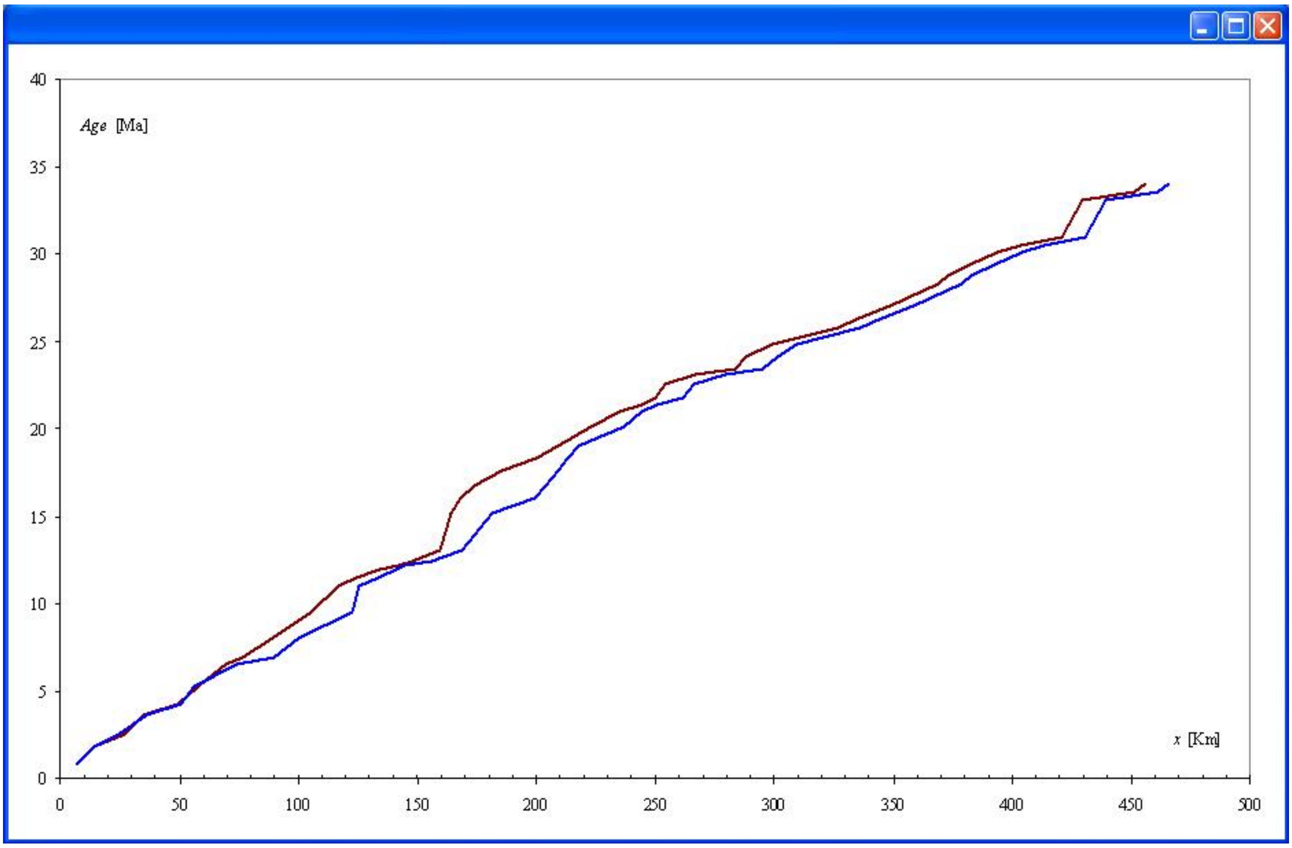

Figure 4. Time-Distance Windows. The two lines show the crustal age on each flank of a spreading center at any distance from the ridge axis.

1.3 Flow Lines

Flow lines are an important feature of Magan, which allows the user to generate them manually or in two automatic ways. These are lines where the ship-track (or aeromagnetic) data must be projected before a forward modelling window can be open (Fig. 1). They could be locally parallel to the true flow line of motion, as indicated by existing fracture zones, or simply have a unique strike coincident with the average strike of the ship track. In fact, in most cases a track line swings irregularly about a definite direction. Therefore, generally the user will trace flow lines as arbitrary projection lines that interpolate the ship-tracks. In some cases it will be possible to project different neighboring survey lines onto a unique line of projection, in order to generate an averaged magnetic profile.

A flow line can be simply defined by a pair of points, generated by a couple of mouse clicks. In this instance, magnetic and bathymetric data are projected onto the great circle arc connecting the two points. Alternatively, the user may trace a more refined flow line which is parallel to the existing fracture zones, if a background raster has been defined. Each point in a flow line can be moved by dragging it onto a new location or deleted by a right mouse click. The user may select a flow-line node by clicking on it. The current selected point appears as a red node. The insertion of new points always occur after the currently selected node. One of the points of a flow line must be assigned the role of profile origin (zero offset point). Of course, such a point should be located on an active or extinct ridge. It is important to note that Magan works correctly if and only if successive nodes in a flow line have either monotonically increasing longitudes or monotonically increasing latitudes.

When the user wants to analyze a short profile across a spreading ridge, it is possible that the flow line is represented by a simple small circle arc about the current stage pole. If the location (lat,lon) of this stage pole is known, for instance from global plate motions models such as NUVEL-1A (DeMets et al., 1994), then the user may ask Magan to automatically generate the flow line. In this instance the user only needs to click at the location of the origin, and the program generates automatically all the other points. In the case of longer profiles, which encompass several stages, the flow line has a more complex geometry, which can be assimilated to a sequence of small circle arcs. In this instance the user may trace manually (and eventually edit) a line which is parallel to existing fracture zones, or ask Magan to generate one starting from a preliminary rotation model. Again, the automatic generation of flow lines requires a click at the assumed location of the origin.

Once a flow line has been defined, the user can project the ship-track magnetic and bathymetric data onto it. In order to avoid the projection of points that are too far away from the flow line, the user specifies a maximum allowed distance of the data from the flow line. It should be noted that a reliable analysis of marine magnetic anomalies requires that data do not cross fracture zones. Therefore, the user should select with care this parameter before launching the projection procedure.

When the ship-track is highly oblique with respect to the azimuth of the surrounding fracture zones, it is not appropriate to build a flow line as described above, because this approach would require a large distance of projection. Therefore, in this instance it is convenient to create a flow line which interpolates the real ship-track trend, and use the global spreading obliquity parameter to set the angle between magnetized prisms and profile strike. This trick allows Magan to perform correctly the computation of model anomalies. The next chapter discusses the basic procedures adopted by Magan for the calculation of model anomalies starting from a projected ship-track data set and a flow line. A more comprehensive treatment of this subject can be found in Schettino (2014).

Chapter 2

Calculation of Model Anomalies

2.1 Magnetic Anomalies

A *total field anomaly* is calculated from total field measurements by subtracting a reference regional field, usually the IGRF, and eventually applying a diurnal correction, which removes those components of the measured field associated with solar and ionospheric activity. If $T = T(\boldsymbol{r},t)$ is the measured magnitude of total field at location $\boldsymbol{r}$ and time t, which can be obtained by scalar magnetometer surveys, $F = F(\boldsymbol{r},t)$ is the reference field at the same point and time, e.g., the IGRF or DGRF field, and $\Delta S = \Delta S(\boldsymbol{r},t)$ is a diurnal correction, then the total field anomaly is defined as:

$$\Delta T(\boldsymbol{r},t) = T(\boldsymbol{r},t) - F(\boldsymbol{r},t) - \Delta S(\boldsymbol{r},t) \qquad (1)$$

The IGRF (or DGRF) reference field is predominantly a long wavelength field component, which roughly represents the influence of the core magnetic field and its secular variation, although its truncated spherical harmonic series at order $n = 10$ for dates preceding year 2000 and $n = 13$ from 2000 onward still includes small crustal contributions. This field varies from being horizontal and of magnitude about 30000 nT near the Equator to vertical and about 60000 nT near the poles; the root mean square (rms) magnitude of the vector over the surface is ~45000 nT. The field also varies in time, on a time-scale of months and longer. This is the so-called secular variation (SV), which has a global rms magnitude of about 80 nT/yr.

Another contribution to the observed magnetic field comes from electric currents in the ionosphere and magnetosphere, and from the associated induced fields generated by currents induced in the crust. The so-called solar-quiet (S_q) fields determine daily variations having primarily frequencies of 24, 12, 8, and 6 hours and amplitudes of few tens nT. However, these external contributions can reach 1000 nT during magnetic storms. Determination of these components in Eq. 1 can be performed using magnetic observatory data and/or a special design of the survey tracks. Unfortunately, as most marine surveys lack these kinds of data, the calculation of marine magnetic anomalies is simply performed by subtraction of the reference field.

Let $\Delta\boldsymbol{F}$ be the perturbation of the main reference field caused by a crustal magnetic source. If we ignore the external contribution, then the observed field at location $\boldsymbol{r}$ and time t will be given by (e.g., Blakely, 1995):

$$\boldsymbol{T}(\boldsymbol{r},t)=\boldsymbol{F}(\boldsymbol{r},t)+\Delta\boldsymbol{F}(\boldsymbol{r}) \quad (2)$$

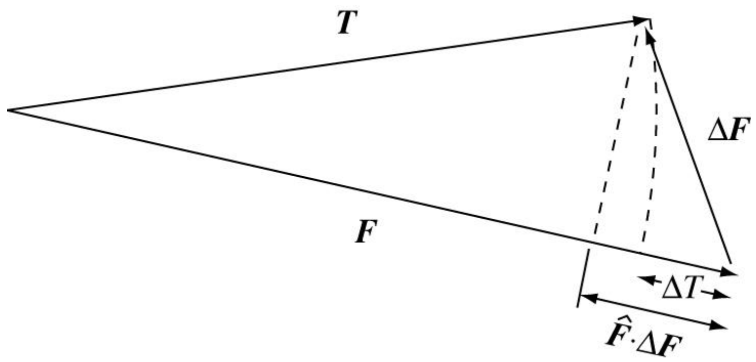

Figure 5. Relationship between main field $\boldsymbol{F}$, observed field $\boldsymbol{T}$, and anomalous field $\Delta\boldsymbol{F}$.

The relationship between observed and reference fields with the vector anomaly is illustrated in Fig. 5. We note that the total field anomaly ΔT is not equivalent to the magnitude of the anomalous field, ΔF , because ΔT = $|\boldsymbol{F}+\Delta\boldsymbol{F}|-|\boldsymbol{F}|\neq\Delta F$. Note that in Equation (2) the anomalous field vector is considered as time-independent, which is only approximately true because a small component of time-varying induced magnetization is always present in $\Delta\boldsymbol{F}$. In order to understand the meaning of total field anomalies ΔT, we must consider that under the typical conditions of crustal studies $|\boldsymbol{F}|>>\Delta F$.

In this instance we can write:

$$\Delta T = \left|\boldsymbol{F} + \Delta\boldsymbol{F}\right| - \left|\boldsymbol{F}\right| \cong \sqrt{\boldsymbol{F}\cdot\boldsymbol{F} + 2\boldsymbol{F}\cdot\Delta\boldsymbol{F}} - \left|\boldsymbol{F}\right| = F\sqrt{1 + \frac{2\boldsymbol{F}\cdot\Delta\boldsymbol{F}}{\boldsymbol{F}\cdot\boldsymbol{F}}} - F \cong$$
$$\cong F\left[1 + \frac{\boldsymbol{F}\cdot\Delta\boldsymbol{F}}{\boldsymbol{F}\cdot\boldsymbol{F}}\right] - F = F\frac{\boldsymbol{F}\cdot\Delta\boldsymbol{F}}{\boldsymbol{F}\cdot\boldsymbol{F}} = \hat{\boldsymbol{F}}\cdot\Delta\boldsymbol{F} \qquad (3)$$

Therefore, the total field anomaly ΔT approximately coincides with the projection of the anomalous field onto the reference field axis. In other words, ΔT approximates the component of the field generated by the crustal sources in the direction of the regional field. Typical total field anomalies range from a few nT to thousands of nT, with an rms value of 200 – 300 nT. Therefore, the condition $\left|\boldsymbol{F}\right| >> \Delta F$ is usually met. Note that in general ΔT is not a function of the position only, even if we consider $\Delta\boldsymbol{F}$ as a time independent vector quantity, because it is obtained by projecting $\Delta\boldsymbol{F}$ onto a time-varying field direction.

2.2 Modelling of Marine Magnetic Anomalies

In general, the forward modelling procedure of identification of marine magnetic anomalies requires the calculation of the vector field $\Delta\boldsymbol{F} = \Delta\boldsymbol{F}(\boldsymbol{r})$, associated with a distribution of magnetized blocks of oceanic crust. Then, total field magnetic anomalies are calculated for the survey time and compared with the observed anomalies. A best match is found by trial and errors varying the spreading rate function, hence the width of crustal blocks having normal or reversed magnetization.

Consider now the problem of calculating the gravitational or magnetic field generated by a distribution of mass or (respectively) magnetization. The method described here was first proposed by Talwani & Ewing (1960) and subsequently modified by Won & Bevis (1987) to improve the computational efficiency. In this approach a body is represented by a stack of infinitely thin laminas. Then, the boundary of each lamina is approximated by a polygon (Fig. 6). The observation point is placed at the origin of a reference frame. Let's consider first the calculation of the gravity of a mass distribution.

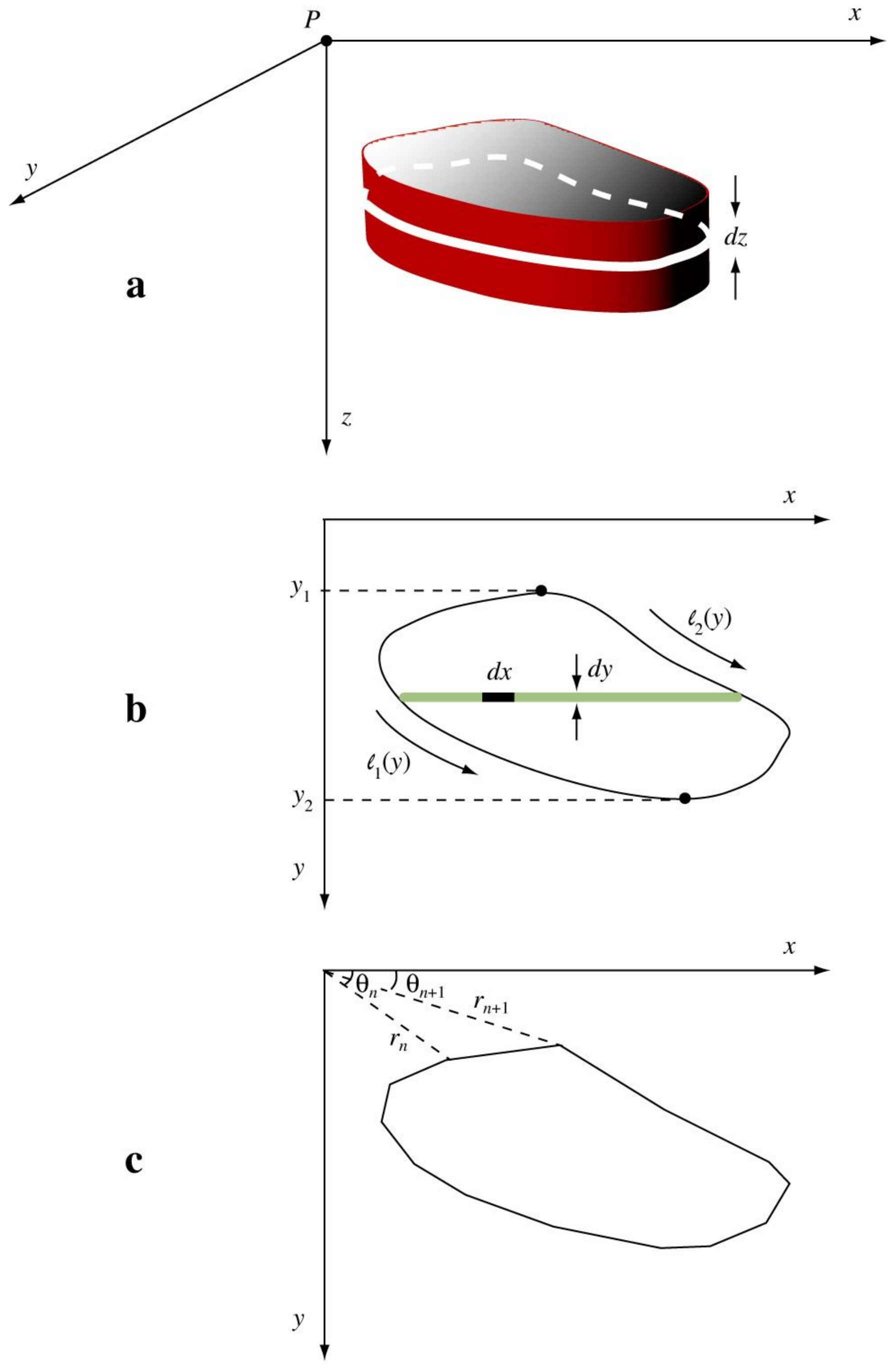

Figure 6. Stack of laminae in the Talwani & Ewing's (1960) method of calculation.

The potential V of the distribution is given by:

$$V = G \int_R \frac{\rho(\boldsymbol{r})}{r} dxdydz \tag{4}$$

where R is the region containing the mass distribution, $\rho = \rho(\boldsymbol{r})$ is the local density, and G is the gravitational constant. The gravity associated with this potential is:

$$\boldsymbol{g} = -\nabla V = G\int_R \frac{\rho(\boldsymbol{r})\hat{\boldsymbol{r}}}{r^2} dxdydz \tag{5}$$

We are generally only interested to the vertical component of gravity, because gravity meters just measure this quantity. If we indicate this component by γ then,

$$\gamma = -\frac{\partial V}{\partial z} = G\int_R \frac{\rho(x,y,z)z}{\left(x^2+y^2+z^2\right)^{3/2}} dxdydz \tag{6}$$

This equation has the general form:

$$\gamma = \int_R \rho(x,y,z)\psi(x,y,z)dxdydz \tag{7}$$

where the function:

$$\psi(x,y,z) = G\frac{z}{\left(x^2+y^2+z^2\right)^{3/2}} \tag{8}$$

is called a *Green's function*. We now assume that the density is constant within the region R.

In this instance, Equation (6) reduces to:

$$\gamma = G\rho \int_{z_1}^{z_2} \left[\int_{S(z)} \frac{dxdy}{\left(x^2 + y^2 + z^2\right)^{3/2}} \right] zdz \equiv G\rho \int_{z_1}^{z_2} \Gamma(z) zdz \tag{9}$$

where:

$$\Gamma(z) = \int_{S(z)} \frac{dxdy}{\left(x^2 + y^2 + z^2\right)^{3/2}} \tag{10}$$

The integral $\Gamma(z)$ represents a surface integral over a single horizontal lamina of the body. As shown in Fig. 6b, it can be converted into a line integral around the perimeter of the lamina. In fact, let (x_1,y_1) and (x_2,y_2) be respectively the points having absolute minimum and maximum of y within the region $S(z)$. We also assume that the region $S(z)$ has not relative maxima or minima for variable y. In this instance, the boundary of $S(z)$ can be represented by two functions $x = \ell_1(y)$ and $x = \ell_2(y)$ connecting (x_1,y_1) to (x_2,y_2). For any function $f(x,y)$ on the surface of the lamina it results:

$$\int_{S(z)} f(x,y) dxdy = \int_{y_1}^{y_2} dy \int_{\ell_1(y)}^{\ell_2(y)} f(x,y) dx = \int_{y_1}^{y_2} dy \left[F(\ell_2(y), y) - F(\ell_1(y), y) \right] = \oint_{\mathrm{B}(z)} F(x,y) dy \tag{11}$$

where B(z) is the boundary of $S(z)$. Therefore, the quantity $\Gamma(z)$ in Eq. 10 assumes the following expression:

$$\Gamma(z) = \oint_{B(z)} \frac{x}{\left(y^2 + z^2\right)\sqrt{x^2 + y^2 + z^2}} dy \tag{12}$$

This integral can be calculated by approximating the perimeter B(z) of the lamina through a polygon having vertices $(\xi_1,\zeta_1),(\xi_2,\zeta_2),\ldots,(\xi_n,\zeta_n)$, as shown in Fig. 6c. This is equivalent to approximate the functions $\ell_1(y)$ and $\ell_2(y)$ by piecewise first-order polynomials. Therefore, the line integral (12) will be converted into a sum of simple integrals:

$$\Gamma(z) \cong \sum_{n=1}^{N} \int_{\zeta_n}^{\zeta_{n+1}} \frac{x}{\left(y^2+z^2\right)\sqrt{x^2+y^2+z^2}}\, dy \;\; ; \;\; \zeta_{N+1} \equiv \zeta_1 \tag{13}$$

The variable x in this equation can be easily expressed in terms of y, because the path is composed by straight line segments:

$$x = \alpha_n y + \beta_n \tag{14}$$

where:

$$\alpha_n = \frac{\xi_{n+1} - \xi_n}{\zeta_{n+1} - \zeta_n} \;\; ; \;\; \beta_n = \xi_n - \alpha_n \zeta_n \tag{15}$$

Finally, substitution in Eq. (13) provides:

$$\Gamma(z) \cong \sum_{n=1}^{N} \int_{\zeta_n}^{\zeta_{n+1}} \frac{\left(\alpha_n y + \beta_n\right)}{\left(y^2+z^2\right)\sqrt{\left(\alpha_n^2+1\right)y^2 + 2\alpha_n\beta_n y + \beta_n^2 + z^2}}\, dy \;\; ; \;\; \zeta_{N+1} \equiv \zeta_1 \tag{16}$$

The solution of these integrals gives:

$$\Gamma(z) \cong \sum_{n=1}^{N} \left[\arctan \Omega_n\left(\xi_{n+1}, \zeta_{n+1}, z\right) - \arctan \Omega_n\left(\xi_n, \zeta_n, z\right)\right] \tag{17}$$

where:

$$\Omega_n(x,y,z)=\frac{z\left(\beta_n y-\alpha_n z^2\right)}{x\left[\left(1+\alpha_n^2\right)z^2+\beta_n^2\right]-\left(\alpha_n^2 z^2+\beta_n^2\right)\sqrt{x^2+y^2+z^2}} \tag{18}$$

Substituting the solution (17) into equation (9) provides the vertical component of gravity in the origin. In general, integration over z can be performed using standard numerical techniques and should not constitute a problem. The basic idea of converting a surface integral into a line integral around the surface boundary also represents the starting point of the method proposed by Talwani, Worzel & Landisman (1959) for calculating the gravity anomalies of two-dimensional bodies. A geological structure having a linear trend, for example a long horizontal cylinder, generates linear magnetic or gravity anomalies and can be modelled by sources, respectively magnetic or gravitational, that are invariant along the direction parallel to the long side. In this case the y axis is often chosen parallel to the invariant direction (Fig. 7), leaving calculations to be performed only with respect to the x and z dimensions. We say that the corresponding problem is two–dimensional. This class of forward-modelling problems can be solved by approximating the cross-section of the body by an N–sided polygon, in a way similar to that illustrated in Fig. 6c. As the density of a two–dimensional source does not vary along the y dimension, we can set: $\rho = \rho(x,z)$.

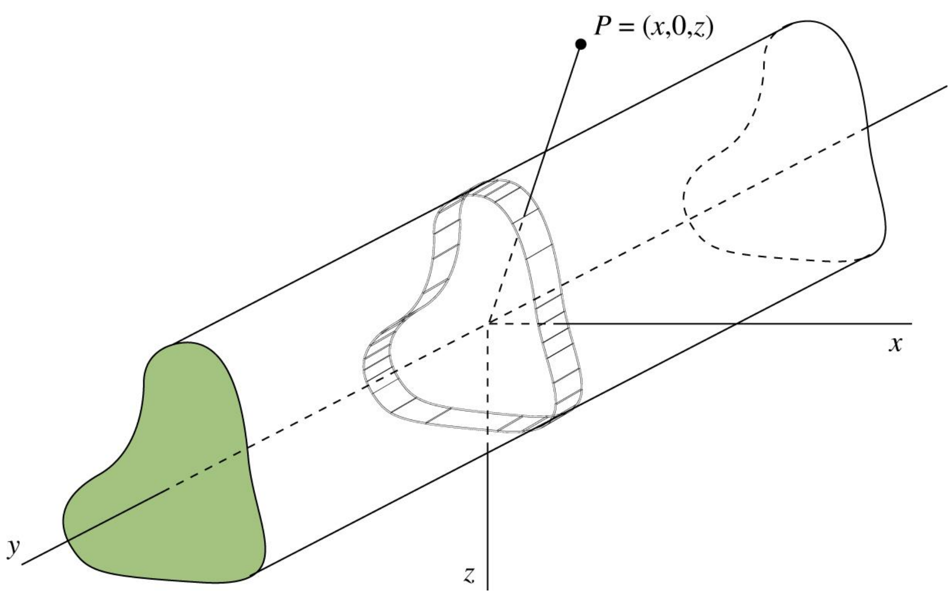

Figure 7. Geometry of a two-dimensional problem.

The gravitational potential of a linear body such that illustrated in Fig. 7 can be written as:

$$V(x,0,z)=G\int_R \frac{\rho(x',z')}{\sqrt{(x-x')^2+y'^2+(z-z')^2}}dx'dy'dz'=$$

$$=G\int_S \rho(x',z')\left[\int_{-\infty}^{+\infty}\frac{dy'}{\sqrt{(x-x')^2+y'^2+(z-z')^2}}\right]dx'dz'=$$

$$=G\int_S \rho(x',z')\left[\lim_{a\to\infty}\int_{-a}^{+a}\frac{dy'}{\sqrt{r^2+y'^2}}\right]dx'dz'=$$

$$=G\int_S \rho(x',z')\left\{\lim_{a\to\infty}\left[\log\left(a+\sqrt{r^2+a^2}\right)-\log\left(-a+\sqrt{r^2+a^2}\right)\right]\right\}dx'dz'=$$

$$=G\int_S \rho(x',z')\left\{\lim_{a\to\infty}\log\frac{a+\sqrt{r^2+a^2}}{-a+\sqrt{r^2+a^2}}\right\}dx'dz' \tag{19}$$

where $r\equiv\sqrt{(x-x')^2+(z-z')^2}$ and S is the cross-section of the volume R orthogonal to the y axis. Clearly, as $a\to\infty$ the limit in (19) diverges, and the potential approaches infinity. This problem is overcome by changing the definition of the potential for infinitely extended bodies. The potential of an infinite body is defined to be zero at a unit distance from the body (r = 1). This is accomplished by adding a constant quantity to the previous equation:

$$V(x,0,z)=G\int_S \rho(x',z')\left\{\lim_{a\to\infty}\left[\log\frac{a+\sqrt{r^2+a^2}}{-a+\sqrt{r^2+a^2}}-\log\frac{a+\sqrt{1+a^2}}{-a+\sqrt{1+a^2}}\right]\right\}dx'dz'=$$

$$=2G\int_S \rho(x',y')\log\frac{1}{r}dx'dz' \tag{20}$$

If we move the observation point to the origin of the reference frame and assume a constant density ρ, the vertical component of gravity will be given by:

$$\gamma = -\frac{\partial V}{\partial z} = 2G\rho \int_S \frac{z' dx' dz'}{x'^2 + z'^2} \tag{21}$$

Integration over x' yields:

$$\gamma = 2G\rho \int_{z_1}^{z_2} dz' \left[\arctan \frac{\ell_2(z')}{z'} - \arctan \frac{\ell_1(z')}{z'} \right] = 2G\rho \oint_{B(S)} \arctan \frac{x'}{z'} dz' \tag{22}$$

where ℓ_1 and ℓ_2 are function of z' and B(S) is the boundary of S. As before, we now approximate the perimeter of S with an N–sided polygon having vertices $(\xi_1,\zeta_1),(\xi_2,\zeta_2),\ldots,(\xi_n,\zeta_n)$.

Equation (22) becomes:

$$\gamma = 2G\rho \sum_{n=1}^{N} \int_{\zeta_n}^{\zeta_{n+1}} \arctan \frac{x'}{z'} dz' \;\; ; \;\; \zeta_{N+1} = \zeta_1 \tag{23}$$

Expression for x' in terms of z' are similar to that discussed previously (eq. 14). We can write:

$$x' = \alpha_n z' + \beta_n \tag{24}$$

where α_n and β_n are given by eq. (15).

Finally, substitution in Eq. (23) provides:

$$\gamma = 2G\rho\sum_{n=1}^{N}\left\{\begin{aligned}&\frac{\pi}{2}\left(\zeta_{n+1}-\zeta_n\right)+\left(\zeta_n \arctan\frac{\zeta_n}{\xi_n}-\zeta_{n+1}\arctan\frac{\zeta_{n+1}}{\xi_{n+1}}\right)+\\&+\frac{\beta_n}{1+\alpha_n^2}\left[\log\frac{\sqrt{\xi_{n+1}^2+\zeta_{n+1}^2}}{\sqrt{\xi_n^2+\zeta_n^2}}-\alpha_n\left(\arctan\frac{\zeta_{n+1}}{\xi_{n+1}}-\arctan\frac{\zeta_n}{\xi_n}\right)\right]\end{aligned}\right\}\ ;\ \xi_{N+1}=\xi_1\ ;\ \zeta_{N+1}=\zeta_1 \tag{25}$$

The first two terms in parentheses of summation give zero after summation. Therefore:

$$\gamma = 2G\rho\sum_{n=1}^{N}\left\{\frac{\beta_n}{1+\alpha_n^2}\left[\log\frac{\sqrt{\xi_{n+1}^2+\zeta_{n+1}^2}}{\sqrt{\xi_n^2+\zeta_n^2}}-\alpha_n\left(\arctan\frac{\zeta_{n+1}}{\xi_{n+1}}-\arctan\frac{\zeta_n}{\xi_n}\right)\right]\right\}\ ;\ \xi_{N+1}=\xi_1\ ;\ \zeta_{N+1}=\zeta_1 \tag{26}$$

This solution implies that the gravity of a body in a two-dimensional problem only depends upon the coordinates of the vertices of a polygon that approximates its cross-section.

Vertex coordinates (ξ_n,ζ_n) in Equation (26) can be replaced by quantities r_n and θ_n illustrated in Fig. 6c. In fact,

$$r_n=\sqrt{\xi_n^2+\zeta_n^2}\ ;\ \theta_n=\arctan\frac{\zeta_n}{\xi_n} \tag{27}$$

In this instance the solution assumes the following simple form:

$$\gamma = 2G\rho\sum_{n=1}^{N}\left\{\frac{\beta_n}{1+\alpha_n^2}\left[\log\frac{r_{n+1}}{r_n}-\alpha_n\left(\theta_{n+1}-\theta_n\right)\right]\right\}\ ;\ \xi_{N+1}=\xi_1\ ;\ \zeta_{N+1}=\zeta_1 \tag{28}$$

Therefore, the normal gravity of a two-dimensional problem depends upon the distances of the polygon vertices from the observation point and from the angles that the radii r_n make with the horizontal. Angles θ_n are calculated through Eq. (27) by calling the *atan2*() C library function. This call may lead to improper evaluation of these quantities when the observation point is located between ζ_n and ζ_{n+1}. Therefore, the following tests are performed:

if ($sgn(\zeta_n) \neq sgn(\zeta_{n+1})$) then
{
if ($\xi_n\zeta_{n+1} < \xi_{n+1}\zeta_n$ and $\zeta_{n+1} \geq 0$) then $\theta_n \leftarrow \theta_n + 2\pi$;
else if ($\xi_n\zeta_{n+1} > \xi_{n+1}\zeta_n$ and $\zeta_n \geq 0$) then $\theta_{n+1} \leftarrow \theta_{n+1} + 2\pi$;
else if ($\xi_n\zeta_{n+1} = \xi_{n+1}\zeta_n$) then $\gamma \leftarrow 0$;
}
if ($\xi_n = \zeta_n = 0$ or $\xi_{n+1} = \zeta_{n+1} = 0$) then $\gamma \leftarrow 0$;
if ($\xi_n = \xi_{n+1}$) then $\dfrac{\beta_n}{1+\alpha_n^2}\left[\log\dfrac{r_{n+1}}{r_n} - \alpha_n\left(\theta_{n+1}-\theta_n\right)\right] \leftarrow \xi_n \log\dfrac{r_{n+1}}{r_n}$

The typical conventions for the calculation of normal gravity through Eq. (28) require clockwise polygons, and a downward directed *z* axis, as shown in Fig. 7.

Consider now the problem of calculating the magnetic anomaly generated by a magnetized 2-dimensional body. This anomaly can be easily computed by the Poisson's relation using the previous equations. Consider a body with uniform magnetization $\boldsymbol{M}$ and density ρ. A small element of the body can be considered as a single dipole having magnetic moment $\boldsymbol{m} = \boldsymbol{M}dxdydz$. If the observation point is placed at the origin, then a dipole at location $\boldsymbol{r}$ generates a small magnetic field $d\boldsymbol{B}$ which is approximately given by:

$$d\boldsymbol{B} \cong \frac{\mu_0}{4\pi}\left(3\frac{\boldsymbol{M}\cdot\boldsymbol{r}}{r^5}\boldsymbol{r} - \frac{\boldsymbol{M}}{r^3}\right)dxdydz \tag{29}$$

where μ_0 is the vacuum magnetic permeability:

$$\mu_0 = 4\pi\times10^{-7}\ \text{H/m}$$

Therefore, the potential *dV* is given by:

$$dV \cong \frac{\mu_0}{4\pi} \frac{\boldsymbol{M} \cdot \boldsymbol{r}}{r^3} dxdydz = -\frac{\mu_0}{4\pi} \boldsymbol{M} \cdot \nabla \left(\frac{1}{r} \right) dxdydz \tag{30}$$

Integrating Equation (30) over the region *R* occupied by the body gives the total magnetic potential *V*:

$$V \cong \frac{\mu_0}{4\pi} \int_R \frac{\boldsymbol{M} \cdot \boldsymbol{r}}{r^3} dxdydz = -\frac{\mu_0}{4\pi} \boldsymbol{M} \cdot \nabla \int_R \left(\frac{1}{r} \right) dxdydz \tag{31}$$

This formula is similar to solution (4) for the gravitational force of a mass distribution if the body density is constant. In fact, in this instance Equation (4) gives:

$$V = G\rho \int_R \frac{1}{r} dxdydz \tag{32}$$

$$\boldsymbol{g} = -\nabla V = -G\rho \nabla \int_R \left(\frac{1}{r} \right) dxdydz \tag{33}$$

Therefore, the magnetic potential of a uniformly magnetized body having constant density can be written as:

$$V = \frac{\mu_0}{4\pi G\rho} \boldsymbol{M} \cdot \boldsymbol{g} = \frac{\mu_0 \chi}{4\pi G\rho} \boldsymbol{H} \cdot \boldsymbol{g} \tag{34}$$

where χ is the magnetic susceptivity and $\boldsymbol{H}$ is the inducing geomagnetic or palaeomagnetic field. This Equation is called the *Poisson's relation*. It states that the magnetic potential of a uniformly magnetized body having constant density is proportional to the component of the gravity field in the direction of magnetization. Therefore, taking the gradient of Eq. (34) we obtain that the anomalous field of a body in a 2-dimensional problem can be written as:

$$\Delta \boldsymbol{F} = \nabla V = \frac{\mu_0 M}{4\pi G\rho}\frac{\partial \boldsymbol{g}}{\partial n} = \frac{\mu_0 \chi H}{4\pi G\rho}\frac{\partial \boldsymbol{g}}{\partial n} \tag{35}$$

where n is the direction of induced or remnant magnetization. This solution implies that unlike the gravity anomaly, the magnetic anomaly also depends on the strike of the body, as this affects the direction of magnetization. Let I and α be respectively the mean palaeomagnetic field inclination in the survey area, and the strike of the body measured counterclockwise from the paleomagnetic North to the negative y-axis (Fig. 8).

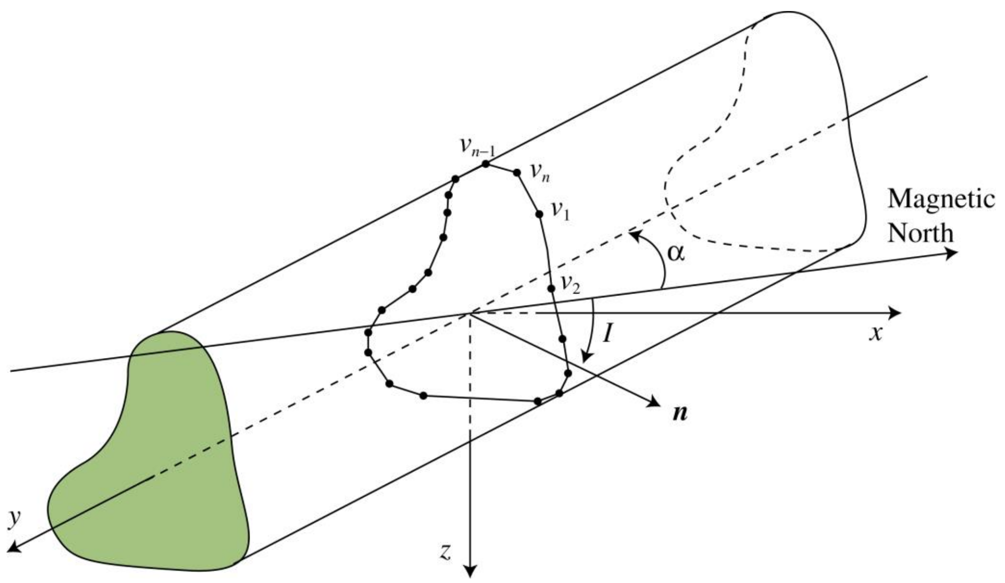

Figure 8. Conventions and geometry of a two-dimensional problem. The polygon approximating the body cross-section has vertices v_i which are ordered clockwise.

The unit vector associated with the magnetization direction can be written as:

$$\begin{cases} n_x = \cos I \sin \alpha \\ n_y = \cos I \cos \alpha \\ n_z = \sin I \end{cases} \tag{36}$$

Therefore, for any scalar field ϕ, constant in the y direction, the directional derivative of ϕ along direction n results to be:

$$\frac{\partial \phi}{\partial n} = \nabla \phi \cdot \boldsymbol{n} = \frac{\partial \phi}{\partial x} \cos I \sin \alpha + \frac{\partial \phi}{\partial z} \sin I \tag{37}$$

It is easy to determine the vertical and horizontal components of the anomalous field combining Equations (35) and (37). We obtain:

$$\Delta F_x = \frac{\mu_0 M}{4\pi G \rho} \frac{\partial g_x}{\partial n} = \frac{\mu_0 M}{4\pi G \rho} \left(\frac{\partial g_x}{\partial x} \cos I \sin \alpha + \frac{\partial g_x}{\partial z} \sin I \right) \tag{38}$$

$$\Delta F_z = \frac{\mu_0 M}{4\pi G \rho} \frac{\partial g_z}{\partial n} = \frac{\mu_0 M}{4\pi G \rho} \left(\frac{\partial g_z}{\partial x} \cos I \sin \alpha + \frac{\partial g_z}{\partial z} \sin I \right) \tag{39}$$

Quantities g_z and g_x can be calculated respectively using Equation (28) (because $g_z \equiv \gamma$) and a similar formula for g_x. These formulae can be written as follows:

$$g_x = 2G\rho \sum_{n=1}^{N} X_n \ ; \ g_z = 2G\rho \sum_{n=1}^{N} Z_n \tag{40}$$

where,

$$X_n = \frac{\beta_n}{1+\alpha_n^2}\left[\alpha_n \log\frac{r_{n+1}}{r_n} + \left(\theta_{n+1} - \theta_n\right)\right] \tag{41}$$

$$Z_n = \frac{\beta_n}{1+\alpha_n^2}\left[\log\frac{r_{n+1}}{r_n} - \alpha_n\left(\theta_{n+1} - \theta_n\right)\right] \tag{42}$$

Therefore, substituting these expressions into Equations (38) and (39) we get:

$$\Delta F_x = \frac{\mu_0 M}{2\pi}\sum_{n=1}^{N}\left(\frac{\partial X_n}{\partial x}\cos I \sin\alpha + \frac{\partial X_n}{\partial z}\sin I\right) \tag{43}$$

$$\Delta F_z = \frac{\mu_0 M}{2\pi}\sum_{n=1}^{N}\left(\frac{\partial Z_n}{\partial x}\cos I \sin\alpha + \frac{\partial Z_n}{\partial z}\sin I\right) \tag{44}$$

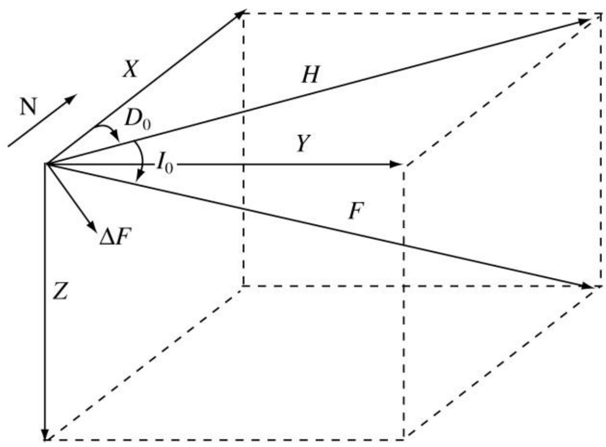

Figure 9. Components of the Earth's reference field ***F*** in a local frame of reference. *H* is the horizontal component, *X* and *Y* are respectively the North and East components, *Z* is the vertical component, (positive if downward directed). *Declination* D_0 is the angle between the North direction and the horizontal projection of the field, measured clockwise. The angle between projection *H* and the field is the *inclination* I_0, positive if ***F*** is downward directed.

We have shown that the total field anomaly can be easily calculated by projecting the vector $\Delta\boldsymbol{F}$ onto the present-day reference field axis (Eq. 3). Let D_0 and I_0 be respectively the declination and inclination of the reference field (Fig. 9). The components of the anomalous field vector $\Delta\boldsymbol{F}$ that are calculated through Eq. (43) and (44) are expressed in the local (x,y,z) frame of a prism. In order to combine the contributions of several blocks through the superposition principle we must represent the anomalous vector components in a common reference frame. Then, the expected total field anomaly, ΔT, associated with the crustal field $\Delta\boldsymbol{F} = \Delta\boldsymbol{F}(\boldsymbol{r})$ can be calculated by projecting the vector $\Delta\boldsymbol{F}$ onto the axis of the present-day reference field $\boldsymbol{F}$, which has declination, D_0, and inclination, I_0, in the (X,Y,Z) local reference frame of Fig. 9. Therefore, it is convenient to express the components of the anomalous magnetic field vectors generated by each block in the standard (X,Y,Z) coordinate system. Let β ($0° \le \beta < 360°$) be the local strike of the y axis, measured clockwise from the North. As it is shown below, this quantity is determined by the local trend of the flow line. Then, the components of the vector $\Delta\boldsymbol{F}$ in the local frame of reference can be easily obtained by the following simple transformation:

$$\begin{cases} \Delta F_X = \Delta F_x \sin\beta \\ \Delta F_Y = -\Delta F_x \cos\beta \\ \Delta F_Z = \Delta F_z \end{cases} \tag{45}$$

It should be noted that the anomalous field vectors don't have y-components in the (x,y,z) reference frames, whereas they have non-zero Y-components with respect to the standard (X,Y,Z) coordinate system. Therefore, the total field anomaly at an observation point $\boldsymbol{r}$, ΔT, is given by:

$$\Delta T = \Delta\boldsymbol{F} \cdot \hat{\boldsymbol{F}} = \hat{F}_X \Delta F_X + \hat{F}_Y \Delta F_Y + \hat{F}_Z \Delta F_Z = \cos I_0 \left(\Delta F_X \cos D_0 + \Delta F_Y \sin D_0\right) + \Delta F_Z \sin I_0 \tag{46}$$

Evaluation of derivatives in formulae (43) and (44) is simple:

$$\frac{\partial Z_n}{\partial z} = \frac{\left(\xi_{n+1} - \xi_n\right)^2}{R^2} \left[\frac{\zeta_{n+1} - \zeta_n}{\xi_{n+1} - \xi_n} \log \frac{r_{n+1}}{r_n} - \left(\theta_{n+1} - \theta_n\right) \right] - P \tag{47}$$

Furthermore,

$$\frac{\partial Z_n}{\partial x} = -\frac{(\xi_{n+1}-\xi_n)(\zeta_{n+1}-\zeta_n)}{R^2}\left[\frac{\zeta_{n+1}-\zeta_n}{\xi_{n+1}-\xi_n}\log\frac{r_{n+1}}{r_n} - (\theta_{n+1}-\theta_n)\right] + Q \tag{48}$$

$$\frac{\partial X_n}{\partial z} = \frac{(\xi_{n+1}-\xi_n)^2}{R^2}\left[\log\frac{r_{n+1}}{r_n} + \frac{\zeta_{n+1}-\zeta_n}{\xi_{n+1}-\xi_n}(\theta_{n+1}-\theta_n)\right] + Q \tag{49}$$

Finally,

$$\frac{\partial X_n}{\partial x} = -\frac{(\xi_{n+1}-\xi_n)(\zeta_{n+1}-\zeta_n)}{R^2}\left[\log\frac{r_{n+1}}{r_n} + \frac{\zeta_{n+1}-\zeta_n}{\xi_{n+1}-\xi_n}(\theta_{n+1}-\theta_n)\right] + P \tag{50}$$

where,

$$R^2 = (\xi_{n+1}-\xi_n)^2 + (\zeta_{n+1}-\zeta_n)^2 \tag{51}$$

$$P = -\frac{\xi_n\zeta_{n+1}-\xi_{n+1}\zeta_n}{R^2}\left[\frac{\xi_n(\xi_{n+1}-\xi_n)-\zeta_n(\zeta_{n+1}-\zeta_n)}{r_n^2} - \frac{\xi_{n+1}(\xi_{n+1}-\xi_n)-\zeta_{n+1}(\zeta_{n+1}-\zeta_n)}{r_{n+1}^2}\right] \tag{52}$$

$$Q = -\frac{\xi_n\zeta_{n+1}-\xi_{n+1}\zeta_n}{R^2}\left[\frac{\xi_n(\zeta_{n+1}-\zeta_n)+\zeta_n(\xi_{n+1}-\xi_n)}{r_n^2} - \frac{\xi_{n+1}(\zeta_{n+1}-\zeta_n)+\zeta_{n+1}(\xi_{n+1}-\xi_n)}{r_{n+1}^2}\right] \tag{53}$$

Also in this case the evaluation of angles θ_n through the *atan2*() C library function must take into account of three special situations. The first two conditions are the same of the gravity case, whereas the third one is now,

if ($\xi_n = \xi_{n+1}$) then {

$$\frac{\partial Z_n}{\partial z} = -P \; ; \; \frac{\partial Z_n}{\partial x} = -\frac{(\zeta_{n+1}-\zeta_n)^2}{R^2}\log\frac{r_{n+1}}{r_n} + Q \; ; \frac{\partial X_n}{\partial z} = Q \; ; \; \frac{\partial X_n}{\partial x} = -\frac{(\zeta_{n+1}-\zeta_n)^2}{R^2}(\theta_{n+1}-\theta_n) + P$$

}

2.3 Forward Modelling

We now face the problem of applying the previous equations to the forward modelling procedure of marine magnetic anomalies. The crustal magnetization model is started with a sequence of m linear prisms draped on bathymetry, having constant height h equal to the user-defined magnetized layer thickness, and width w_i proportional to the corresponding chron duration:

$$w_i = \frac{1}{2} v \Delta t_i \tag{54}$$

where v is the default full spreading rate and Δt_i is the duration (in Myrs) of the i-th chron. The magnetization direction for each prism is determined on the basis of APWPs that are calculated through an user-supplied rotation model or, if the user doesn’t specify one, on the basis of the local geographic latitude and direction of spreading. In plate kinematics, the magnetization direction of a prism cannot be chosen as coincident with the present day reference field $\boldsymbol{F}$, not even when the data ages encompass the last 2–3 Myrs. In fact, assuming that the rock magnetization is entirely of NRM type, even in the case of rocks that formed during the last polarity chron, the average magnetization direction would be aligned with the *time–averaged geomagnetic field* for the last 0.78 Myrs, which is a GAD field. Therefore, in this instance the paleomagnetic direction in (38) and (39) would be I = 90°, D = 0° and *not* that of the local IGRF field (i.e., I_0 and D_0). These parameters can also be used for rocks of Pliocene – Pleistocene age, but in general older crust requires a different approach.

The along-track magnetic anomaly is computed applying Equation (46) to the vector summation of the anomalous fields associated with each block in the magnetization model. In order to determine the quantities I and α in Equations (43) and (44), we start from a palaeopole location (or the geographic North pole if an APWP is not available) and calculate the inclination using the well-known GAD (or dipole) formula:

$$\tan I = 2 \cot p \tag{55}$$

where p is the local palaeo-colatitude of the profile. If an APWP has not been defined, the inclination is calculated using the present day geographic colatitude. Calculation of α requires a knowledge of the site declination. Let β be the local strike of the spreading axis, $0° \leq \beta < 360°$, measured clockwise from the North (Fig. 10). Let D be the palaeopole declination. If an APWP is not available, then we set $D \leftarrow 0$. It can be easily shown that α is given by:

$$\alpha = D - \beta + 180° \tag{56}$$

The previous calculations assume that a palaeopole location (λ_p, φ_p) is available for calculating inclination, I, and declination, D, of remnant magnetization for the given prism. Conversely, quantities I and D are determined using the prism geographic colatidude, θ, in the GAD formula and assuming $D = 0$ when an APWP cannot be calculated. However, if an APWP is available for one of the two conjugate plates, quantities I and D must be determined also for the other plate when the flow line is symmetric with respect to the present-day or exinct spreading axis. Let I' and D' be respectively the inclination and declination of magnetization along the conjugate prism. Clearly, the two blocks formed at the same latitude. Therefore, we can assume that $I' = I$. Conversely, the declination will be different for the two conjugate prisms. However, knowing the local strike β' of the conjugate block it is possible to calculating D' through Equation (56), because the strike α is the same for the conjugate prisms:

$$D' = \alpha + \beta' - 180° \tag{57}$$

The algorithm of calculation of model magnetic anomaly profiles has in input a time table (t_j, t_{j+1}, χ_j), $j = 1,2,\ldots,T$, the rows of which specify top and base (in Ma) of each chron, and its formal name (e.g., "C2n"). Each chron name must terminate with an 'n' or an 'r', according to the chron polarity. The program uses this information to determine the orientation of magnetization. Also, the algorithm requires to specify offset, d_i, and altitude, h_i, of the observation points (in km). Altitudes h_i have a unique default value $h_i = h$, which is generally zero in the case of ship-track data. However, the user may wish assigning to this quantity a different value in the case of aeromagnetic surveys or special situations. A sequence of T values of the spreading rate is the third input data set (one for each chron in the time table). Velocities are initially set to a unique default value $v_k = v$, $k = 1,2,\ldots,T$, but the user generally changes these quantities interactively during the forward modelling procedure. Similarly, the default spreading obliquity ψ is initially set to 90° for all blocks, but the user can change this value when the observed magnetic stripes are oblique with respect to the local fracture zone trend. Finally, the algorithm accepts a sequence of magnetization amplitudes M_k, $k = 1,2,\ldots,T$. Also these quantities are initially set to a unique value $M_k = M$, which is typically changed during the subsequent modelling phase.

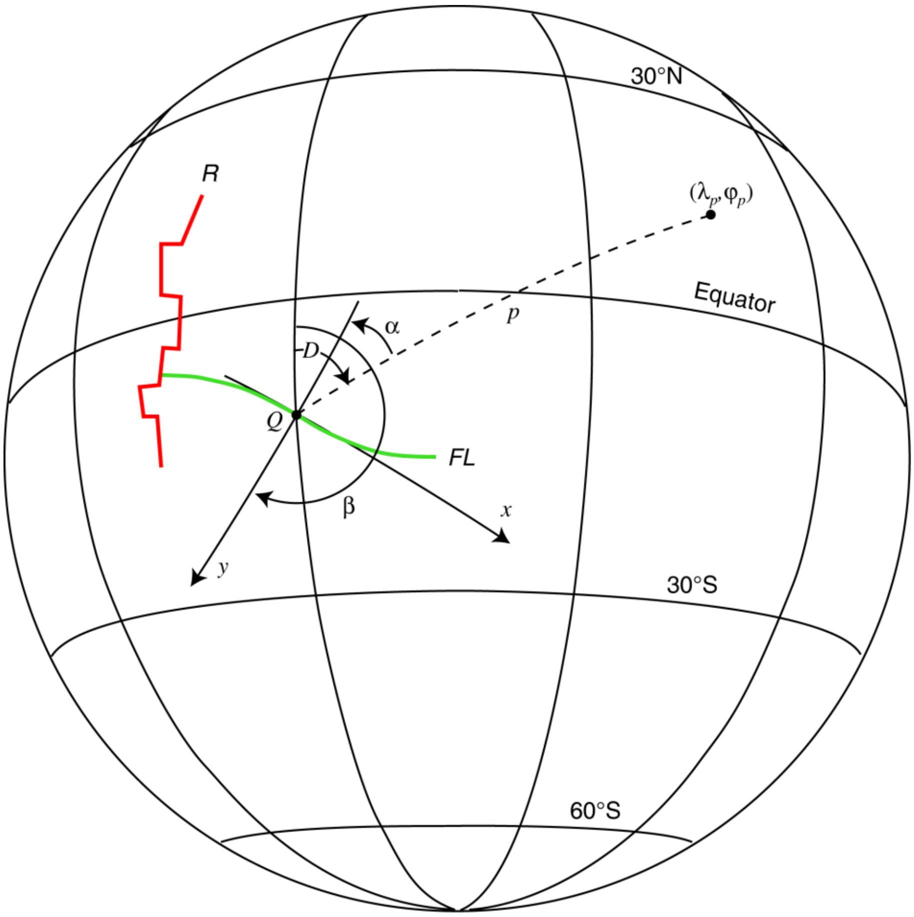

Figure 10. Local coordinate system for a prism at location Q along a flow line (FL) starting from a present ridge axis (R). (λ_p,φ_p) is the palaeopole location for the prism, calculated from the mean age of the associated chron. z axis (not shown) points downwards.

The modelling algorithm starts with the generation of a crustal magnetization model, according to the selected time scale and full spreading rates v_k (Fig. 11). The model consists of a sequence of polygons P_k, $k = 1,2,\ldots,S$, $S \leq 2T$, having vertices $a_{kn} = (\xi_{kn},\zeta_{kn})$ that are computed from the bathymetric data, the spreading velocities, and the magnetized layer thickness. Although the algorithm computes magnetic anomalies for the restricted range of x offsets where projected ship-track data are available, calculations are accomplished using blocks that are located along the full range of *x* offsets associated with the user-defined flow-line, as far as an user-specified cut-off distance is reached. In this way the algorithm tries to minimize boundary effects which generally determine unreliable results towards the profile edges. Once the quantities ΔT_i have been calculated for all the station points, the program displays the resulting plot in a model profile window (Fig. 2), along with the magnetization model and observed anomalies. Then, the user can select one or more blocks at a time by mouse clicking and change remnant magnetization or full spreading rate during the corresponding chron. The model is automatically changed after these operations.

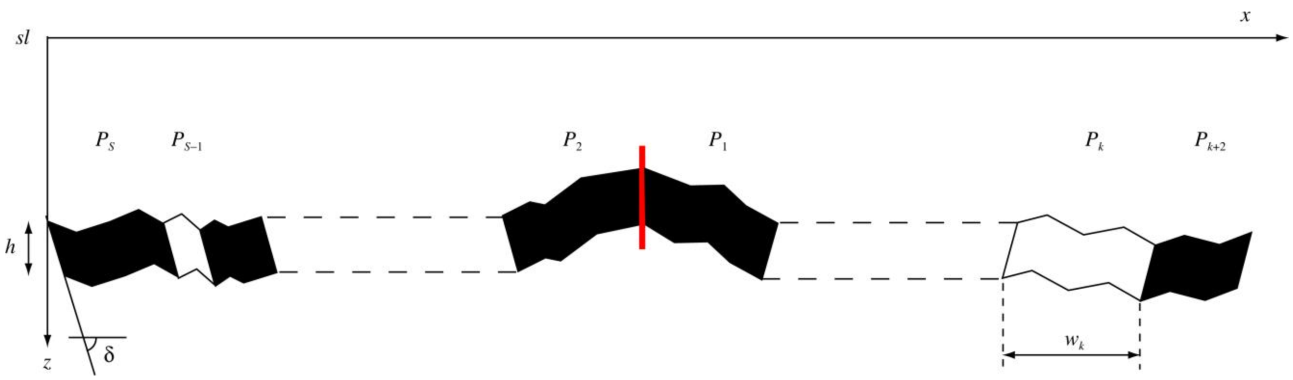

Figure 11. Geometry and numbering of magnetized prisms. The program starts building the magnetized blocks from the youngest (e.g., C1n), and stops when a block lies at offsets located outside the flow line cutoff distance. For each chron, the algorithm tries to build two conjugate blocks. Note that block walls always dip towards the spreading axis.

Chapter 3

Magan Commands

3.1 File Menu

File $\rightarrow$ *New Project*

This command creates an empty project. A new project window is open, ready to receive further commands and flow-line editing. The default background image is the low-resolution (5 min) Terrainbase grid, which has worldwide coverage and is available from NGDC. The flow line editing rules are simple:

a) A single mouse click far away from the current chain of nodes inserts a new point after the selected point;
b) Clicking on an existing node causes the selection of the point. The currently selected node is represented by a red circle. After insertion of a new node, this point becomes the selected node;
c) A right-click deletes an existing node;
d) The selected node can be moved to another location by dragging it across the window;
e) A flow line can be deleted at any time by pressing the key "Del".

Available commands when the active window is a project window are:

- All *File* menu commands;
- *Edit –> Flow Line*, which allows automatic creation of flow lines;
- All *Parameters* menu commands, which allow to set the global parameters of a model;

- *View –> Zoom in / Zoom out*, which allow to zoom over a window region or return to the previous view;
- *View –> Background image*, which displays or hide the background image;
- *View –> Ship–Track data points*, which displays or hide locations of ship-track data. Of course, this command is available when a ship-track has been imported;
- *View –> Projected data points*, which displays or hide the data after their projection onto the flow line;
- All *View –> Projected Data* menu commands. These commands are available when an NGDC or other ship-track data set has been imported and data have been projected;
- All *View –> NGDC/Source Data* menu commands. These commands are available when an NGDC or other ship-track data set has been imported;
- *View –> Velocity model*, which opens a velocity vs time window. This command is only available when a time scale has been loaded and a flow line origin has been defined;
- *View –> Age-Distance model*, which opens a crustal age vs distance window. This command is only available when a time scale has been loaded and a flow line origin has been defined;
- *Tools –> Measure Distance*, which allows to measure a distance over the background map;
- *Tools –> Theoretical Profile*, which allows to generate theoretical magnetic anomaly profiles according to specified parameters;
- All *Tools –> Import Data* menu commands;
- *Tools –> Project ship-track data*, which allows to project raw magnetic and bathymetric data onto a flow line;
- *Tools –> Set magnetic layer depths from gridded data*, which allows to define the depth of track-line magnetic data from gridded bathymetry;
- *Tools –> Export magnetic profile for filtering*, which allows to generate an ASCII table of magnetic data and offset that can be filtered by an external program;
- *Tools –> Forward Modelling*, which opens a new modelling window.

File → Open Project

This command opens an existing project and creates a project window for editing or running modelling windows, velocity windows, or age – distance windows. Magan projects are ASCII files containing a sequence of *param* = *value* pairs separated by newlines.

File → Save Project

This command saves the current project. Projects are ASCII files containing a sequence of rows with the format *param* = *value*, where *param* is a project parameter name and *value* is the current value. Allowed keywords and values for project parameters are listed in Table 1. The order of inclusion in the project file is non influential.

Table 1. Parameter keywords and allowed values in project files

Parameter Keyword	*Value*
Time_Scale	Full path of an ASCII file containing the time scale (*.txt)
RotModel	Full path of an ASCII file containing the rotation model (*.rot)
Background_Image	Full path of a 256-colors raster to be used as background image (*.bmp)
Project_Folder	Path to the folder where the project data are stored
Basement_Grid	Full path of a single-precision floating point grid containing basement depth data (*.flt)
Velocity	Default velocity [mm/yr]
Magnetization	Default magnetization [A/m]
Thickness	Block thickness [km]
Dip	Dip of block walls [30° ≤ δ ≤ 90°]
Altitude	Altitude of survey [km]
Cutoff	Cut-off distance for model anomalies calculation
D	Declination of reference field [°deg]
I	Inclination of reference field [°deg]
Mod_Res	Spacing of modelling station points along the flow line [km]
PosOffsetPlateId	Identifier (in the user-defined rotation model) of plate at positive offsets
NegOffsetPlateId	Identifier (in the user-defined rotation model) of plate at negative offsets
Last_Chron	Chron of ridge extinction or “C1n” for currently active ridges
First_ChronL	Chron associated with the oldest block in the left side magnetization model
First_ChronR	Chron associated with the oldest block in the right side magnetization model
Origin	Offset of origin in flow line list
Selected	Offset of currently selected node in flow line list
Background_Color	RGB code of current background color
Spr1_X, Spr2_X	*X* window coordinates of spreading ridge symbol end points
Spr1_Y, Spr2_Y	*Y* window coordinates of spreading ridge symbol end points
BmpOverlaid	Flag indicating if a background image is currently displayed
ShipTrackPoints	Flag indicating if ship track data points are currently displayed
ProjectedPoints	Flag indicating if projected data points are currently displayed
Aeromag	Flag indicating if ship track data points are aeromagnetic data
Data_Sorting	Integer which specifies the flow line sorting criterium (0,1,2)

Table 1 (Continued)

Parameter Keyword	*Value*
Projection_Distance	Maximum original distance of projected data points from the current flow line
Geomag_Params	Full path of an ASCII file containing geomagnetic field parameters (*.txt)
Version	Version of Magan which created the project
Axial_Magnetization	Default axial magnetization [A/m]
Obliquity	Default obliquity of the magnetized blocks [$30° \le \psi \le 150°$] with respect to flow line
Asymmetry	Default spreading asymmetry
Pen__Size_#*k*	If $k \le 8$, this is the size of a pen in graphics (e.g., velocity, track lines, etc.)
Pen_Color_#*k*	If $k \le 8$, this is the RGB code of a pen in graphics (e.g., velocity, track lines, etc.)

File → Save As

This command saves the current project in a different file.

File → Close

This command closes the current project.

File → Print

This command generates a printout of the window content.

File → Page Setup

This command allows the user to select the printer and setup the printer page.

File → Exit

This command terminates Magan.

3.2 Edit Menu

Edit → Flow Line → Generate from Euler pole

This command automatically generates a flow line as a small circle arc about an Euler pole. The command opens a dialog window (Fig. 12) where the user specifies the coordinates (Lat,Lon) of the Euler pole, the opening angle (in degrees), and if the rotation is clockwise or counterclockwise. It should be noted that Magan only accepts flow lines in which successive nodes have monotonically increasing longitudes or flow lines in which successive nodes have monotonically increasing latitudes. Therefore, the selection of the correct direction of rotation about the Euler pole is essential.

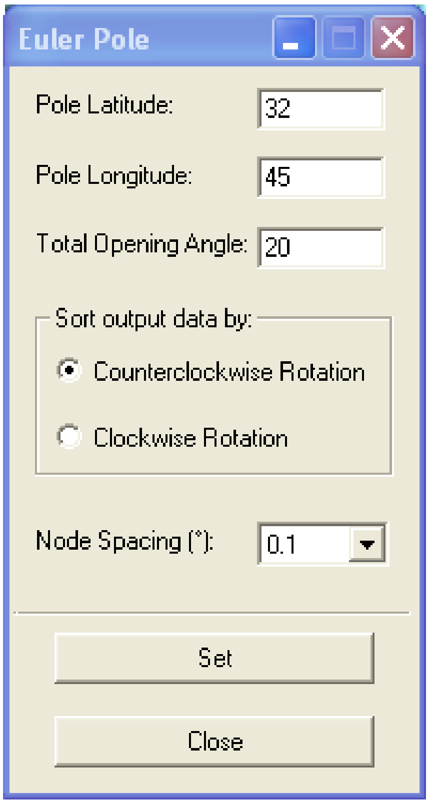

Figure 12. Dialog for the automatic generation of flow lines from Euler poles.

The selection of a node spacing in this dialog window (Fig. 12) determines the angular distance of the flow line nodes about the Euler pole. When all the parameters have been inserted, you must press the button “Set” and return to the project window without closing the dialog. Here you click at the assumed location of the flow line origin and the program immediately generates a flow line passing through that point. A successive click at a different location deletes the previous flow line and forces the creation of a new list. You may even change one or more parameters in the dialog, press the “Set” button again, and come back to the project window. When you are satisfied, press the “Close” button to close the dialog and return to the current project.

Edit → Flow Line → Generate from rotation model

This command automatically generates a flow line as a sequence of small circle arcs using the algorithm of Shaw (1987). To this purpose the program opens a dialog (Fig. 13) where the user specifies a rotation model, the plate identifiers at negative and positive offsets, the age of the oldest point (Start Time), and the age of the youngest point (End Times). The buttons “Set” and “Close” have the same meaning of the previous command.

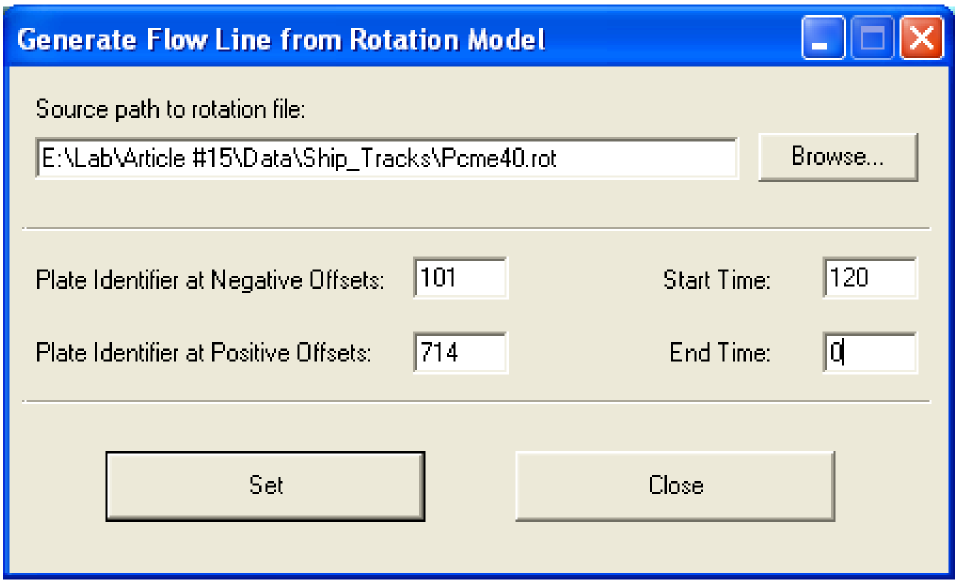

Figure 13. Dialog for the automatic generation of flow lines from rotation models.

Magan follows the Paleomap Project conventions regarding rotation models. Therefore, a rotation model is an ASCII table (*.rot) whose rows have the field structure listed in Table 2.

Table 2. Fields of a rotation model

Field Name	*Value*
Plate	3-digit plate identifier. “999” for comment lines
Time	Age of reconstruction pole [Ma]
Lat	Latitude of finite Euler reconstrruction pole [°deg]
Lon	Longitude of finite Euler reconstrruction pole [°deg]
Angle	Angle of finite rotation [°deg]
Ref. Plate	3-digit reference plate identifier
References	Up to 50 characters of comment

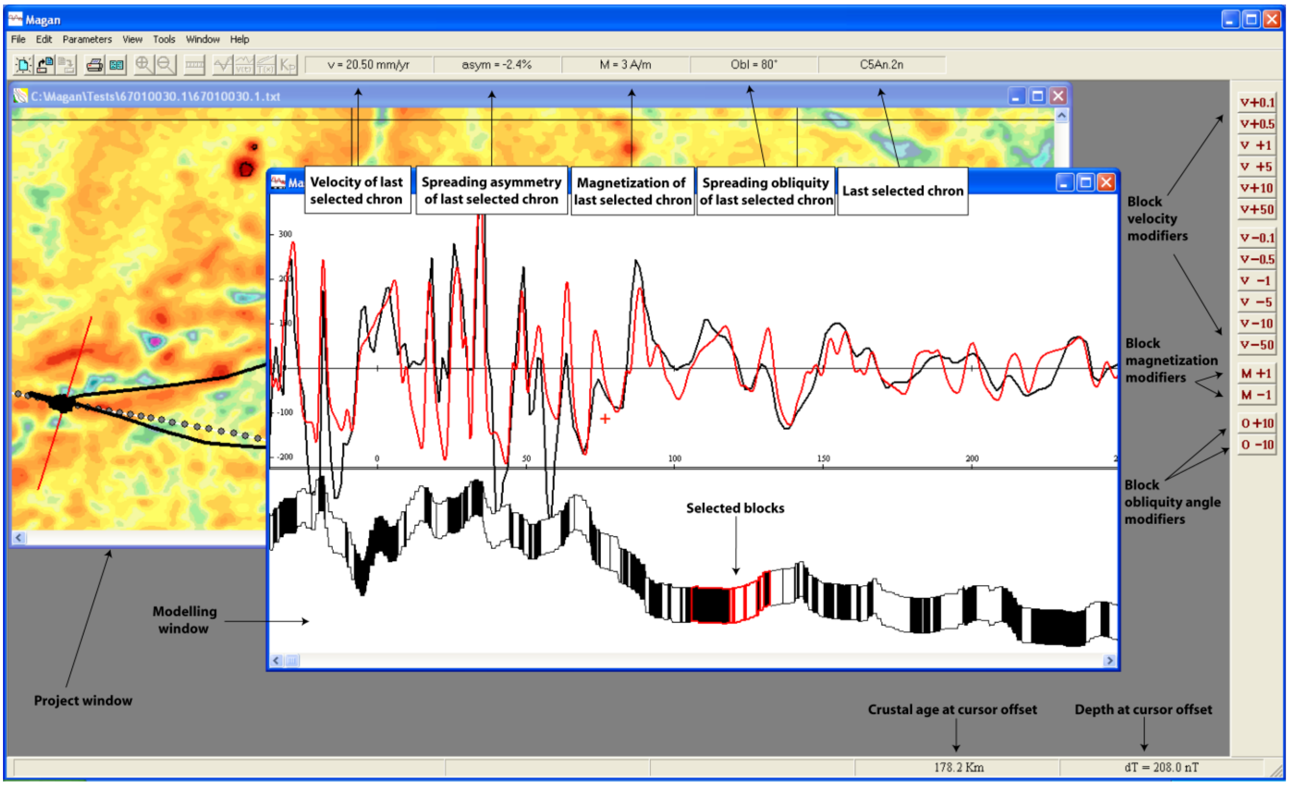

Figure 14. Elements of a modelling window.

A simplified version of the Schettino & Scotese (2005) rotation model is included in the Magan distribution package. A tutorial on rotation models and their definition can be found at: http://www.serg.unicam.it/Tutorial.html.

Edit → Velocity Submenu

This set of commands is only available when the active window is a modelling window. They may also be executed pushing the buttons on the right-side control bar (Fig. 14). When you have selected one or more blocks, they appear bounded by a red frame, as shown in Fig. 14. You can increase or decrease the velocity on the side where the block is located, during the corresponding chron, by the specified amount. This operation does not affect the velocity on the opposite flank of the ridge. Therefore, both the average full spreading rate and asymmetry during the selected chrons change after this operation. To select a single block, simply click on its area. In order to select a set of blocks, not necessarily adjacent each other, hold the SHIFT button pressed while clicking successive blocks. When you want to select a sequence of adjacent blocks from *both* flanks of a ridge, it is more convenient to select the first block and then press repeatedly SHIFT+TAB to select all the successive blocks. Finally, when you want to select a sequence of adjacent blocks from *one* flank only, press repeatedly ALT Gr+TAB or the SpaceBar to select all the successive blocks

Edit → Magnetization Submenu

This set of commands is only available when the active window is a modelling window. They may also be executed pushing the buttons on the right-side control bar (Fig. 14). When you have selected one or more blocks, you can increase or decrease the magnetization on both sides of the ridge, during the corresponding chron, by 1 A/m. Therefore, this operation affects the magnetization of the blocks on both sides of the ridge even if you have selected only one block.

Edit → Obliquity Submenu

Also this set of commands is only available when the active window is a modelling window. They may also be executed pushing the buttons on the right-side control bar (Fig. 14). When you have selected one or more blocks, you can increase or decrease the obliquity ψ of the magnetic stripe with respect to the local trend of the flow line, on both sides of the ridge, by 1° or 10°. In this instance, the effective distance of an observation point, having offset x from the block, is reduced to $x\sin\psi$. The default value is $\psi = 90°$, whereas the range of accepted values is $30 \leq \psi \leq 150°$. In order to assign correctly this parameter, you should take into account that the computation of the anomalus field components through Equations (43) – (44) is performed assuming an *x* axis which is oriented towards increasing flow line offsets. This axis is locally tangent to the flow line only when the obliquity angle ψ is 90°. Therefore, ψ is the angle between the positive *y* axis (namely, the magnetized stripe axis) and the positive flow line direction. The following Figure illustrates an example of appropriate attribution of the spreading obliquity angle.

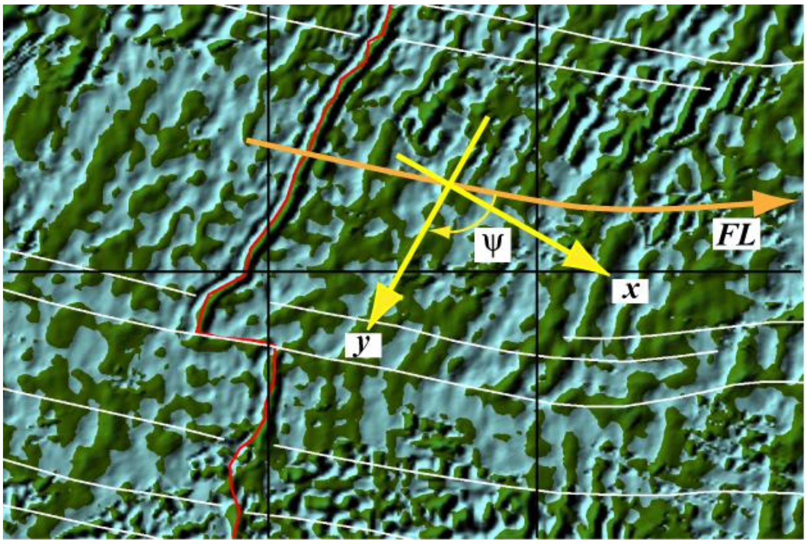

Figure 15. Example of determination of the spreading obliquity angle ψ.

In this example a W-E directed flow line, parallel to the fracture zones, has obliquity $\psi > 90°$ with respect to the strike of the magnetic stripes, as evidenced by the background pattern of magnetic anomalies. Note that the *y* axis is always directed southwards in the case of W-E flow lines.

Edit $\rightarrow$ Add Ridge Jump

This commands is only available when the active window is a modelling window and a single block is selected. It allows to introduce a ridge jump in the magnetization model. The command opens a dialog window (Fig. 16) where you can specify the number of blocks *n* that are jumped at the end of the current chron. The jump direction is specified through the sign of the *n*: a positive integer implies a rightward jump, whereas a negative integer means leftward jump.

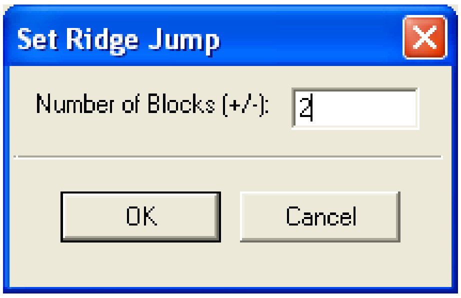

Figure 16. Dialog for the addition of ridge jumps.

For instance, if you select the block C18n.2n on the left side of the origin and specify n = +3, then at the end of this chron the ridge is moved rightwards at the right side of C19n.

Therefore, the left-side block sequence would be modified as follows:

… C20n, C19r, C19n, C18r, C18n.2n, C18n.2n, C18r, C19n, C18n.1r, C18n.1n,…

Conversely, the sequence of blocks from C18n.2n to C19n would be missing on the right side of the origin (positive offsets), and the normal sequence would be substituted by the following:

… C18n.1n, C18n.1r, C19r, C20n,...

Figure 17. Dialog for the removal of ridge jumps.

Edit → Remove Ridge Jump

This commands is only available when the active window is a modelling. It allows to remove an existing ridge jump in the magnetization model. The command opens a dialog window (Fig. 17) where you can select the chron at the end of which a ridge jump must be removed.

Edit → Set Chron Grouping Mode

Also this commands is only available when the active window is a modelling. It allows to simplify the construction of a block magnetization model through the grouping of blocks within chrons in single selections. In other words, a single click allows to select the parameters of all the blocks within a chron (e.g., C2An.1n, C2An.1r, C2An.2n, C2An.2r, C2An.3n, and C2Ar within chron C2A) and change the their parameters. Similarly, the navigation keys (TAB, SPACE, etc.) now operate on chrons and not on the single subchrons.

3.3 Parameters Menu

Parameters → Time Scale

This command allows to specify the time scale that must be used in the construction of the magnetization model. A dialog opens where the user selects the path to an ASCII table file containing the time scale (Fig. 18).

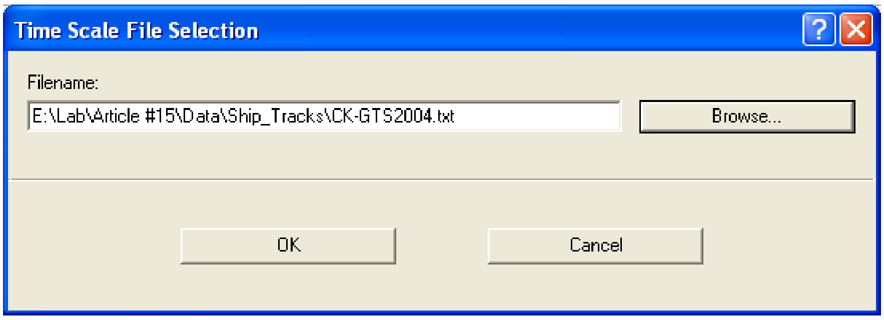

Figure 18. Dialog for the definition of the time scale.

A time scale table must be composed by three-fields rows that specify *top age*, *base age*, and *name*, of each chron, from the youngest (C1n) to the oldest. The time scale *CK-GTS2004.txt* included in the Magan distribution package is a combination of the Cande & Kent (1995) (C-series) and Gradstein et al. (2004) (M-series) time scales.

Parameters → Background Image

This command allows to specify a background image to be used in the current project window. A dialog opens where the user selects the path to a 256-colors bitmap file (*.bmp) containing the raster image (Fig. 19). Magan only reads Microsoft Windows indexed color bitmaps having a color depth of 8 bits per pixel.

The file must be accompanied by an ASCII header file (*.hdr), having the the same file name but different extension, with the following rows:

ncols	*number of columns*
nrows	*number of rows*
xllcorner	*longitude of lower-left corner*
yllcorner	*latitude of lower-left corner*
cellsize	*bitmap resolution (°deg per pixel)*

Magan assumes that the map projection of the background image is a simple planar geographic projection. The parameters included in this header file are used not only for the appropriate display of the background image, but also in a number of other computations. Therefore, it is essential that the user specifies correctly the parameters of the background image.

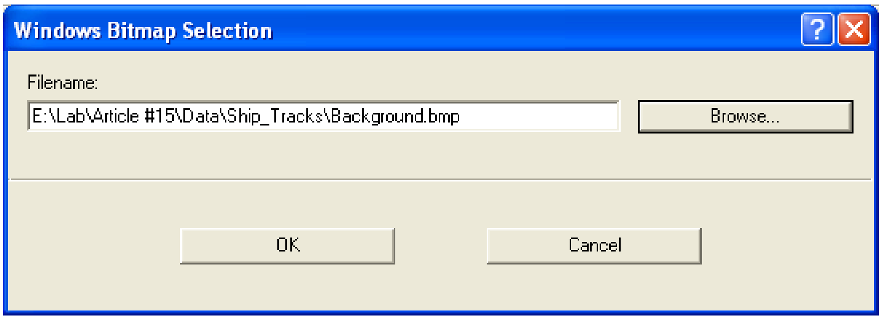

Figure 19. Dialog for the definition of a background image.

Parameters → Background Color

This command allows to specify a background color for the current project window when the background image is hidden. A dialog opens where the user selects the RGB values of the new background color (Fig. 20).

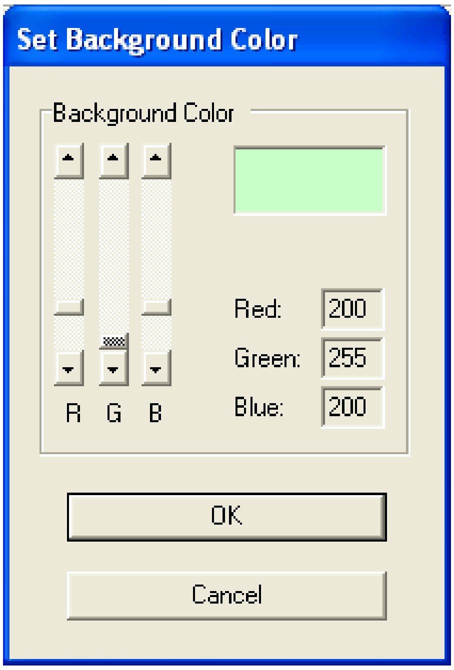

Figure 20. Dialog for setting a background color.

Parameters → Bathymetry/Basement grid

This command allows to specify the path to a 32-bits floating point file (*.flt) containing basement or bathymetric depths (as negative real numbers representing the depth in meters). The file can be easily generated using any GIS software (e.g., GlobalMapper). It must be accompanied by an header file having the same structure of the header files which are attached to background images. Figure 21 shows the dialog that is used to select a basement/bathymetry grid.

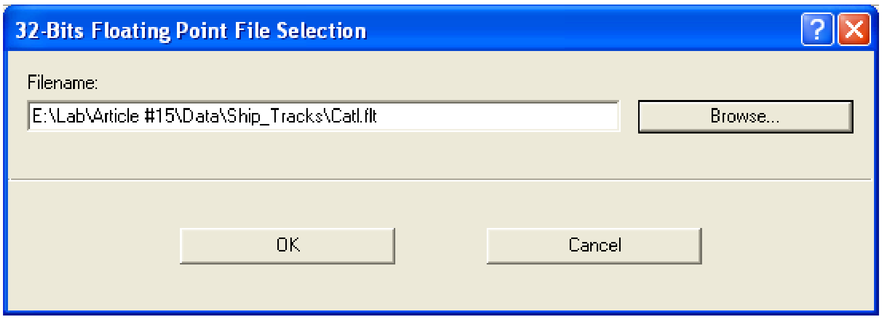

Figure 21. Dialog for the definition of a basement/bathymetric grid.

Magan uses the information included in this file to determine the geometry of all magnetized blocks in a model. Therefore, it is mandatory to specify a basement/bathymetry grid before opening modelling windows. Furthermore, the program could generate run-time errors if the the geographic extent of the selected grid is not sufficient to cover the location of all the blocks.

Parameters → Global parameters

This command allows to specify the global parameters of a block model. A dialog opens where the user enters the values of the new parameters, as shown in Fig. 22. The structure of rotation model files has been discussed above. This field is not mandatory. If the user does not specify any rotation model, then the plate identifier fields are disabled and the program uses a constant axial pole (I = 90° ; D = 0°) for all magnetization directions. This could be an appropriate choice for profiles that encompass the last 4-5 Myrs. However, it gives a very crude approximation in the case of profiles on old crust at low latitudes. When a rotation model has been specified, the user must also fill the plate identifier fields with appropriate numbers, and those plates must exist in the rotation model. Magan uses these information to build an APWP for the plates on the two flanks of the spreading ridge and determine the direction of remnant magnetization of any block in the model.

The *Default Full Spreading Rate (mm/yr)* and *Default Spreading Asymmetry (%)* fields are used to specify constant velocity and spreading asymmetry values for the construction of the initial magnetization model. The *Default Magnetization (A/m)* and *Default Axial Magnetization (A/m)* fields allows to specify, respectively, a value of default magnetization for all blocks older than C1n, and a value of default magnetization for the blocks associated with C1n.

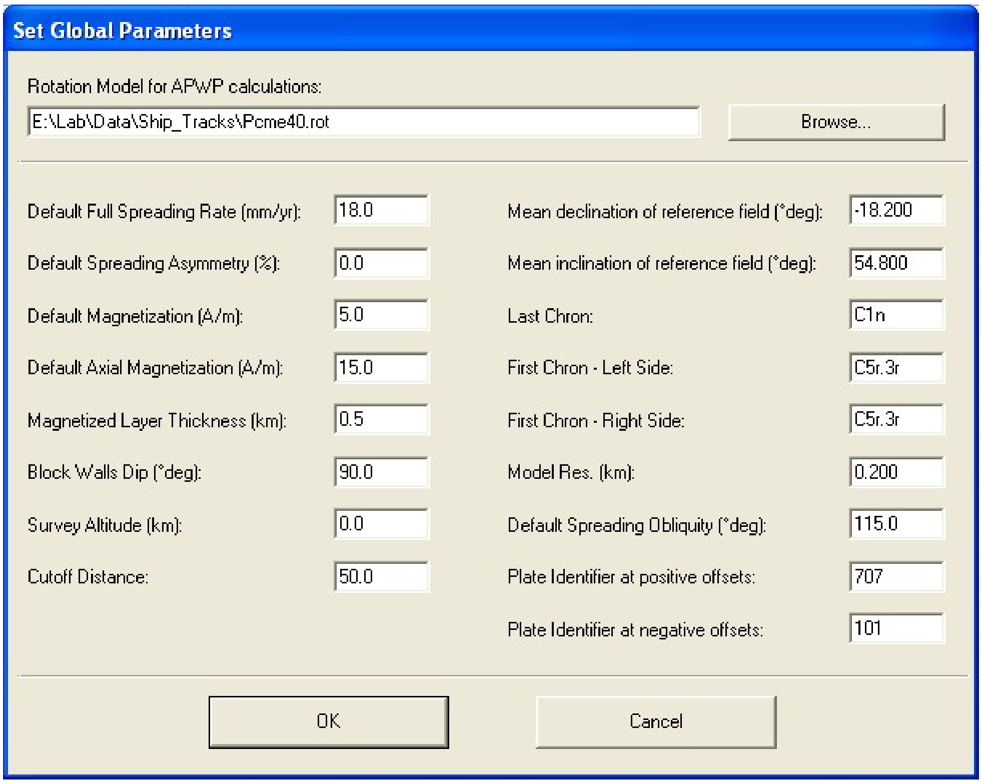

Figure 22. Dialog for the definition of the global parameters.

The *Magnetized Layer Thickness (km)* field specifies the thickness of the magnetized layer. The default 0.5 km value should be appropriate for most situations. The *Block Walls Dip (°deg)* parameter specifies the inclination of the block walls. The default value (90°) is a correct choice in the case of normal to fast spreading ridges. However, according to Tivey (1996) prisms should have dipping polarity boundaries, especially in the case of slow spreading rates (e.g., Red Sea). Therefore, Magan allows to specify an angle other than 90° for the dip of block walls. The *Survey Altitude (km)* allows to specify the altitude of the observation points. Use a positive value in the case of aeromagnetic surveys, zero (default) for most marine surveys, a negative value when the magnetometer is towed at significant depth. The *Cutoff Distance* field is used to accelerate the calculation of model anomalies of long profiles. This is the maximum distance (in km) at which the anomalous field generated by a block may influence an observation point. The default value (50 km) may be appropriate during the initial phase of forward modelling, but should be substituted by a larger value (e.g., 100 km) when the model only needs few refinements. The *Mean declination/inclination of reference field (°deg)* fields allow to specify the mean geomagnetic field direction at the survey time in the case of small-scale surveys. You can use the NGDC web server at: http://www.ngdc.noaa.gov/geomagmodels/IGRFWMM.jsp to calculate these parameters. If the survey area is large (more than 200 km), it is possible to import a geomagnetic field direction for each point in the projected trackline. In this instance Magan calculates the model anomaly at a point using the declination and inclination of the closest trackline point. The field *Last Chron* is used to specify the name of the chron of extinction of a spreading ridge or, if it is still active, “C1n” (default value). Similarly, *First Chron – Left Side* and *First Chron – Right Side* specify the chron that will be associated to the oldest magnetized block, respectively along the left and right side of the flow line. If you leave one of these fields empty, the program will assume that the oldest chron along the corresponding side of the profile coincides with the oldest chron included in the selected time scale. The *Model Res. (km)* entry is used to specify the spacing (in km) that Magan must use to generate model profiles. Uses a small value (e.g., 0.5 km) when you want to gain a better look at the details of a profile. Finally, the *Default Profile Obliquity (°deg)* allows to specify a common value of the profile obliquity angle ψ for all blocks. This value must be set according to the conventions illustrated in Fig. 15. This parameter can be also used to analyze ship tracks that are too oblique with respect to the true flow lines of motion, thereby preventing a correct projection of the magnetic data. In this instance, it is convenient to manually generate a flow line which interpolates the ship track (independently from the real trend of the fracture zones) and project the magnetic data. Then, it is possible to use the default spreading obliquity parameter to allow Magan to perform a correct computation of the strike of each magnetized prism.

Parameters → Pen Styles

This command allows to change the appearance of line features in all Magan windows. A dialog opens where the user specifies thickness and color of flow lines, ship tracks, model magnetic anomalies, etc. (Fig. 23).

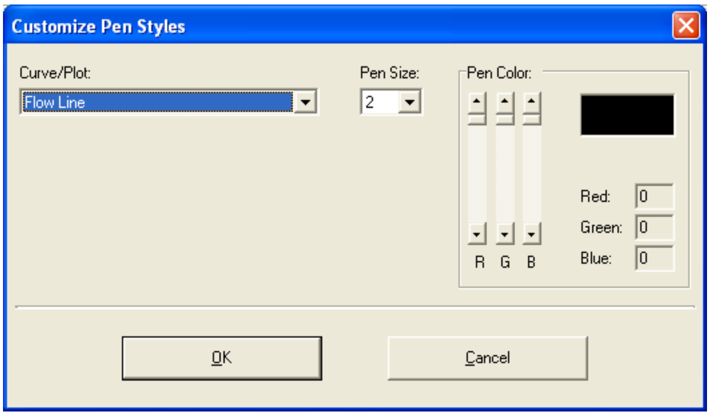

Figure 23. Dialog for the selection of line styles (thickness and color).

Parameters → *Set Origin*

This is the last command in the *Parameters* menu. It allows to specify that the current flow line node in a project window, which appears in red, must be considered as the profile origin, which has zero offset. This point should be located on the ridge axis and its position can be changed after inspection of the observed and model magnetic anomaly profiles. Magan marks the flow line origin by a red line. If the location of the origin is subsequently changed dragging the corresponding node across the window, it is necessary to launch this command again. Such a procedure generally represents the first step of forward modelling. It has the objective to position correctly the axial model anomaly relatively to the observed profile.

3.4 View Menu

View → *Zoom in/out*

These commands allow respectively to select a region of the current project window for closer inspection or return to the previous view.

View → *Background Image*

This command allows to display or hide the current background image.

View → *Ship-Track data points*

This command allows to display or hide the nodes of a ship-track line.

View → Projected data points

This command allows to display or hide the relocated ship-track data on the current flow line.

View → Projected Data Submenu

This sub-menu allows to open windows displaying respectively the magnetic, bathymetric, or *Kp* profile of a projected data set. Therefore, these commands are only available after projection of ship track data onto the current flow line. Note that the bathymetric profile could not be available. This is the case when NGDC bathymetric data are missing, or when the magnetic data have been imported as simple XYZ files. In this instance you can use the command *Tools → Set magnetic layer depths from gridded data* to assign a depth value to each projected data point.

The difference between standard and unsorted magnetic profiles is associated with the procedure of projection onto a flow line. In general, a standard magnetic profile (Fig. 24) is used to display the final result of the procedure of projection and averaging of several segments of a ship track onto a flow line. In fact, depending on the maximum distance of projection (see the command: *Tools → Project ship-track data*), one or more track segments can be combined to form a magnetic profile that will be subsequently used in the forward modelling procedure. Such a profile is ever displayed in the modelling windows along with the model profiles calculated by Magan. However, you may wish to generate a plot of the projected magnetic data independently from the modelling procedure. In this case you can use the command *View → Projected Data → Magnetic Profile* to open a window which displays the result of the projection procedure, as shown in Fig. 24.

When different segments of the same ship-track are combined, some care must be put in using the averaged profile in the forward modelling procedure. In fact, because of navigation errors (up to 10 km), different track segments could not be correlable, thereby the final magnetic profile would be affected in an unpredictable way by the combination of various data sets. Therefore, if you are using complex ship tracks, it is good practice to generate an unsorted magnetic profile, in order to test the self-correlation of the ship-track segments and detect incoherencies of the averaged profile. This is done using the command: *View → Projected Data → Unsorted Magnetic Profile*. Fig. 25

shows an example of good self-correlation of up to four ship-track segments. The averaged magnetic profile is shown in Fig. 24.

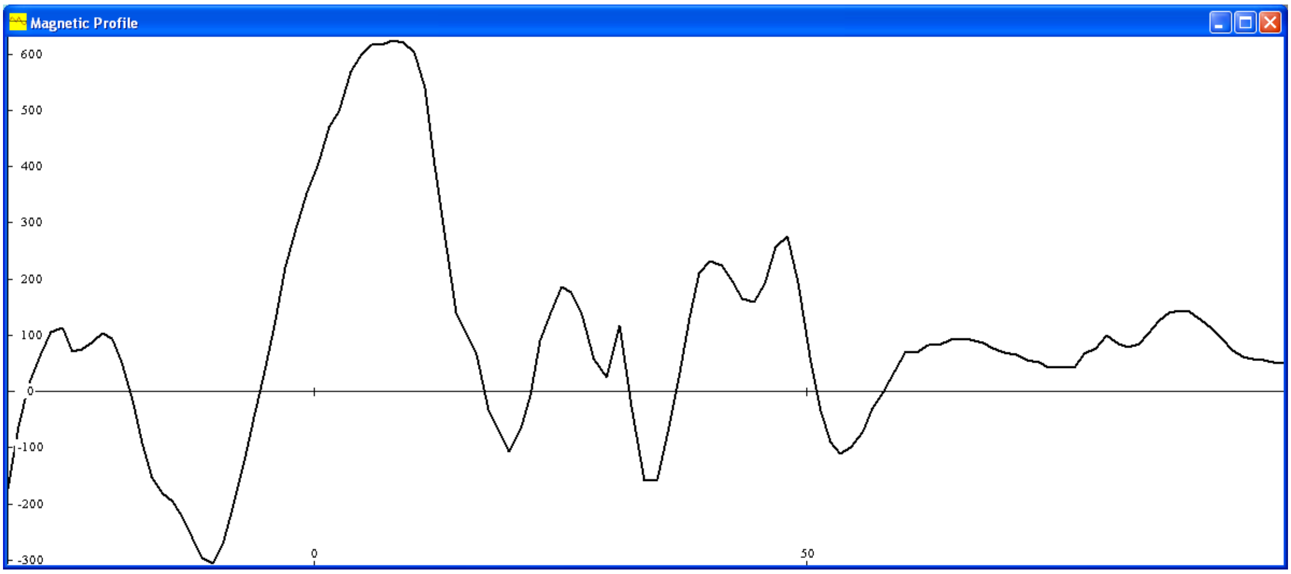

Figure 24. Projected magnetic profile window. Vertical scale is in nT, whereas the horizontal scale displays the offset in km along the flow line, starting from the origin.

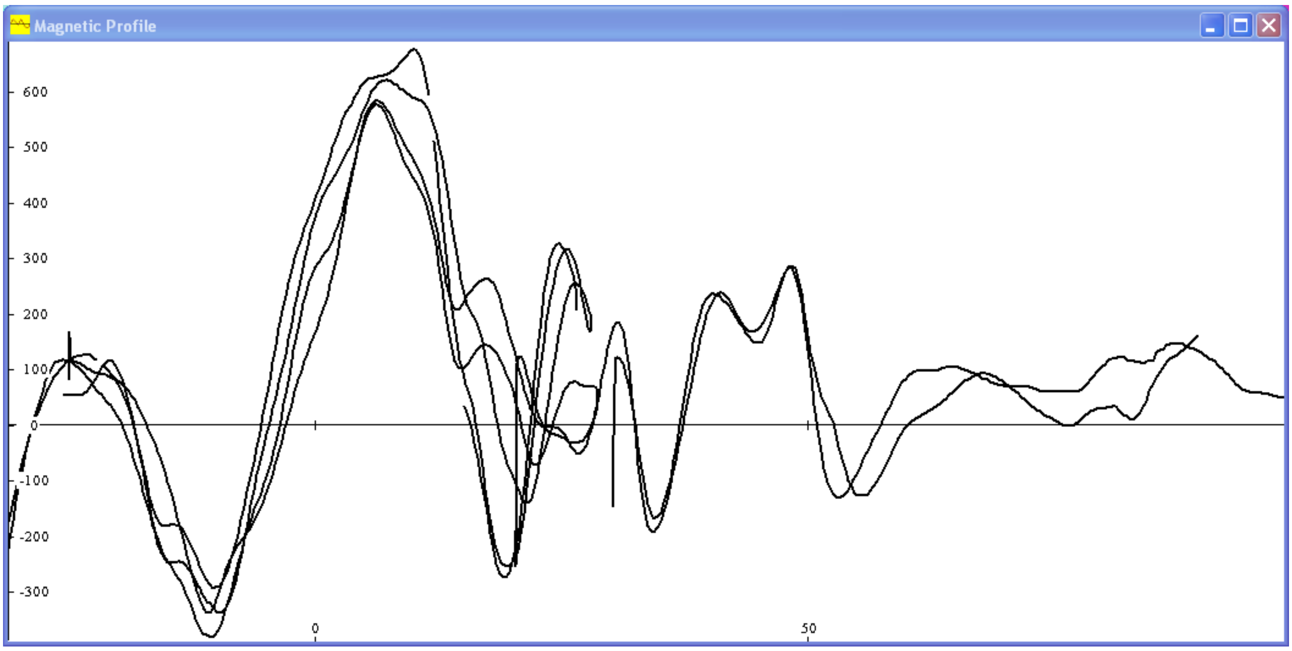

Figure 25. Unsorted projected magnetic data. Vertical scale is in nT, whereas the horizontal scale displays the offset in km along the flow line, starting from the origin. This plot shows that the magnetic profile of Fig. 24 has been generated combining several (up to 4) ship-track segments.

The other two kinds of windows that can be opened through the *View* → *Projected Data* submenu are the bathymetric and the *Kp* index plots of a projected data set (Figs 26-27). In order to display *Kp* index profiles, the current data set must have been imported from an NGDC GEODAS MGD77/MGD77T/MAG88T trackline file and you must have loaded a *Kp* geomagnetic activity indices table. The graphic content of these windows can be saved as compressed PNG (Portable Network Graphics) files or standard Microsoft Windows bitmaps, or printed.

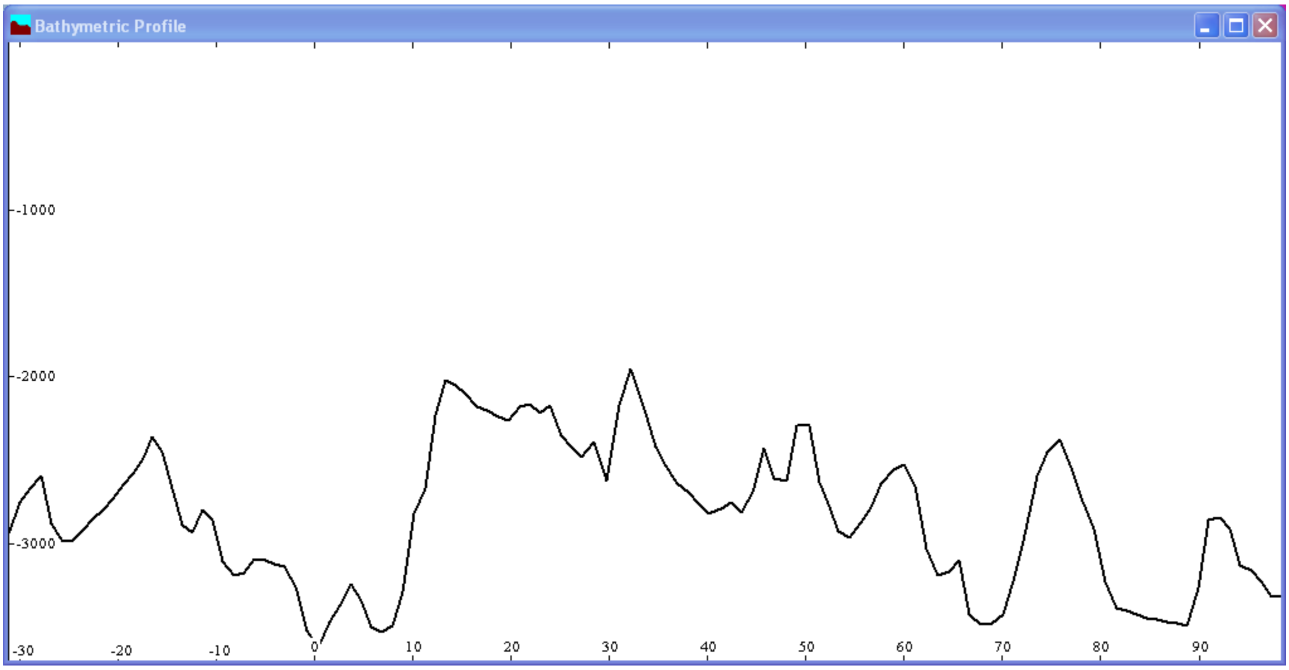

Figure 26. Projected bathymetric profile window. Vertical scale is in mt, whereas the horizontal scale displays the offset in km along the flow line, starting from the origin.

View → *NGDC/Source Data Submenu*

This submenu allows to open windows displaying respectively the magnetic, bathymetric, or *Kp* profile of an entire NGDC track line, or an imported XYZ magnetic data set. These windows are similar to those displayed in Figs. 24, 26, and 27, but in this case the horizontal scale displays the offset along the flow line starting from the beginning of the ship-track.

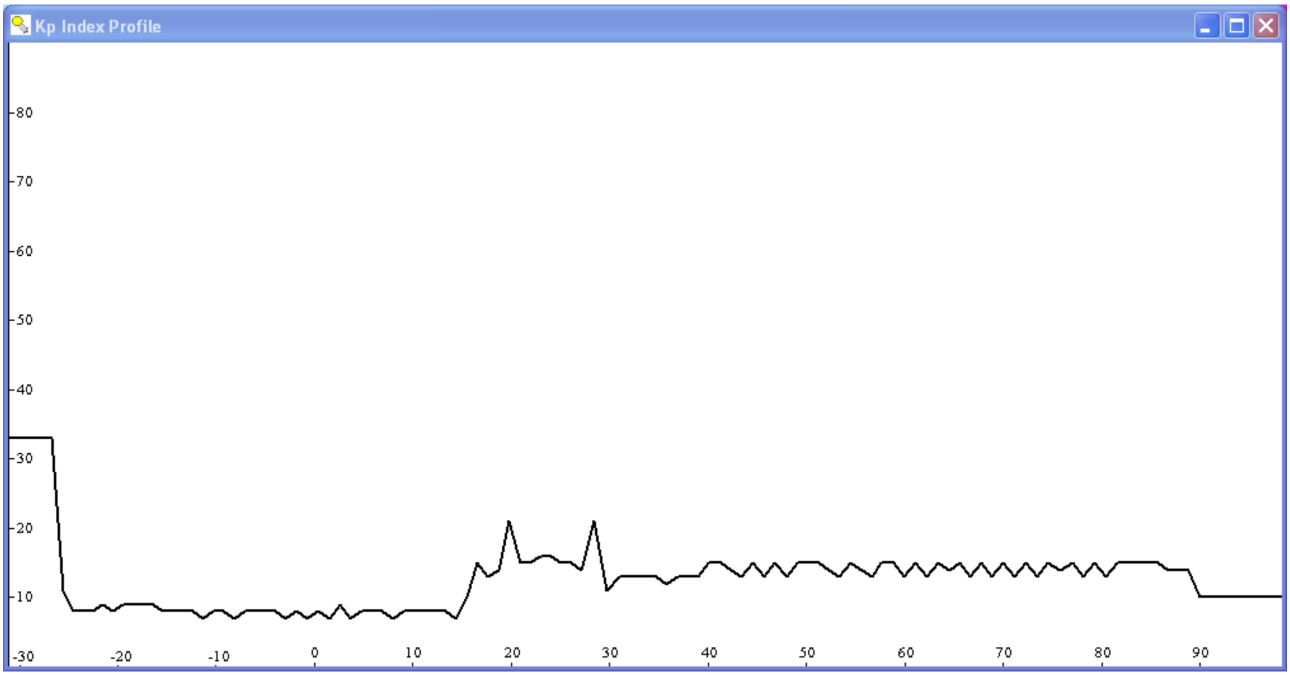

Figure 27. Projected *Kp* index profile window. Vertical scale is dimensionless (0 – 100), whereas the horizontal scale displays the offset in km along the flow line, starting from the origin.

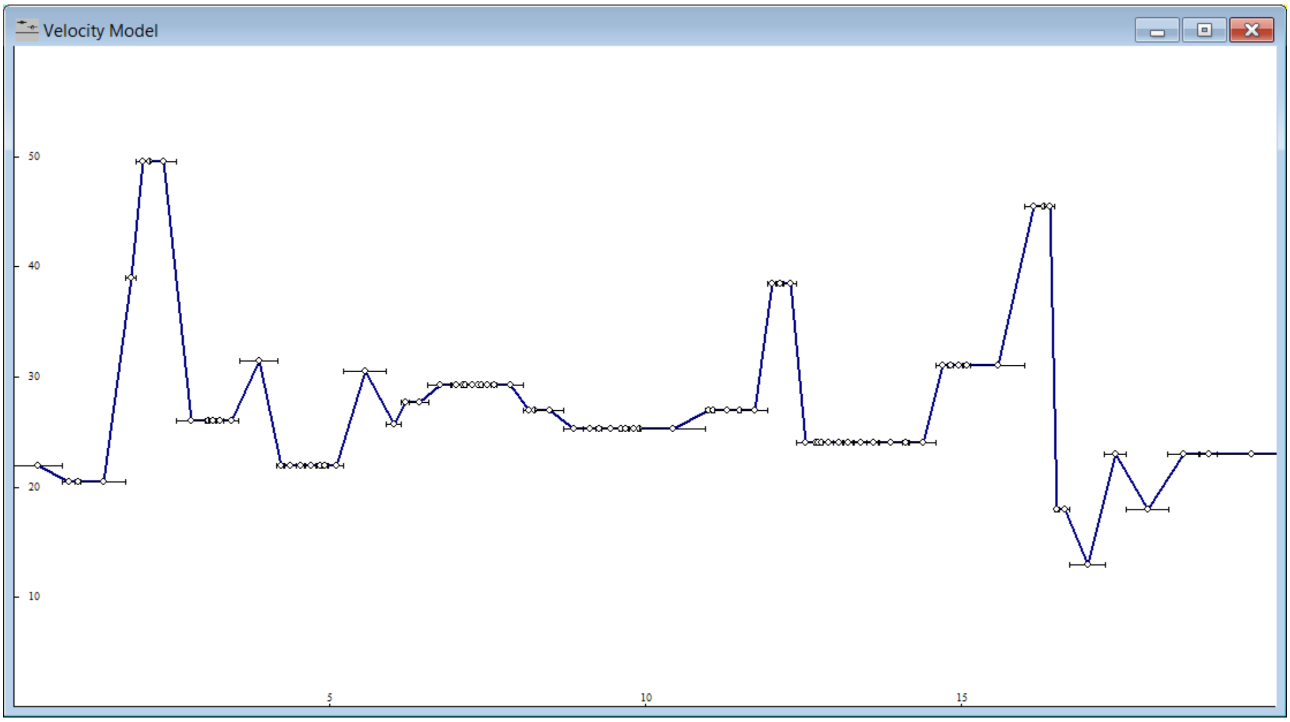

Figure 28. Velocity model window. Vertical scale is mm/yr, whereas the horizontal scale is in Ma.

View → Velocity Model

This command opens a new window displaying the current velocity model (if any), as shown in Fig. 28. In this window each chron in the magnetization model is represented by a point whose horizontal error bar indicates the chron duration (in Myrs). Also in this case the graphic content can be saved as compressed PNG (Portable Network Graphics) files or standard Microsoft Windows bitmaps, or printed.

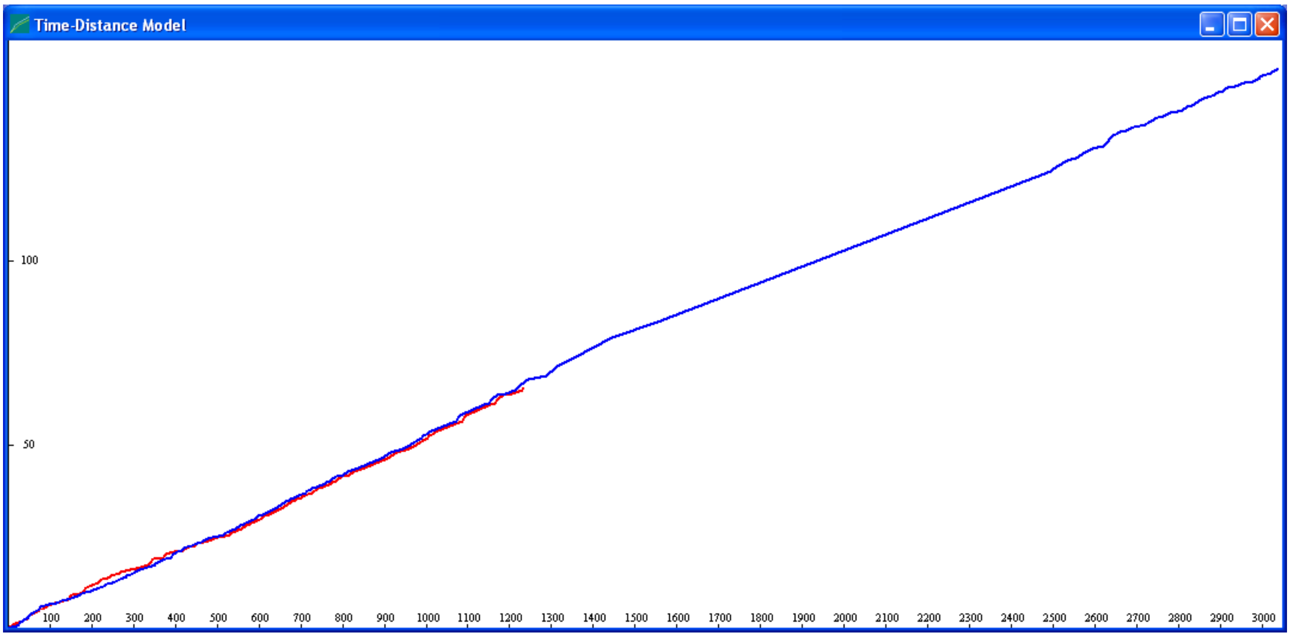

Figure 29. Age-Distance window. Vertical scale is in Ma, whereas the horizontal scale is in km. In this example the redu curve refers to the eastern side (positive offsets), whereas the blue curve represents ages along the western side (negtive offsets).

View → Age-Distance model

This command opens a new window displaying age – distance plots, as shown in Fig. 29. These curves show the predicted crustal age at any orthogonal distance from the spreading axis, according to the current velocity model. It should be noted that in these windows the distance *x* corresponding to any given time *T* is always calculated as an offset from the ridge along a theoretical flow-line of motion, assuming obliquity ψ = 90°, independently from any user-defined flow line and obliquity angles. Conversely, modelling windows show an age-distance relation which depends from both the spreading rates and the obliquity of the magnetized prisms with respect to the flow line. In the case of symmetric spreading the two age – distance curves overlap. In the example of Fig. 29 the magnetic profile reaches 1200 km offset from the origin along the eastern side and 3000 km along the western side.

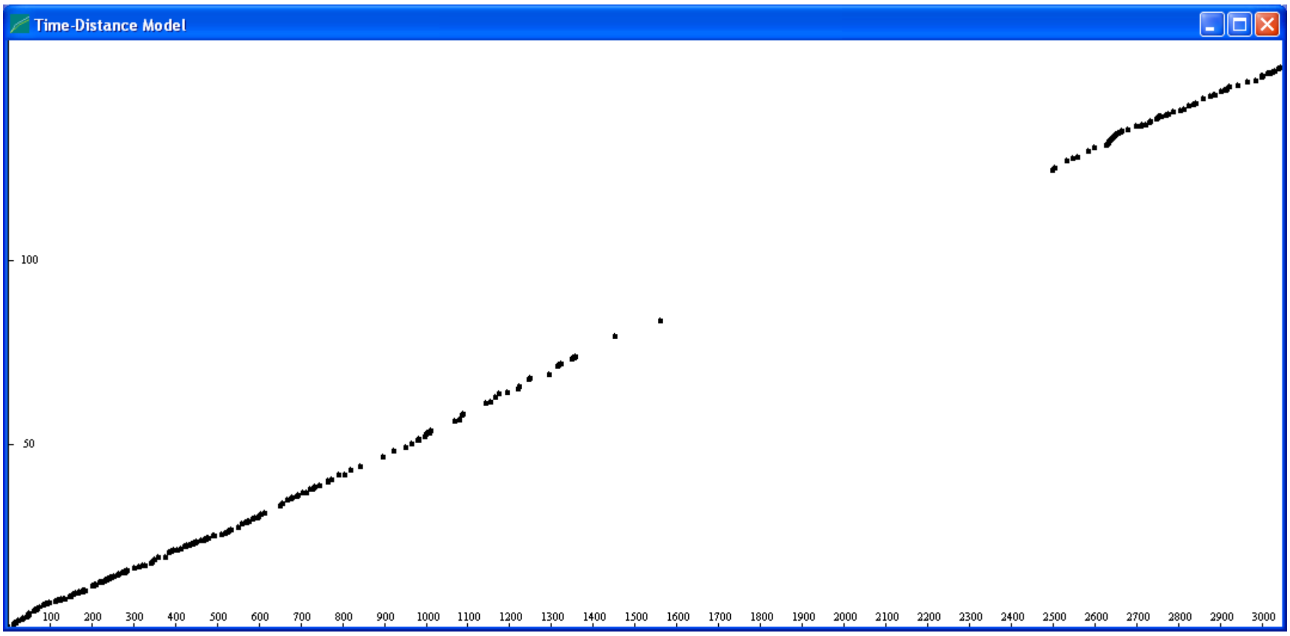

Figure 30. Mean Age-Distance window. Vertical scale is in Ma, whereas the horizontal scale is in km. Each point represents the mean crustal age at any distance from the origin, where the average is performed between the two flanks of the spreading ridge.

View $\rightarrow$ *Mean Age – Linear Distance*

This command is only available when the active window is an age – distance plot (Fig. 29). It calculates the average crustal age $T(x)$ at each offset x and displays a point for each chron in the model (Fig. 30). It is used for the detection of tectonic stages characterized by approximately constant spreading velocity through the command *Tools* $\rightarrow$ *Find Stages*. Use the command again to switch back to the standard view.

View $\rightarrow$ *Angular Distances*

This command is only available when the active window is an age – distance plot in the *mean age mode* (Fig. 30). It allows to convert the linear distances (expressed in km) into angular distances about the sequence of stage poles, which are independent from the location of the profile. Magan uses the rotation model specified through the *Global Parameters* dialog (Fig. 22) to calculate the angular distance corresponding to each top age of the block model. Assume that each chron in the time scale forms a stage, whose stage pole can be calculated on the basis of the current rotation model. In this instance, if Ω_k is the stage angle and ΔT_k is the chron duration, and if θ_k is the angular distance of a small profile segment from the stage pole during this stage, then the linear distance Δx_k travelled by a point during the time interval ΔT_k is scaled to angular distance $\Delta\alpha_k = \Omega_k \Delta T_k$ about the stage pole by the following relation:

$$\Delta\alpha_k = \frac{\Delta x_k}{R \sin\theta_k} \quad (58)$$

where R is the Earth's radius. The brown line in Fig. 31 shows the time – angular distance plot, $T = T(\alpha)$, predicted on the basis of the current rotation model. Conversely, black dots in Fig. 31 show the $T = T(\alpha)$ plot associated with the current magnetization model. Therefore, the user can compare the two plots and decide if the current block model is viable.

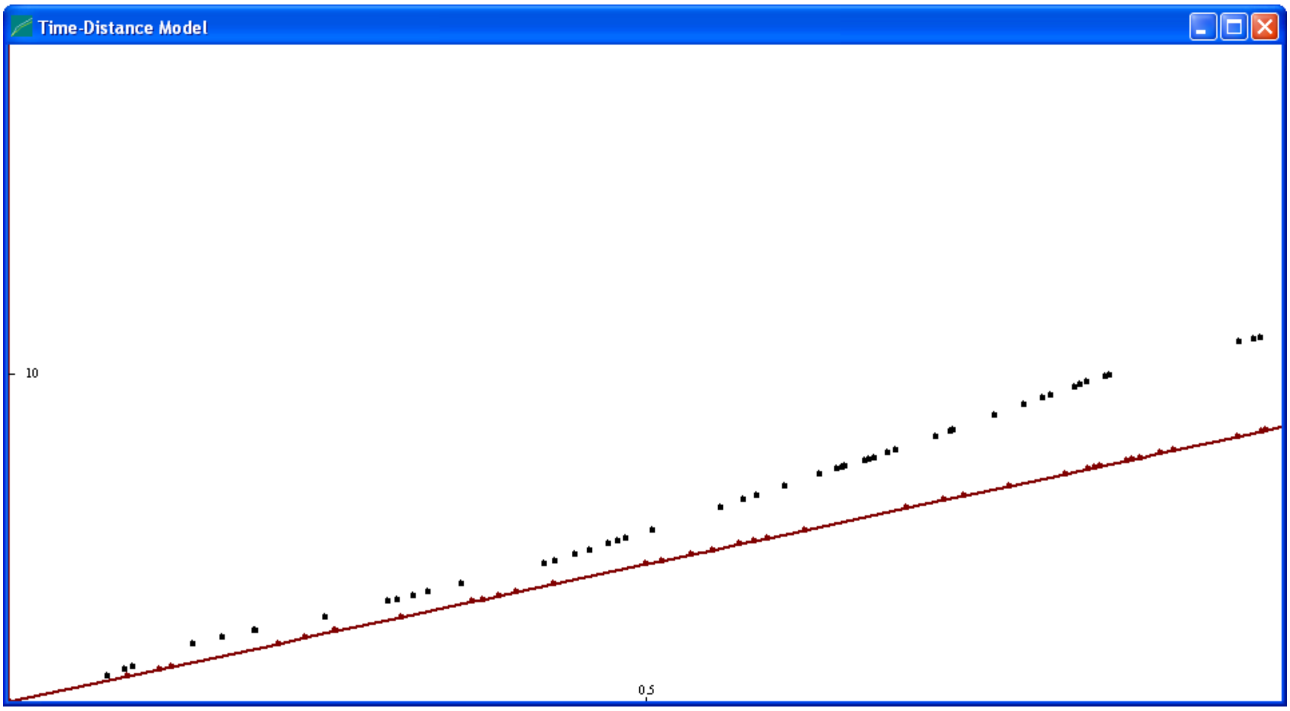

Figure 31. Mean Age-Angular Distance window. Vertical scale is in Ma, whereas the horizontal scale is in °deg. Each point (black dots) represents the predicted mean crustal age at any angular distance from the origin, according to the current magnetization model. The brown line displays the plot $T = T(\alpha)$ accoring to the current rotation model.

3.5 Tools Menu

Tools → Measure Distance

This command is available from project windows. Once you have launched the command, click at the location of a starting point on the background image. A small dialog opens which displays the distance (in km and angular) from the selected starting point as you move the mouse. Click again to close this dialog and switch back to the editing mode.

Tools → Theoretical Profile

This command allows to generate theoretical magnetic anomaly profiles, e.g., for teaching and testing purposes. It is available when a time scale has been defined. Once you have launched the command, the following dialog window allows to specify the profile parameters (Fig. 32).

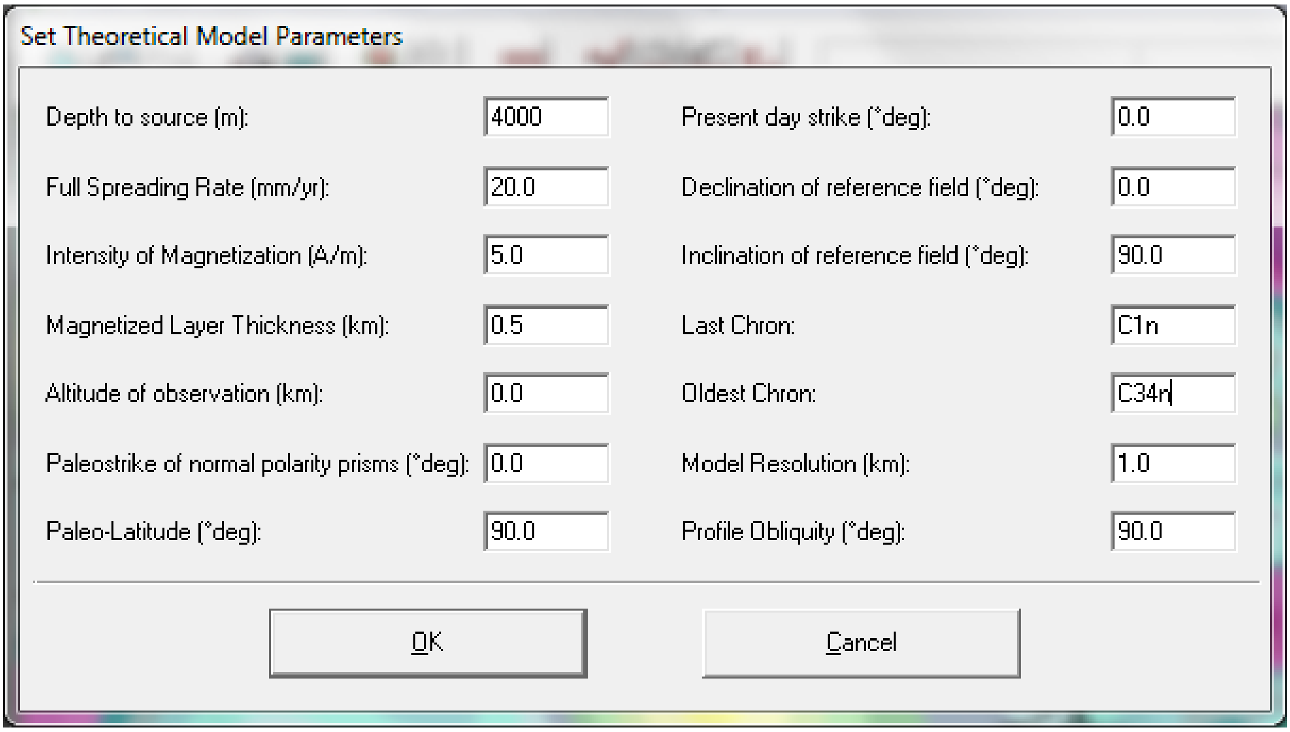

Figure 32. Dialog for the selection of the parameters of construction of theoretical magnetic anomaly profiles.

The *Depth to source* (*m*) field specifies the depth of the magnetized layer (zero is sea level). The default 4000 m value should be appropriate for most simulations. *Full spreading rate*, *intensity of magnetization*, *thickness*, *altitude*, *declination and inclination of the reference field*, *first and oldest chrons*, *model resolution*, and *profile obliquity* have the same meaning of equivalent global parameters (see Fig. 22). *Paleostrike of normal polarity chrons* allows to specify the parameter α (strike of magnetized prisms at the time of formation) that will be used to calculate the anomalous field through (43) and (44). Note that this quantity is the strike of a magnetized block measured counterclockwise from the paleomagnetic North to the negative *y*-axis (Fig. 8). The *paleolatitude* parameter will be used by Magan to determine the inclination of magnetization *I*. Finally, the *present day strike* specifies the parameter β of Fig. 10. It is the local strike of the *y* axis, measured clockwise from the North. Once you have pressed "OK", a new window opens, which shows the magnetization model and the corresponding theoretical magnetic anomaly profile. The user interface of these windows is similar to that of the modelling windows (Fig. 33).

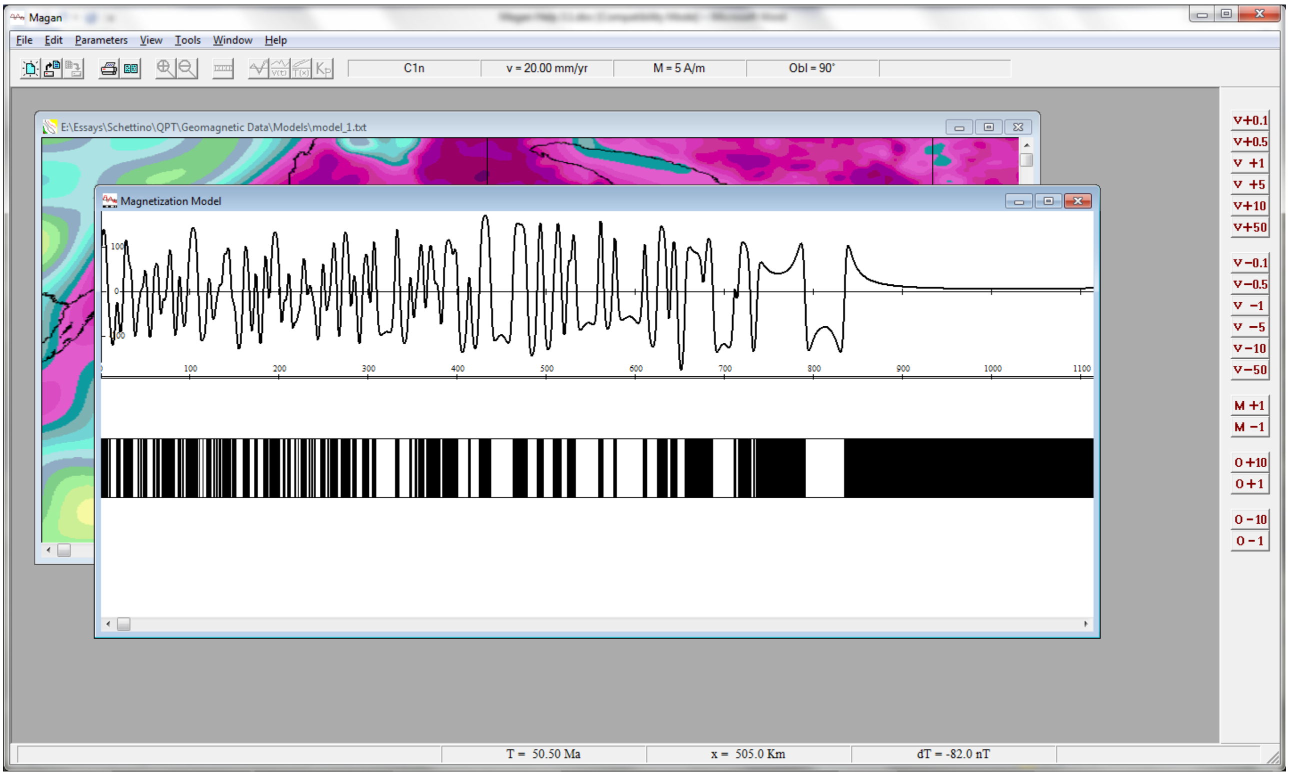

Figure 33. User interface for theoretical magnetic anomaly profile windows.

Also in this instance you can click a block in the block model to obtain information (corresponding chron name, velocity, etc.). Finally, you can change the spreading velocity, magnetization, and profile obliquity using the control bar on the right pane.

Tools → Import Data → NGDC Trackline

This command of the *Tools → Import Data* submenu allows to import NGDC GEODAS MGD77/MGD77T trackline files (*.a77,*.m77t) and the new MAG88T (*.m88t) aeromagnetic data format into Magan (Fig. 34). You should consult the NGDC GEODAS site at http://www.ngdc.noaa.gov/mgg/geodas/geodas.html for more information about these data formats. NGDC trackline files are the primary data source for which Magan has been designed, although you may wish to import standard trackline data in ASCII format (see below).

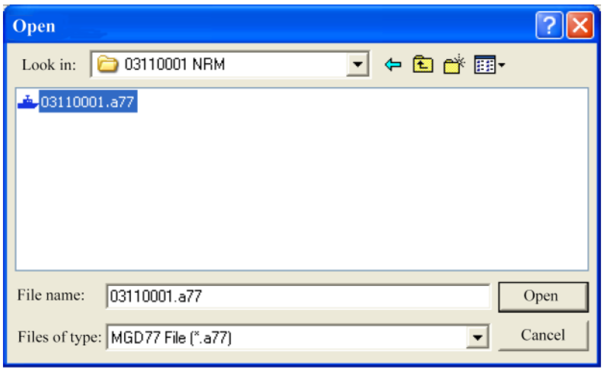

Figure 34. Dialog for the selection of an NGDC track line file to import.

If the operation is successful, Magan displays the imported track line and is ready for data projection, provided that a flow line has been loaded. The magnetic and bathymetric data can be displayed through the *View → NGDC/Source Data* submenu.

Tools → Import Data → XYZ ASCII File

This command allows to import any XYZ ASCII table (*.xyz) containing (*Lon,Lat,Anomaly*) triples when an MGD77/MGDC77T/MAG88T file is not available (Fig. 35). In this case the bathymetric and *Kp* index profiles cannot be displayed through the *View → NGDC/Source Data* submenu.

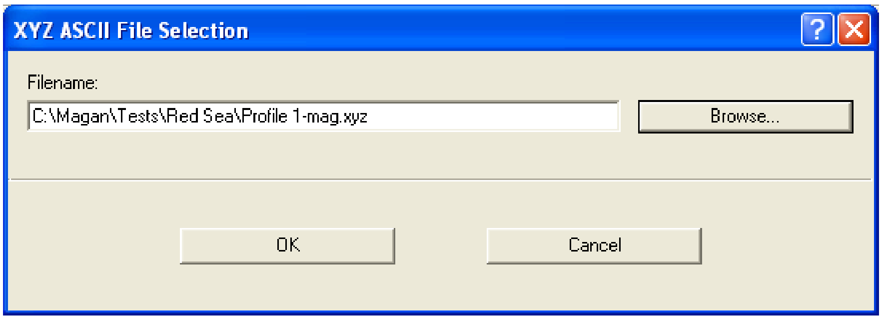

Figure 35. Dialog for the selection of an XYZ magnetic profile to import.

Tools → Import Data → Projected XYZ Data

This command is similar to the previous one, except that in this instance the data are considered as already-projected data and the ship track coincides with the flow line. Therefore, a flow line coinciding with the track is implicitly loaded along with the track and there is no need to project further the data. Also in this case an XYZ ASCII table (*.xyz) containing (*Lon*,*Lat*,*Anomaly*) triples is supplied by the user through the dialog shown in Fig. 35.

Tools → Import Data → XY ASCII Flow Line

This command allows to import any XY ASCII table (*.txt) containing (*Lon*,*Lat*) pairs of a flow line, for instance when this line has been generated through a GIS software. Figure 36 shows the import dialog for this command.

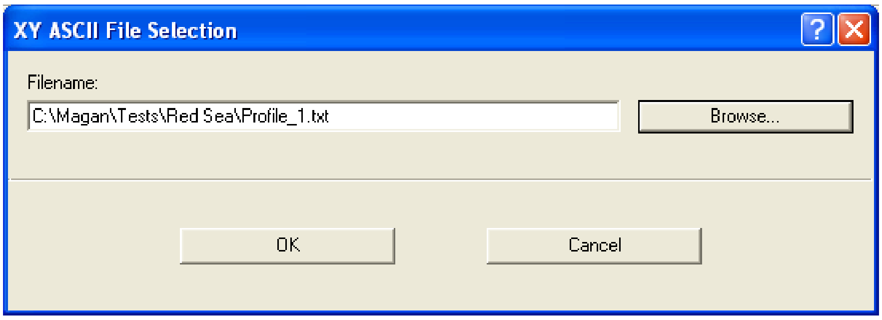

Figure 36. Dialog for the selection of an XY flow line to import.

Tools → Import Data → Filtered magnetic profile

This command allows to import any XZ ASCII table (*.txt) containing (*Offset,Anomaly*) pairs. It is assumed that the user has first exported the current magnetic profile of projected data through the command: *Tools → Export magnetic profile for filtering*, and that the data have been filtered through an external program. Then, this command substitutes the original magnetic data set by filtered data at the same offsets. If one or more data offsets are different from those associated with the current profile, the command fails and an error is displayed. Figure 37 shows the import dialog for this command.

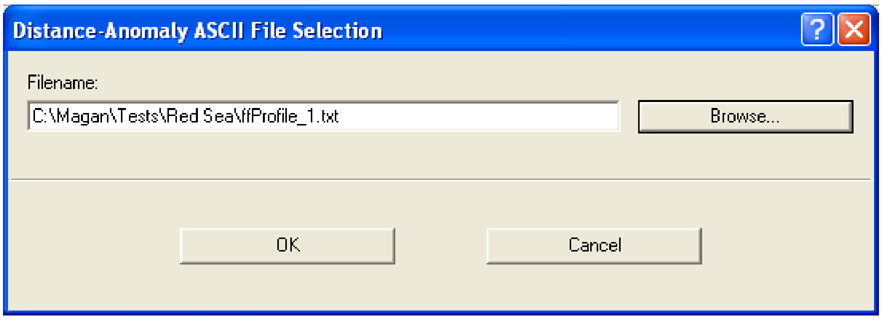

Figure 37. Dialog for the selection of an XZ filtered profile to import.

Tools → Import Data → Kp Geomagnetic activity indices

This command allows to import UKSSDC ASCII tables (*.txt) containing sequences of *Kp* indices, which are available from the UK Solar System Data Centre at: http://www.ukssdc.ac.uk/. The first 8 rows of these files are ignored by Magan. The renaining rows must have the following format:

YYYY MM DD Time - Index

where *YYYY* is the year, *MM* is the month, *DD* is the day, *Time* is the three-hour time, and *Index* is the *Kp* geomagnetic index in the range 0 – 90. A *Kp* index file *Kp-index_1960-Jan-01_2009-Feb-28.txt* for the time interval from 1960 through February 28th 2009 is already included in the Magan distribution package. Figure 38 shows the import dialog for this command.

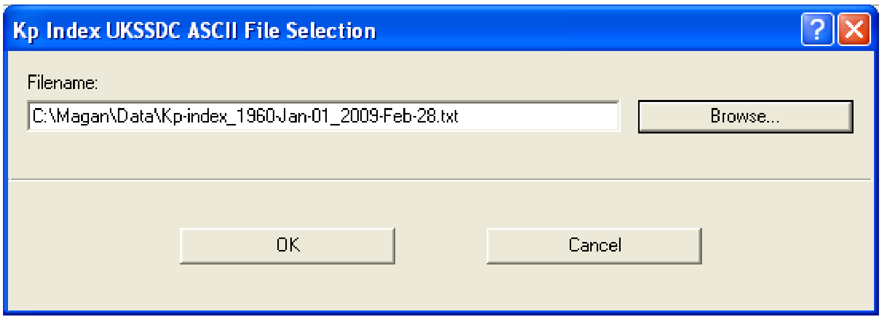

Figure 38. Dialog for the selection of a *Kp* index file to import.

Kp index profiles, which are available for NGDC data sets through the commands: *View* → *NGDC/Source Data* → *Kp Index Profile* and *View* → *Projected Data* → *Kp Index Profile*, can only be displayed after that a *Kp* index table has been imported.

Tools → *Import Data* → *Geomagnetic field parameters*

The default survey-time geomagnetic field direction (D_0,I_0), which is used in Eq. 46 to calculate model total field anomalies, is specified through the global parameters dialog (see p. 43). However, in the case of large ship tracks, the model reference field (e.g., the IGRF at survey time) may change considerably across the survey area. In this instance a more accurate computation of the model anomalies can be performed using a different geomagnetic field direction (D_0,I_0) for each point along the flow line. This operation is enabled through the import of a sequence of geomagnetic field directions for the set of ship track points that have been projected onto the flow line. In this case Magan calculates the model anomaly at a point using the declination and inclination of the closest control point. The name of the ASCII (*.txt) file that will contain the geomagnetic field directions (D_0,I_0) for each control point (*Lon*,*Lat*) along the flow line is specified through the dialog of Fig. 39. The rows of the file that is generated by this command have the following 4-fields format:

Lon Lat Dec Inc

This information is then used in modelling windows to generate the magnetic anomalies that form model profiles. The (D_0,I_0) pairs are calculated starting from a table of reference field records, which can be generated using the NGDC routine *Geomag70*. This table, which must have the standard *Geomag70* format (see p. 60), is specified through the dialog of Fig. 39.

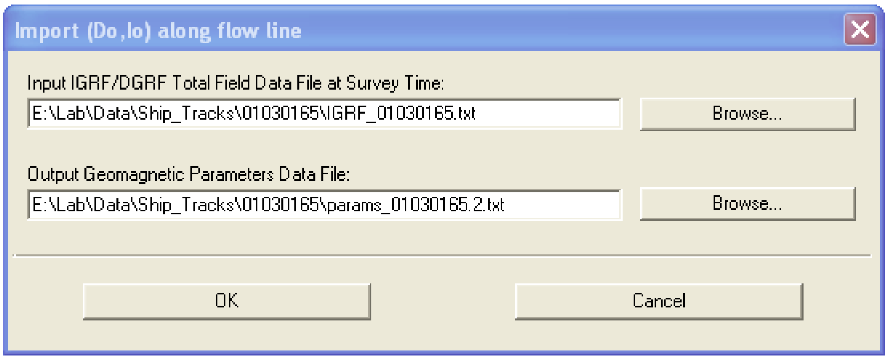

Figure 39. Dialog for the generation of a geomagnetic field parameters file.

Tools → *Project ship-track data*

This is a key command of Magan, which allows to project a ship track data set onto the current flow line. Figure 40 shows the dialog that is displayed after the execution of this command. I remind that Magan requires flow lines in which successive nodes have either monotonically increasing longitudes or monotonically increasing latitudes. This information is supplied to the program in the projection dialog through the *Output Data Sorting* option. In the *Decimation distance along x-axis [km]* control the user specifies the minimum distance between projected points along the flow line. Therefore, the program performs data averages in order to assure the desired output resolution.

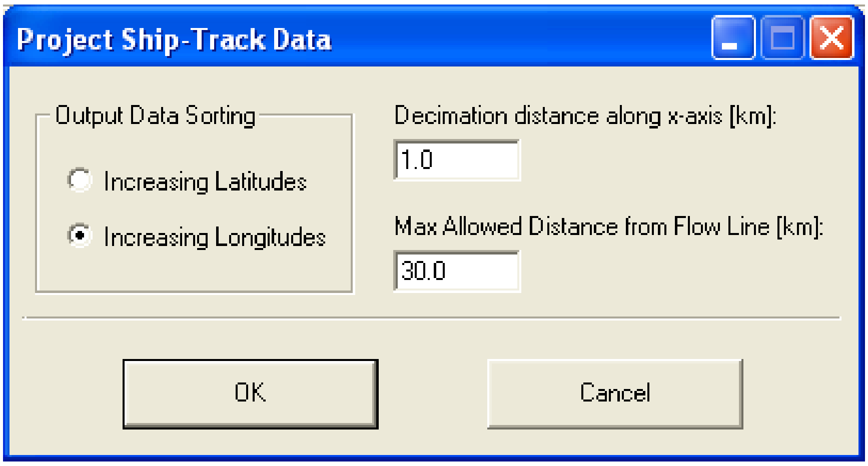

Figure 40. Dialog for the projection of ship-track data onto flow lines.

Finally, in the *Max Allowed Distance from Flow Line [km]* control the user specifies the maximum distance from the flow line that a data point must have in order to be projected. All other data are discarded. This command may be executed again if the resulting projected data set is incomplete (for instance, if the user selected a too large distance from the flow line), or when the decimation distance was incorrect.

Tools → Set magnetic layer depths from gridded data

I admit that this command is not much useful. It simply substitutes the depth of the magnetic source at the location of each projected datum by a new value, which is extracted from a grid. For instance, the user may want to use true basement depths instead of bathymetry. However, the command is uninfluential for the construction of the magnetization model, because modelling windows always employ user-supplied basement/bathymetry grid. Therefore, it is only useful when the user wants a display of the magnetic profile through the command *View → Projected Data → Bathymetric Profile* and the correct depth to basement must be shown. The grid file selection occurs through the dialog of Fig. 21.

Tools → Export magnetic profile for filtering

This command allows to export a projected data set as an ASCII XZ table containing (*Offset*,*Anomaly*) pairs. Then, the file can be sent to other computer programs (e.g., Autosignal) for filtering procedures. For instance, you could want to remove the profile trend through a Fourier filtering algorithm. Use the command *Tools → Import Data → Filtered magnetic profile* to import the filtered data set. Fig. 41 shows the data set of Fig. 24 after a high-pass filtering which removed a ~100 nT constant component.

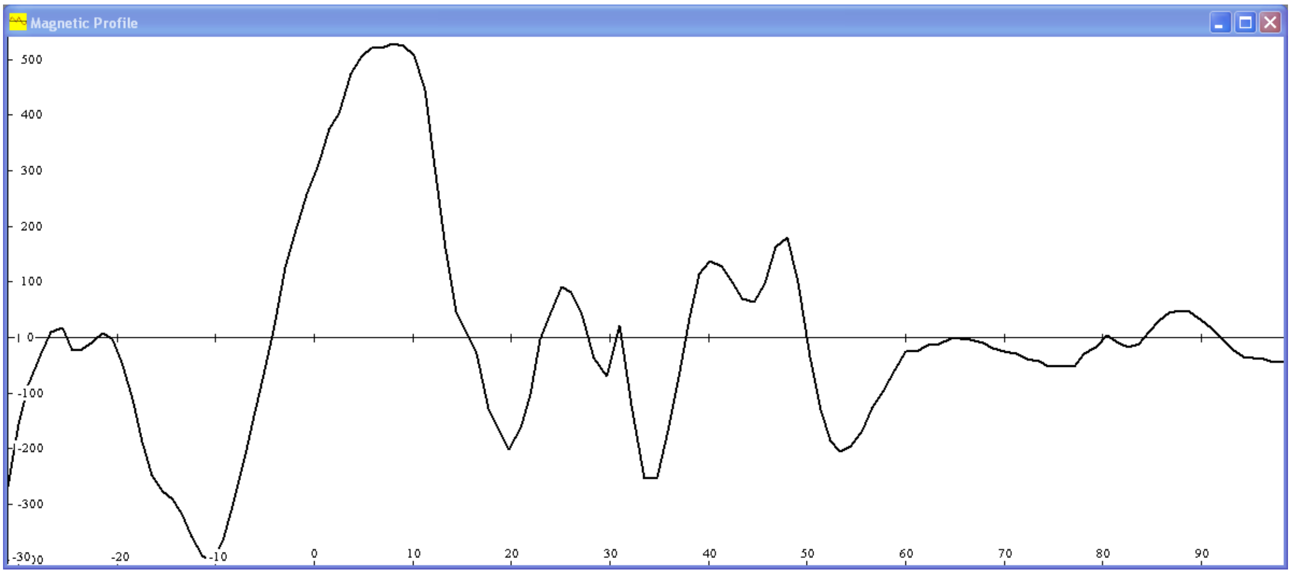

Figure 41. Magnetic profile of Fig. 24 after external high-pass filtering.

Tools → Set ship-track anomalies from IGRF/DGRF data

This command is available from project windows when an NGDC ship-track has been loaded into the current project. It allows to recalculate and set the ship-track anomalies on the basis of an updated Earth's magnetic field model. It is particularly useful when some ship track records specify the total field value but not the corresponding magnetic anomaly (which is obtained subtracting a reference field value). The command assumes that you have compiled a table of reference field records containing a set of field parameters for each ship-track location. The format of this table must coincide with the standard output of *Geomag70*, namely:

Date Coord-System Altitude Latitude Longitude D_deg D_min I_deg I_min H_nT X_nT Y_nT Z_nT F_nT dD_min dI_min dH_nT dX_nT dY_nT dZ_nT dF_nT

You can easily generate such table using the following *Geomag70* syntax:

Geomag70 model f locations.txt parameters.txt

where "model" is the name of an IGRF model (e.g., *igrf11.cof*), "locations.txt" is the name of a table which specifies dates and locations of the ship-track points, and "parameters.txt" is the name of the output file.

The locations table must have 5 fields for each record, according to the *Geomag70* syntax, for instance:

1974.39	D	K0	36.9433	-25.9418
1974.39	D	K0	36.9421	-25.9448
1974.39	D	K0	36.9409	-25.9478
1974.39	D	K0	36.9397	-25.9508
…	…	…	…	…

Please read the *Geomag70* syntax documentation, available through the NGDC web server, in order to set appropriately these fields.

Tools → *Spike Filtering*

This command is available when the active window is a projected magnetic profile window (e.g., Fig. 41). It allows to remove spikes that could result from solar activity, measurement errors, ship track data projection, etc. Magan uses a moving average algorithm for spike removal, which substitutes the magnetic anomaly at any point along the profile with the average in a data window surrounding the point. The window size is selected through the dialog window shown in Fig. 42. This command does not automatically update the projected profile in the main project window. To this purpose, you must execute the command: *Tools* → *Update Project*.

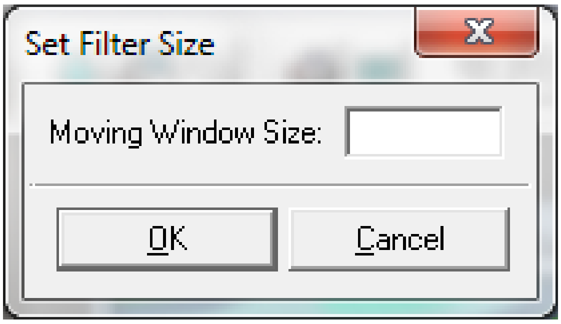

Figure 42. Dialog for the definition of the window size in the despike algorithm.

Tools → Update Project

This command is available when the active window is a projected magnetic profile window in which the magnetic anomalies have been modified by de-spike filtering, or a modelling window after any change of velocity or magnetization. In the former case the program updates the projected magnetic anomalies. In the case of modelling windows the program updates an internal table that is used for the construction of velocity windows, age – distance windows, etc.

Tools → Forward Modelling

This command is available from the main project window. It launches the forward modelling procedure through the construction of a magnetization model and the progressive match between observed and model anomalies (Fig. 2). The program allows to save the graphic content of these windows as compressed PNG (Portable Network Graphics) files or standard Microsoft Windows bitmaps. The graphic content can also be printed. Finally, the user can save an ASCII (*.txt) text table with the observed and model magnetic anomaly profiles using the commnd *File → Save as*. This kind of windows also allows to generate crossing point files through the command: *Tools → Generate Crossing Points File*.

These files are ASCII tables (*.txt) containing as much rows as are the magnetized blocks in the model. Each row has the following five fields:

Chron name *Top age* *Offset* *Longitude* *Latitude*

Chron name is the name of a chron (e.g., C6n) according to the current time scale. *Top age* is the upper age of the corresponding chron. *Offset* is the anomaly distance along the flow line, starting from the origin. *Longitude* and *Latitude* are the geographic coordinates of the crossing point. By convention, Magan writes the positive offset crossing point row first.

Tools $\rightarrow$ *Reset* $\rightarrow$ *Current Model*

This command is available from modelling windows. It resets the current model to the initial values of spreading velocity, asymmetry, magnetization, and obliquity. It also removes any ridge jump.

Tools $\rightarrow$ *Reset* $\rightarrow$ *Left Side*

This command is available from modelling windows. It resets the current model to the initial values of spreading velocity, asymmetry, magnetization, and obliquity along the left side only. It also removes any ridge jump.

Tools $\rightarrow$ *Reset* $\rightarrow$ *Right Side*

This command is available from modelling windows. It resets the current model to the initial values of spreading velocity, asymmetry, magnetization, and obliquity along the right side only. It also removes any ridge jump.

Tools $\rightarrow$ *Rebuild Current Model*

Alos this command is available from modelling windows. It simply rebuilds and displays the current model when some global parameter has been changed from the main window.

Tools $\rightarrow$ *Generate Crossing Points File*

This command is available when the active window is a modelling window and generates a crossing point file having the structure discussed above (see the command *View* $\rightarrow$ *Age-Distance model*).

Tools → Find Stages

This command is available when the active window is an age – distance window in the "mean age" mode (see the command *View → Mean Age – Linear Distance*). It opens a dialog window where the statistical parameters of a linear spline regression fit of the mean age – distance curve are displayed (Fig. 43).

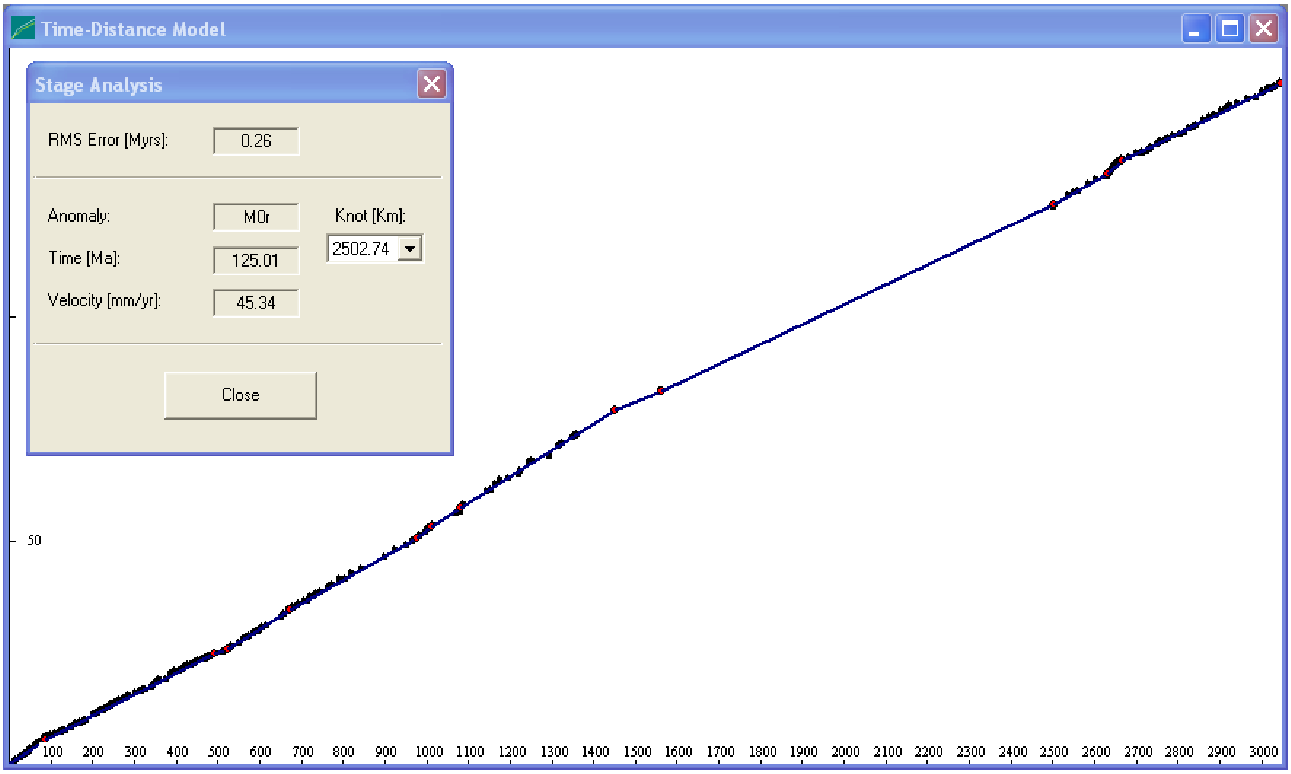

Figure 43. Linear splines fitting of a mean age – distance plot. Red points are the user-defined regression knots. The dialog shows the rms error of regression and the stage parameters (anomaly, time, mean stage velocity, location).

Then the program waits for the insertion of knot locations, which is performed clicking at a point where a change of dip occurs. Only the *x* coordinate of the clicked screen location is important for the definition of new knots. Conversely, deletion of a knot requires a precise right click on the corresponding regression curve node. After each knot insertion or deletion the program updates the content of the report dialog with the new rms error of regression and list of stage boundaries. For each stage are displayed the anomaly name of the old boundary, the anomaly time, and the mean stage velocity. The user can browse other stage parameters by selecting other knot locations.

3.6 Window Menu

Window $\rightarrow$ *Cascade*

This command stacks all open windows and overlaps them so that part of each underlying window is visible.

Window $\rightarrow$ *Tile vertical*

This command arranges your open windows from left to right so that they display next to each other. If there are more than three open windows, Magan arranges them in a manner that allows more height than width.

Window $\rightarrow$ *Tile horizontal*

This command arranges your open windows from top to bottom without overlapping one another. If there are more than three open windows, the IDE arranges them in a manner that allows more width than height.

Window $\rightarrow$ *Arrange icons*

his command rearranges any icons on the desktop. The rearranged icons are evenly spaced, beginning at the lower left corner of the desktop. This command is useful when you resize your desktop that has minimized windows. It is unavailable when no windows are minimized.

Window $\rightarrow$ *Close all*

This command closes all open windows.

3.7 Help Menu

Help $\rightarrow$ *About Magan*

This command displays the Magan version and contact information.

Chapter 4

Miscellaneous

4.1 Magan Files

All Magan files are simple ASCII text files. As already mentioned, project files contain a sequence of rows with the format *param*=*value*, where *param* is a project parameter name and *value* is the current value. Allowed keywords and values for project parameters are listed in Table 1. The order of inclusion in the project file is non influential. These files are created by executing the *File* → *Save Project* and *File* → *Save as* commands. You may edit these files directly using a text editor, for instance if you want to change a file path.

Once you have created a project, the folder where you have stored the project file becomes the *project folder* and Magan uses this location to store any other internal file. If you import an NGDC GEODAS MGD77 trackline file having file name *name*.a77, where *name* is any string allowed by the operating system, Magan creates an ASCII table having the following file name: a77_*name*.txt, which contains the same information of the original file but can be easily read by a spreadsheet program such as Microsoft Excel. Similarly, when you import an NGDC GEODAS MGD77 trackline file having file name *name*.m77t, Magan creates an ASCII table having name: m77t_*name*.txt. Finally, a file having name m88t_*name*.txt is created when you import an NGDC GEODAS MAG88 file having file name *name*.m88t. In the latter case, altitudes are converted from feet to meters. These files are not used by Magan, they are only created for your convenience. However, the execution of the command *Tools* → *Import Data* → *NGDC Trackline* determines the creation of another file which is for internal use only and should not be edited by the user. Its name has the *an* prefix in the current folder: an*name*.txt.

Another Magan internal file is generated after the creation of a flow line. It simply stores the (*Lon*,*Lat*) pairs associated with each node in the flow line ordered list. Such a file has a filename with the *fl* prefix in the current folder: fl*name*.txt. Files having a *pr* prefix (pr*name*.txt) are generated after the projection of magnetic data onto the current flow line. They have the same table structure as the an*name*.txt, but only projected points are included in these files.

Finally, the execution of the command *Parameters* → *Time Scale* determines the immediate creation of an internal table containing the magnetization and velocity model. This file has name: md*name*.txt and has an entry for each chron in the selected time scale.

4.2 Future versions

Magan will be updated periodically as soon as people find bugs, or after suggestions of improvements by the public. Please do not hesitate to contact me if necessary. A first improvement for the next version could be the capability of importing more NGDC track lines at a time, rescaling the total field anomaly to a common time. Another improvement could be represented by a more sophisticated de-spiking algorithm.

4.3 Acknowledgments

The Magan project had its origin in the necessity of new software tools for a comprehensive re-examination of the central Atlantic magnetic anomalies. I give special thanks to my former PhD student Luca Tassi, who helped me both in the design and debug of Magan. The extensive use of the software for his research project on the central Atlantic plate kinematics allowed me to improve considerably the program design.

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