Chapter 6

Discussion

In the following subsections we would like to discuss certain key aspects related to magnetic modelling of the crust, which were omitted in the previous chapters. Curie-temperature isotherm, remanence and continent-ocean boundary contrast bear special importance while interpreting crustal field anomalies. Each of them is discussed briefly here.

6.1 Curie-temperature isotherm depth

Estimating the depth of the Curie-temperature isotherm (CTD) has been attempted from magnetic maps using either the shape of isolated magnetic anomalies (Bhattacharyya and Leu, 1977) or the patterns of magnetic anomalies (Shuey et al., 1977). Shuey et al. (1977) showed that it was not possible to obtain CTD from individual anomalies in space domain and therefore used a spectral method. Maus et al. (1997) pointed out that large survey areas are required to resolve the power at long wavelengths. They assert that a reliable estimate of the CTD cannot be obtained from an area smaller than 1000 km X 1000 km. Consequently, it could be difficult to estimate the CTD from individual aeromagnetic surveys, typically having dimensions of not more than a few hundred kilometers. A consequence of the large survey areas required is that realistic maps of the CTD will have a very low lateral resolution. It is unlikely that it is possible to resolve lateral CTD variations for distances of less than several hundred kilometers from magnetic data by spectral methods. Such CTD maps would not shed much light on geological features with strong lateral temperature variations, such as subduction zones.

In the present work, the derivation of VIS model did not include the CTD variation in the lower crust, nor any attempt has been made to estimate CTD from the observed vertical field anomaly map. Frost and Shive (1986) based on measured geothermal gradients, computed 600° C isotherm and concluded that the isotherm is above the lower crust (20 km) e.g. in the basin and range province, eastern Australia, Central Australia while in the cratons and shields the isotherm could be below the lower crust in the upper mantle. In Sierra Nevada he finds the isotherm to be at a depth of about 74 km. The assumption of the lower crust being the magnetic boundary may seem invalid in such regions. However, Wasilewski et al. (1979) found a complete absence of magnetites in mantle peridotites, and therefore concluded that the Moho is the lower magnetic boundary. In summary, we expect that the CTD is above the Moho in hot regions, while it is either identical to or below the Moho in cold regions. Unfortunately, current temperature models are not sufficiently accurate. Arguably the most accurate model, by Artemieva and Mooney (2001), has a lateral resolution of only 10° X 10°. I therefore decided not to include a temperature model in the present model, relying on the more accurately known Moho as a lower magnetic boundary, instead.

6.2 Remanence

Total magnetisation is the vector sum of induced and remanent magnetisation. Thus, it is important to consider the remanence carried by different rock types. Two types of remanence are discussed here, stable and viscous. Some rocks have stable remanence acquired when the rocks cooled to below the blocking temperature of their minerals. This magnetisation is acquired in a direction parallel to the Earth's magnetic field during cooling, which may be different from the present direction of the field because of geomagnetic field reversals in the geologic past. Single-domain grain bearing rocks, like the rapidly solidified basalts, carry these remanences most effectively. However, in larger multi-domain size grains, dominant in slowly solidified and metamorphosed rocks, the stable remanence undergoes viscous decay with time. Then, the original remanence is replaced by viscous remanent magnetisation (VRM) parallel to the present field direction. For the present modelling, it is therefore not necessary to distinguish between VRM and induced magnetisation.

Stable remanence is likely to be less important in deep crustal conditions than in upper crustal conditions. Stable remanence decreases with increasing temperature and degree of metamorphosis. Stable remanence carried by both single-domain and multi-domain grains decays exponentially with time. According to Shive et al. (1992) stable remanence cannot be responsible for high magnetisation required by magnetic anomaly analyses. Treloar et al. (1986) showed through laboratory and theoretical studies that even VRM in the lower crust cannot be as great as induced magentisation. Moreover, the size of Fe-Ti oxides in lower crust is around 100 microns (Schlinger, 1985), i.e., they are not single-domain grained minerals, and hence cannot carry strong remanence. Shive (1989) and Shive et al. (1992) concluded that the total magnetisation of lower crustal rocks is not significantly greater than their induced magnetisation.

Following the above reported works it is justified not to consider remanence in our present study, which focuses on the continents. The results discussed for various continents in chapter 4 showed some disagreement of the *initial model* anomaly shapes and amplitudes with the observed magnetic anomaly map. However, reinvestigation in some regions of the world (discussed in Chapter 5) showed that assuming induced magnetisation, as the only source for the anomaly is always sufficient to explain the observed anomaly. This holds even in west Africa, though some part of the observed anomaly is yet unaccounted for. Here, either the magnetisation extends in to the upper mantle as suggested by Toft and Haggerty (1988) or the lower crust is more magnetic than has been considered in the present work. In central Africa, basalts in the lower crust and an additional 4 km of basalts in upper crust explain the observed anomaly. Thus, it was not necessary to consider remanence in the present work to explain the observed magnetic anomaly. In summary, we have found no indication that remanence is required to explain the magnetic anomalies of continental crust. This is likely to be different for the oceanic crust.

6.3 Continent-Ocean boundary

Interpretation of satellite derived magnetic anomaly maps has always generated interest in the study of the exposed anomaly caused by the continent-ocean contrast. It is generally asserted that because continent is thicker than ocean, an anomaly should be expected at the continent-ocean boundary and should have influence on the anomalies observed further inside the continents. Some studies have tested the validity of such an assertion.

The 3D global magnetisation model derived by Arkani-Hamed and Strangway (1986a) showed distinct differences between oceanic and continental areas. Hinze et al. (1991) compiled the mean magnetic anomaly amplitude for crustal anomalies and for oceanic anomalies off the coast of South America and found a statistical increase in continental anomaly amplitude. However, a ubiquitous continent-ocean contrast was absent from magnetic anomaly maps prepared from satellite data. This means that either the vertically integrated magnetisation of oceanic crust is the same as that of continents or it has been eliminated in the process of removing the long wavelength main field. This conclusion was verified in the studies of Cohen (1989) and Counil et al. (1991) who modelled the continent-ocean boundary as a step function in susceptibility contrast. They confirmed that continent-ocean boundary is a long-wavelength feature and it is partly removed in subtracting the long wavelength main field. Forward modelling methods based on global models of Meyer et al. (1983) and Hahn et al. (1984), derived from surface geology, seismic structure, and standard susceptibilities also made an effort to study the effect of continent-ocean boundary. The modelled magnetic field, in general, did not reproduce the effect of continent-ocean boundary and they concluded that this effect might be a long wavelength feature, which has been removed while removing long wavelength part of the main field. Purucker et al. (1998) derived a magnetisation model that included a built-in first-order continent-ocean boundary effect.

In the present study, the global VIS modelling permits us to study systematically the effect of continent-ocean boundary. In chapter (1), it was shown that the observed magnetic anomaly map was derived by removing the long wavelength component from the main field. This means that main field masks the wavelengths from the crust and hence we cannot see them. But, one of the most interesting results of our modelling is that using our VIS model, which predicts the magnetic anomaly map for spherical harmonic degrees 16-80 that matches well with the corresponding degrees of the observed magnetic anomaly map, can also predict the long wavelength features of the real crustal field. As the VIS model does not include the parameters of the mantle but only the crustal part, producing the map of degrees 1-80 should show the long wavelength component of the VIS model. *First iteration* vertical field anomaly map for spherical harmonic degrees 1-80 is shown in Figure (6.1). Interestingly, there is no anomaly over the continent-ocean boundary. This means the continent-ocean boundary is not a long wavelength feature and the absence of anomaly over the continent-ocean boundary indicates that the bulk susceptibility of the continents and oceans are comparable. Another feature that is interesting in the map is the presence of strong anomaly features at the edges of major cratons of the world. However, our model is not entirely a complete one as the observed magnetic anomaly map has possible long wavelength components from the upper mantle which our model lacks them.

Though the above result suggests the absence of effect of continent-ocean boundary, we study systematically the possible influence of continent-oceanic boundary on the anomalies that lie further inside the continents and also some observed anomalies that run parallel to the mid-oceanic ridges, e.g. north Atlantic ocean. For this, three VIS models are derived with different parameters for the oceanic region. The susceptibility distribution is shown in Table 6.1

Geological region	**Model-1**	**Model-2**	**Model-3**
Continent	*First iteration* VIS model	*First iteration* VIS model	*First iteration* VIS model
Ocean	0.0	*First iteration* VIS model	3 X *First iteration* VIS model

Table 6.1. The susceptibility distribution of continents and oceans to study the continent-ocean boundary effect.

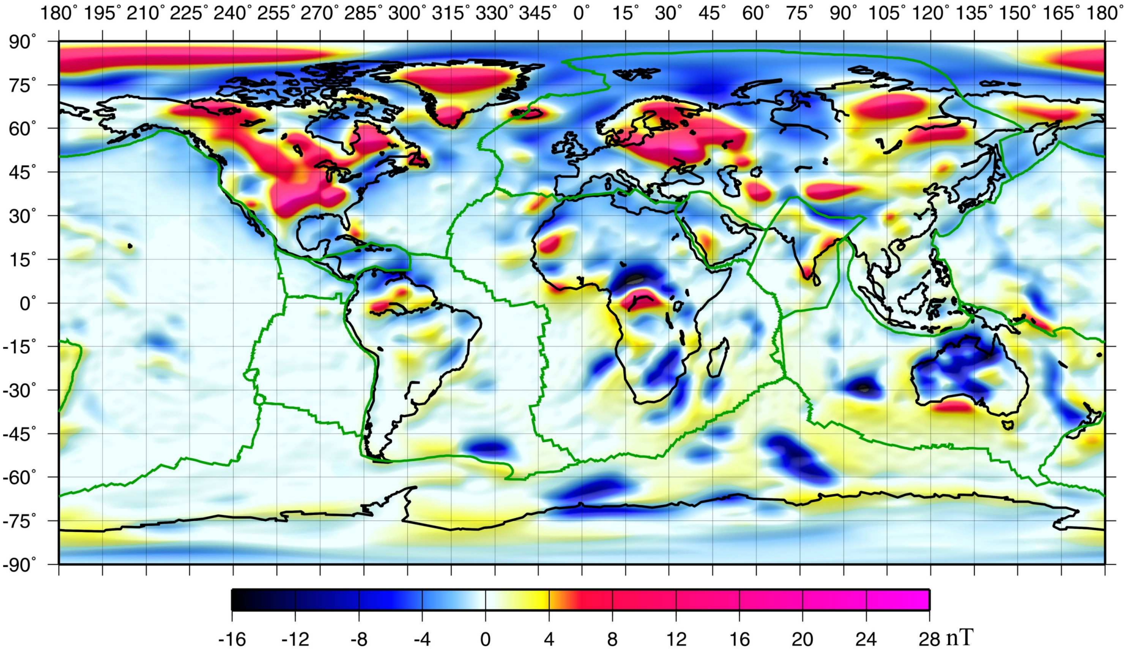

Fig. 6.1. *First iteration* vertical field anomaly map for degrees 1-80 at an altitude of 400 km.

The results for the above three VIS models are shown in Figures (6.2), (6.3) and (6.4) respectively. The predicted anomaly map for the vertical component for degrees 16-80 derived using Model-1 is shown in Figure (6.2). It predicts a few weak anomalies over the eastern boundary of the South American craton. However, largely, the effect of the continent-ocean bulk susceptibility contrast is not apparent in the map. There are some regions of the world, which are influenced by the susceptibility contrast of continents and oceans. Over northern and southern Greenland the positive anomaly is enhanced. The anomaly over the Ungava craton, Canada is also stronger. In Figure (6.3) the effect of continent-ocean boundary is certainly not evident in the predicted vertical field anomaly map for degrees 16-80 derived using Model-2. There are evidently no magnetic anomaly features running parallel to the continents or the oceans, which obviously follow the predictions for the map for degrees 1-80. The predicted anomaly map as shown in Figure (6.4) for model-3 shows enhanced effect at not only the boundary of continent-ocean but also over the continents and oceans. A strong anomaly pattern is seen along the coast of the Pacific ocean. Along the western coast of North America and eastern coast of Russia and Japan, an anomaly pattern is seen. All over the western boundary of north Atlantic ocean a strong anomaly pattern is evident. Surprisingly, over the south Atlantic ocean the effect is not prominent and the same holds true for the Indian ocean. A strong effect is also observed over the coast of Antarctica.

The above results show that the bulk susceptibility contrast for continents and oceanic regions when changed does produce an anomaly at the continent-ocean boundary. There is also modification of anomalies strength and patterns further inside the continents. Absence of anomaly over the continent-ocean boundary, in the *first iteration* magnetic anomaly map both for degrees 1-80 and 16-80, shows that bulk susceptibility contrast of the continents and oceans are comparable. Our modelling result indicates that no long wavelength features related to continent-ocean boundary exist and, hence, there is only minimal effect of the continent-ocean boundary.

6.4 Oceanic plateaus

In chapter 3, the structure of the oceanic plateaus was discussed following the reported work of Carlson et al. (1980) and Nur and Ben-Avraham (1982). A simple 3-layered model was assumed to model the plateaus. The vertical component of the magnetic field was predicted for degrees 16-80 at satellite altitude and compared with the corresponding vertical component of the observed magnetic anomaly map. The results were discussed briefly for all the modelled plateaus in Chapter 4. Generally, for most of the plateaus, the assigned susceptibility values for different layers and the crustal thickness from the 3SMAC seismic model and some results taken from literature, was sufficient to explain the observed anomaly pattern. However, there are anomaly patterns, especially in south Atlantic ocean that are not explained completely on the basis of *initial model* modelling parameters.

The modelling results for the anomalies located northeast of Georgia, South America and over Maud rise, Antarctica, suggests that the crust in these regions is thicker by 10.0 km and 6.0 km respectively, than indicated by 3SMAC seismic model. Over the Walvis ridge, off the western coast of Africa, a part of the observed anomaly is yet unaccounted for, though the crustal thickness in this region has already been increased by 8.0 km over

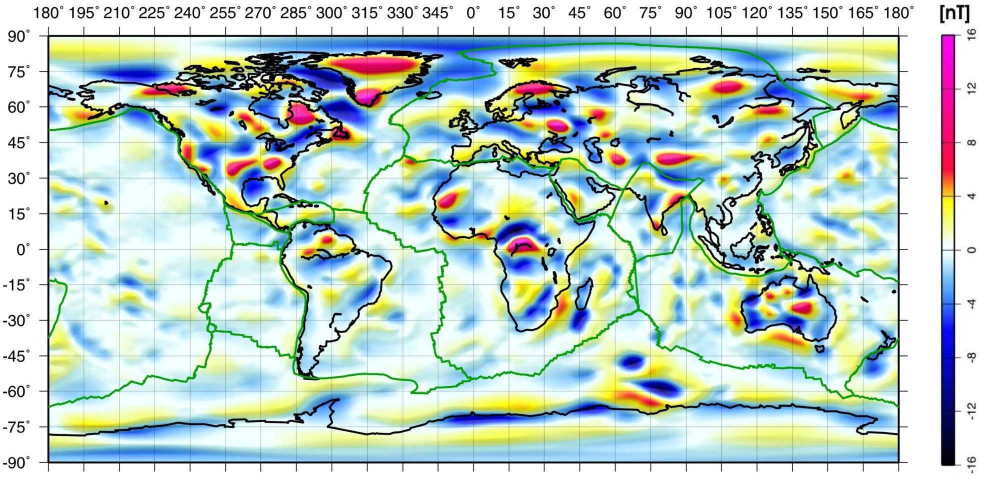

Fig. 6.2. *First iteration* vertical field anomaly map for degrees 16-80 predicted for Model-1, at an altitude of 400 km.

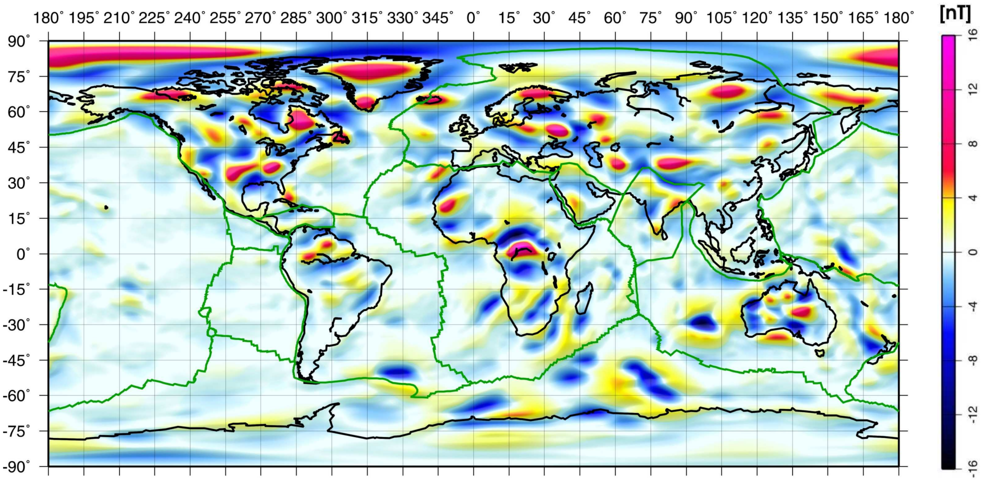

Fig. 6.3. *First iteration* vertical field anomaly map for degrees 16-80 predicted for Model-2, at an altitude of 400 km.

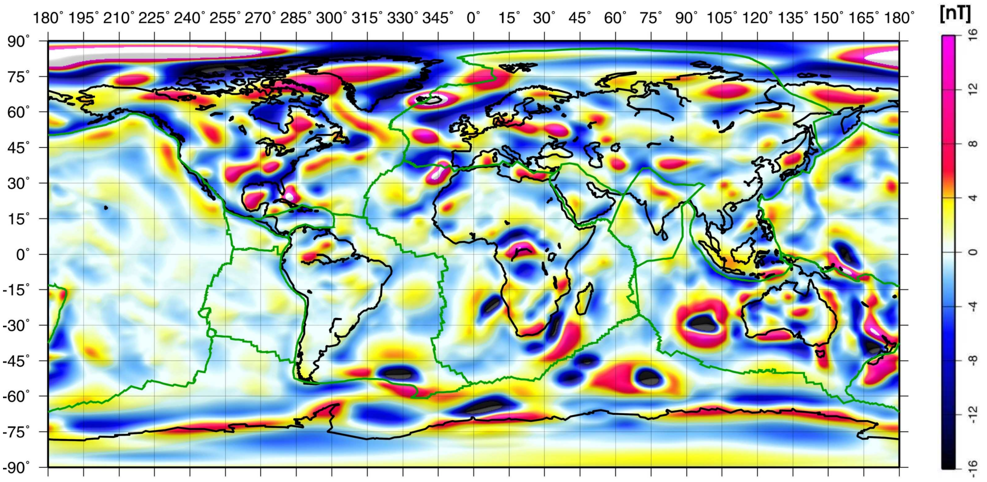

Fig. 6.4. *First iteration* vertical field anomaly map for degrees 16-80 predicted for Model-3, at an altitude of 400 km.

the lower crustal thickness indicated by the 3SMAC model. This increase was allowed following the reported work of Detrick and Watts (1979). The results in south Atlantic ocean indicate that either the crust is thicker in these plateaus or an additional magnetisation in the form of remanence is also contributing to the observed anomaly pattern. Additionally, over the west of Australia, the anomaly trend from the Broken ridge to the Naturliste plateau is completely missing in the *initial model*. This may also be due to the unmodelled remanent magnetisation in our *initial model*. More interesting is the inability of the *initial model* to explain the observed anomaly pattern, between Lord Howe rise and Norfolk plateau, west of Australia. These unexplained anomalies may be caused by the lack of subsurface geological information for these regions and partly due to imprecisely known crustal structure in these regions. However, the possibility of remanent magnetisation also cannot be ruled out as a cause. In summary, some plateau anomalies (Kerguelen ridge, Broken ridge, Crozet and Conrad rise, Agulhas plateau in Indian ocean and Alpha ridge in Arctic ocean) are well explained by induced magnetisation or remanent magnetisation parallel to the present field. Other anomalies (Walvis ridge, Maud bank, South Georgia, anomaly between Lord Howe rise and Norfolk plateau) could possibly be remanently magnetized in direction other than the present main field.

6.5 Key uncertainties

The forgoing discussion concentrated on issues, which had not been taken up in previous chapters. There are, however, some key uncertainities, which may be an important factor in modelling and interpretation of anomalies. According to Haggerty (1978) serpentinization of the upper mantle may produce magnetites. These magnetites can enhance magnetic values locally and can be an added source for anomalies. This may be important in some cratons, like West Africa. Besides, in laboratory experiments, magnetic material shows the ‘Hopkinson effect’. The susceptibility of most magnetic minerals increases with temperature near the Curie-temperature. However, Nagata (1961) showed that lower-crustal materials do not show the Hopkinson effect. Nevertheless, this uncertainty in some regions may be very important. A further uncertainty is caused by the presence of magnetic field annihilators. There are susceptibility distributions across the magnetic equator, which, in the presence of a dipole dominated inducing field, produce no observable magnetic field outside of the earth (Maus and Haak, 2003). Another annihilator derived by Runcorn (1975), states that the spherical shell of homogenous magnetisation does not produce a magnetic anomaly outside in any internal inducing field. These annihilators can be important in modelling anomalies across the magnetic equator.

The discussion of the above results can be summarized as follows. There was no effort made to compute the Curie-temperature isotherm using the observed anomaly pattern nor were geothermal models included in the present modelling work. As the Curie-temperature isotherm for basin and range provinces of the world may be shallower than the Moho, it may have a partial effect on our results for some parts of the world. However, if Moho is a lower magnetic boundary as claimed by Wasilewski and Mayhew

(1992) work the effect of Curie-temperature isotherm could be minimal in most parts of the world as has been shown conclusively through our modelling work. Remanence is not significant while modelling the anomalies over the continent but may be important over the ocean. So, our assumption of keeping our models free of remanence holds reasonably well for interpreting continental anomalies. Continent-ocean boundary effect is absent from the *first iteration* map computed for degrees 1-80. This map contains even the long wavelength components of the crustal field. With the realistic values of susceptibilities for continents and oceans, the bulk vertical susceptibility of continents and oceans may be comparable. The present modelling result indicates that remanence may be important in modelling some oceanic plateaus, especially in south Atlantic ocean. However, as remanence had not been a part of our modelling and the present work emphasizes on interpreting the anomalies observed over the continents, the modelling of oceanic plateaus is not investigated further.