Chapter 2

Global Crustal Magnetisation Model

2.1 Introduction

The varying pattern of Earth's regional magnetic anomalies is caused by a complex superposition of geological features in the lithosphere, covering a broad spectrum of wavelengths. These anomalies are caused by lateral variations of the bulk susceptibility contrasts of the crust. Their sources are ferrimagnetic minerals, predominantly magnetite. They occur in varying quantities in the igneous and metamorphic rocks and to some extent in some sedimentary rock types like banded iron formations (BIF) of all geological ages. Most of these rocks are hidden by overlying younger, generally nonmagnetic, sediments and sedimentary strata, both on the continents and in the oceans.

This chapter provides a review of the crustal tectonic units which are the sources of the magnetic anomalies within the continental lithosphere. Although considerable effort has been put into investigating the magnetic properties of minerals, such studies have focused largely on minerals of direct or indirect importance in magnetic surveys, exploration for natural resources, and for paleomagnetic studies. Much less is known about the nature of geological processes and the resulting magnetic properties of rocks. Even more important is our lack of knowledge of the magnetic character of the lower crust and the upper mantle. Also, the present knowledge of the deeper portions of the lithosphere is rather rudimentary, largely because of the limited access to xenolith samples from those depths. As found by Hall (1974), some long wavelength anomalies correlate with exposed upper crustal sources. This means that upper crustal magnetisation may be an important contributor to long-wavelength anomalies and lower crustal composition may be reflected in surface geology. Blakely and Griscom (1988) continued the aeromagnetic map of North America to a higher altitude and found excellent correlations with Precambrian and Paleozoic provinces. In another study of granitoids of various regions, Chappell et al. (1988) demonstrated that the composition of granitoids largely reflects the composition of their source regions. The distribution of granitoids suites can be used to define terranes, within each of which the lower crust has distinctive geochemical characteristics. Thus, following the geophysical and geochemical investigation as mentioned above, it was desired to adopt a modelling procedure where, based on the surface geology, the geology of the lower crust was assumed to be having the same geochemical characteristics. Hence, we started compiling the rock types exposed at the surface of all the Precambrian regions of the world.

2.2 Geology of the continents

The sources of the continental magnetic anomalies primarily consist of the rock types formed early in the geological history of the earth. The complete stratigraphy of the rock units is categorized in two broad units, the older unit called Precambrian(>570 Ma), and the younger Phanerozoic. The Precambrian unit is further subdivided into an older rock section called Archean(>2500 Ma) and the younger Proterozoic. According to Taylor and McLennan (1985), 75% of the earth's crust had already formed at the end of the Archean. A glance at the anomaly map (Fig 1.5) clearly points to the fact that most of the anomalies lie over the geological regions occupied by Precambrian rocks, either exposed or hidden by younger Phanerozoic cover. However, the exposed Precambrian rocks constitute only 29% of the total Precambrian crust (Goodwin, 1991). This means that a significant portion of the oldest crust on Earth is overlain by Phanerozoic cover. Hence, our aim is to look for the possible extensions of the Precambrian units obscured by younger cover and possibly add to the existing knowledge of geological boundaries of the Precambrian units. For this it is necessary to consider the known geology of the region and its boundary at the surface. This is mentioned in the following subsections. However, for the detailed geology the reader is referred to the references mentioned therein.

The bulk of Earth's Precambrian crust is located in nine Precambrian cratons, which center the main continental masses, Asia, Europe, Greenland, North America, South America, Africa, India, Australia and Antarctica. The Precambrian cratons comprise both the exposed shields, generally termed as cratons, and the buried, i.e. sub-Phanerozoic called Precambrian basement. Additional Precambrian crust lies within median massifs, called inliers, within cratons enclosing Phanerozoic mobile belts and isolated continental fragments scattered in the oceans.

2.2.1. Cathaysian craton

The Cathaysian craton shown in Figure (2.1) comprises three cratons- Sino-Korean (north China), Tarim and Yangtze (southwest China). The Sino-Korean craton includes most of north China and the southern part of northeast China and part of North Korea. Archean rocks are concentrated in the central eastern parts of the craton, where they form the Ordos and Ji-Lu nuclei. The rocks are exposed especially in Shanxi plateau and Jiaoding-Liaodong region in the north and in Henan province along the southern margin. The Tarim craton is situated between Tianshan mountains in the north and the Kunlun-Arjin mountains in the south. Precambrian basement, locally exposed at the periphery, comprises Archean gneiss and early to mid Proterozoic rocks. It is overlain by Paleozoic marine clastics and Mesozoic-Cenozoic sediments. The Yangtze craton covers the territory of the lower-central Yangtze River drainage and the southern part of the Yellow Sea. Early Proterozoic rocks are confined to the periphery of the craton. The central part has extensive mid-late Proterozoic cover, which underlies Phanerozoic cover. The detailed geology can be found in the works by Zhang et al. (1984) and Yang et al. (1986). Their work has been summarised in the book by Goodwin (1991, 1996).

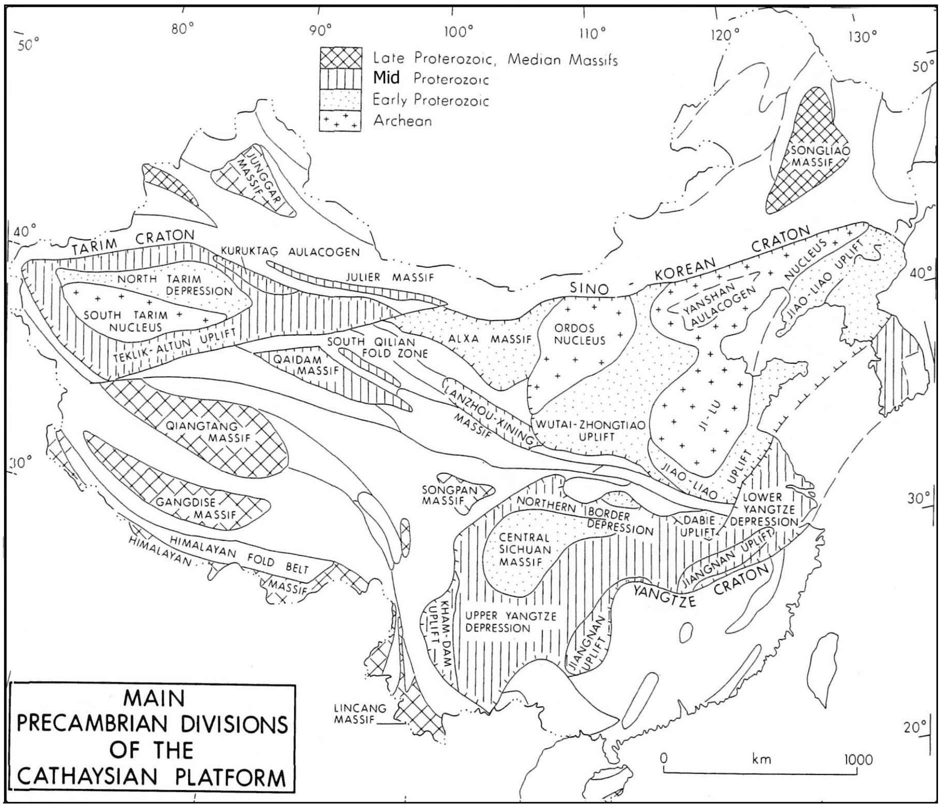

Fig. 2.1. Tectonic map of Cathaysian craton (Goodwin, 1991).

2.2.2 Siberian craton

The Siberian craton includes two main Archean to early Proterozoic shields: Aldan in the southeast and Anabar in the north (Fig. 2.2). The small Olenek uplift east of the Anabar shield lies close to the northeast boundary of the craton. In addition, Precambrian rocks are exposed in six peripheral fold belts, clockwise from the southeast: Stanovoy, Baikal, East Sayan, Yenisei, Turkhansk- the last four accreted to the craton during the end-Proterozoic Baikalian Orogeny – and, to the north, the Taymyr fold belt, which is separated from the craton by the deep intervening Khatanga trough of Phanerozoic age. Precambrian median massifs, of varying size, are present in adjoining Phanerozoic fold belts, notably Okhotsk, Taigonos, Kolyma-Omolon and Anyuy-Chukota in the northeastern Siberia, to the east. Shatzki and Bogdanoff (1959), Salop (1977, 1983), Khain (1985) and Khain(1994) studied the geology of Siberian craton in detail.

The basement of the Siberian craton is formed mainly of Archean rocks partly reworked in early Proterozoic time, with some Proterozoic filled troughs. The basement is submerged to varying depths, forming a number of large depressions filled with sedimentary cover. The main depressions are the huge Triassic trap-filled Tunguska syneclise in the northwest and the Mesozoic Vilyui syneclise in the east, the latter a northeastern extension of the Chara-Lena trough. Syneclises are regions characterised by thick sedimentary cover over the basement, while anteclise are the regions where the basement is raised with respect to the surrounding, and consequently overlying sediments are thin.

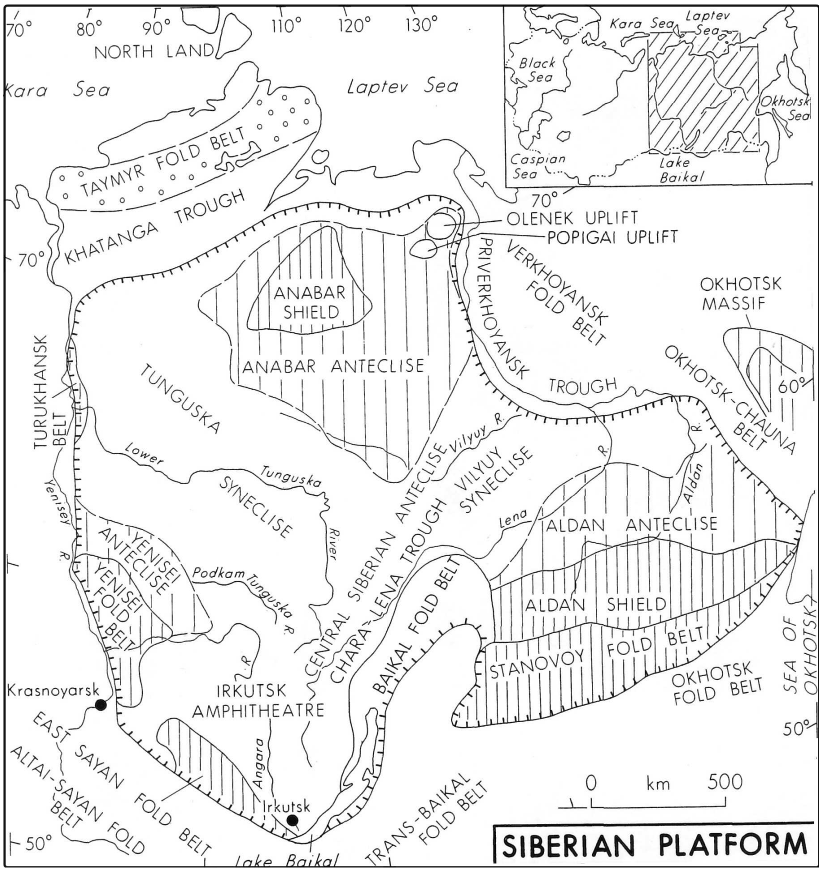

Fig. 2.2. Tectonic map of Siberian craton (from Goodwin, 1991; after Shatzki and Bogdanoff, 1959; Salop, 1977).

2.2.3 East European Craton

The craton shown in Figure (2.3) includes two prominent shields: the larger, rectangular, partly submerged Baltic shield in the northwest and the smaller, curvilinear Ukrainian shield in the southwest. Positive elements include the slightly buried Voronezh anteclise (uplift) and Volga-Urals anteclise to the east and Belorussian anteclise to the northwest. The Riphean-Vendian-Phanerozoic cover is 2-4 km thick but increases in thickness in the main depressions, notably the Moscow-Baltic syneclise in the north and the North Caspian syneclise in the south, the latter attaining the remarkable maximum thickness of 23 km. Goodwin (1991) and Khain (1985) have compiled the detailed Precambrian geology of these regions. The references mentioned therein can also be referred to.

The Baltic shield is divided by deep faults or other tectonic zones into five major provinces, namely, the Kola peninsula in the northeast, the adjoining Belomorian province to the west, the nearby Lapland granulite belt, the succeeding Karelian province to the west extends southward from the Caledonide front to the Lake Onega. The large

Svecofennian province occupies the central part of the Baltic shield and in the southwest the Sveconorwegian province dominates in southern Norway and Sweden.

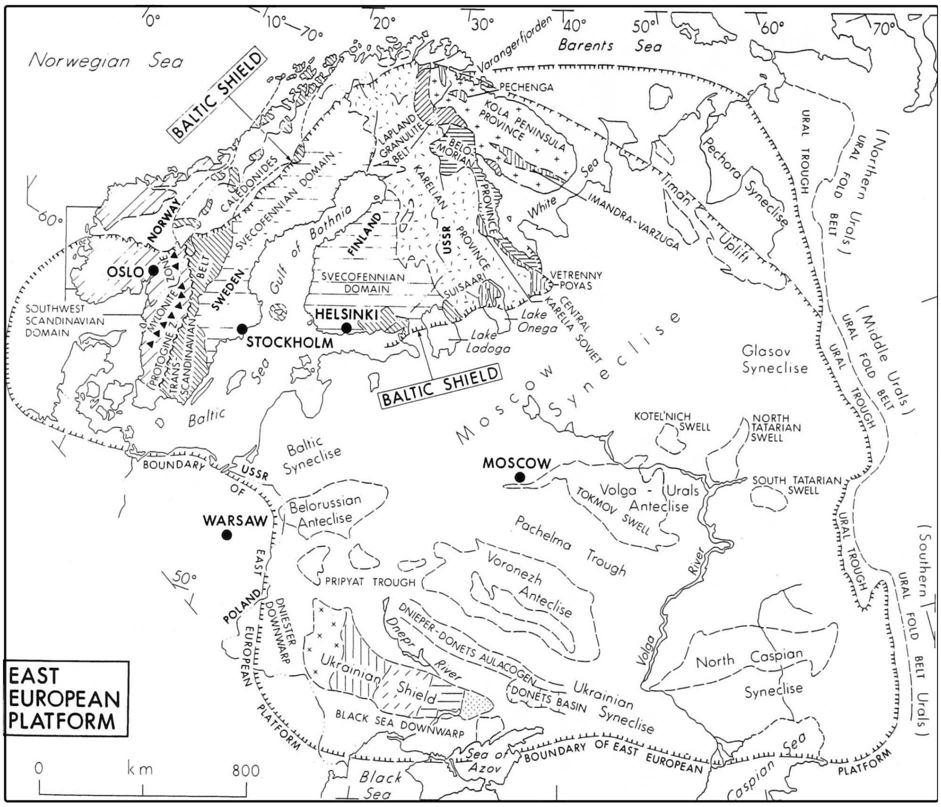

Fig. 2.3. Tectonic map of East European craton (from Goodwin, 1991; after Khain, 1985; Shatzki and Bogdanoff, 1959).

The Ukranian shield consist of five Principal Archean Blocks: Volyn, Bug-Podolian, Kirovograd, Middle Dnieper and Azov. The Archean blocks are separated by narrow meridional Banded Iron Formation (BIF)-bearing early Proterozoic blocks. Among these, Krivoy Rog extends for more than 220 km, as traced by drilling and a total distance of 1000 km, by magnetic anomalies, reaching the Kursk magnetic anomaly of the Voronezh massif located 300 km to the northeast.

The buried basement of the East European Craton comprises 23 relatively small, isometrically-elongated Archean blocks (massifs) with intervening early Proterozoic fold belts. The basement was later buried during the Riphean-Vendian time, with Late-Proterozoic-Phanerozoic cover of varying thickness. The Timan-Pechora occupies the extreme northeastern part of the Russian plain and is separated from the East European Craton by the NW-trending Timan ridge. A long string of Precambrian Massifs lies along the Uralian Fold Belt, which is situated to the east of East European Craton. It comprises large uplifts, notably, Bashkir Uraltau, in the western Uralian zone. Precambrian crystalline rocks are also present in Variscan inliers, mainly, Armorican, Central, Bohemian and Iberian Massifs. The British Isles are largely covered with Caledonide massifs.

2.2.4 Greenland

Inland ice covers 80% of Greenland and, hence, exposures are seen only at the periphery of the continent. Four major structural provinces are recognized in the Precambrian craton of Greenland shield as shown in Figure (2.4). An old Archean block is present in the south of the plateau which is flanked by the Nagssugtoqidian belt to the north and the Ketilidian belt to the south, early Proterozoic in age. To the north of Nagssugtoqidian belt occurs a very broad early Proterozoic Rinkian belt. Some of the older rocks in the Isua region of the central west Greenland have provided one of the oldest preserved rocks on Earth, which date back to 3820 Ma. The east of Greenland is dominated by the Caledonides. Spitsbergen Archipelago, to the northeast, includes patches of Late Proterozoic metsupracrustal rocks. Notable contributions are from Moorbath et al. (1973), Bridgwater et al. (1976), Myers (1984) and Goodwin (1991).

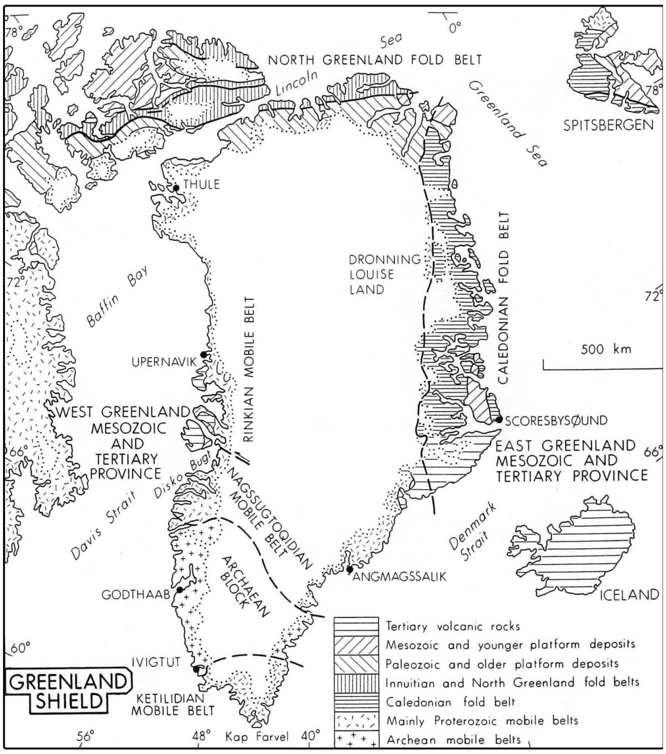

Fig. 2.4. Tectonic map of Greenland shield (from Goodwin, 1991; after Escher and Watt, 1976).

2.2.5 South American craton

The South American craton, as shown in Figure (2.6), comprises three exposed shields – Guiana, central Brazil and Atlantic and buried precambrain basement beneath three large basins, Amazon, Parnaiba and Parana. Guiana Shield contains (1) three comparatively small Archean nuclei – (a) the tectonically overthrust Imataca complex in the north, (b) the poorly defined Pakairama craton in the center-west and (c) the Xingu craton (northern segment) in the southeast; (2) greenstone bearing early Proterozoic Maroni-Itacaiunas Mobile Belt; (3) in the west, NW-trending mid-Proterozoic RioNegro-Juruena Belt.

The Central Brazil shield predominantly consist of (1) Guapore craton, in the western sector (Gibbs and Barron, 1983), represents the southern extension of the Guiana shield south of the Amazon basin. The subordinate eastern sector of the central Brazil shield constitutes the Tocantins province (Almeida et al., 1981).

The Atlantic shield comprises three structural provinces: São Francisco, Barborema and Mantiquiera. Small adjoining basement fragments include São Luis craton in the north and Rio de la Plata craton in the south.

The mid-Proterozoic San Ignacio belt of the Bolivian shield area, is covered by Cenozoic sediments. The adjoining (to the southwest) Sunsas-Aguapei (Rondonian) Belt lines up with basement inliers in Bolivia, Peru, Ecuador and Columbia. The key reference is Litherland et al. (1985).

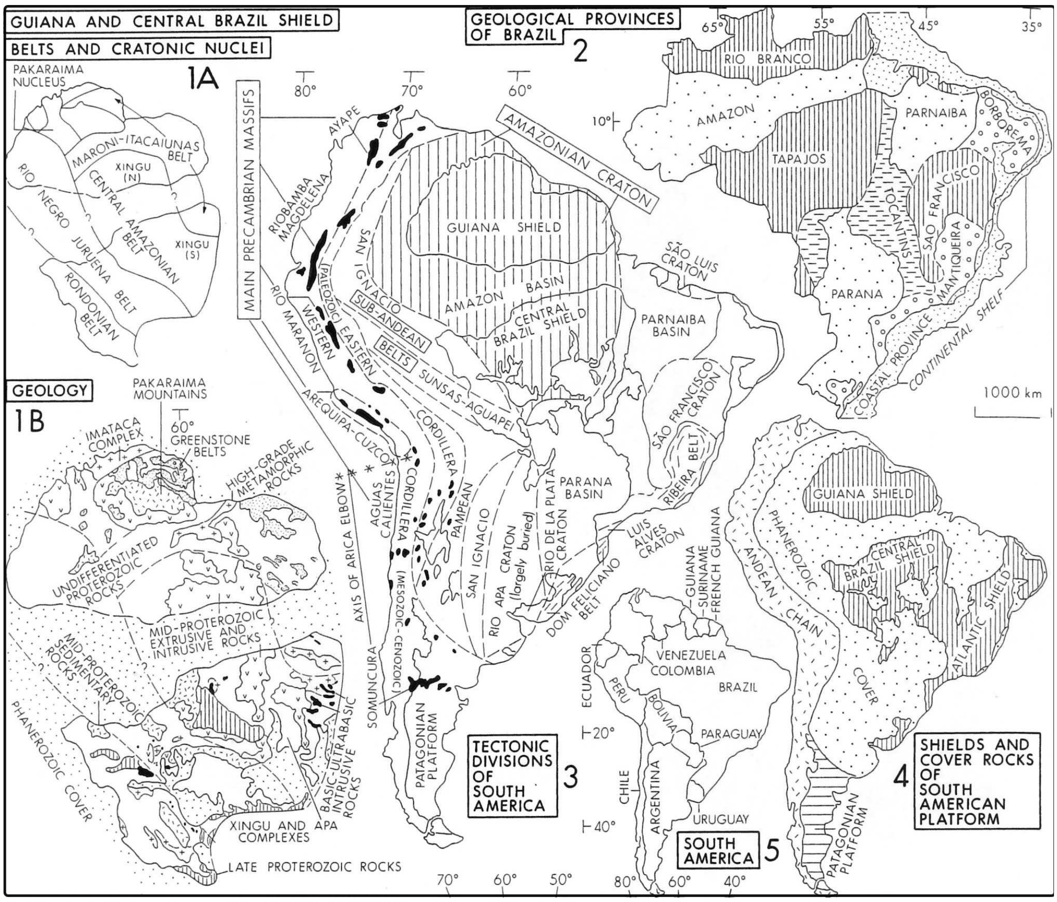

Fig. 2.5. Tectonic map of the South American craton (from Goodwin, 1991; after Almeida et al., 1981; Litherland et al., 1985).

2.2.6 North American craton

The North American craton forms a large ovoid craton and is encircled by Phanerozoic fold belts (Fig. 2.5). About one-third of the complete craton is exposed, dominated by the uniquely large Canadian Shield and a small circular Wyoming uplift in the southwest (Goodwin, 1991).

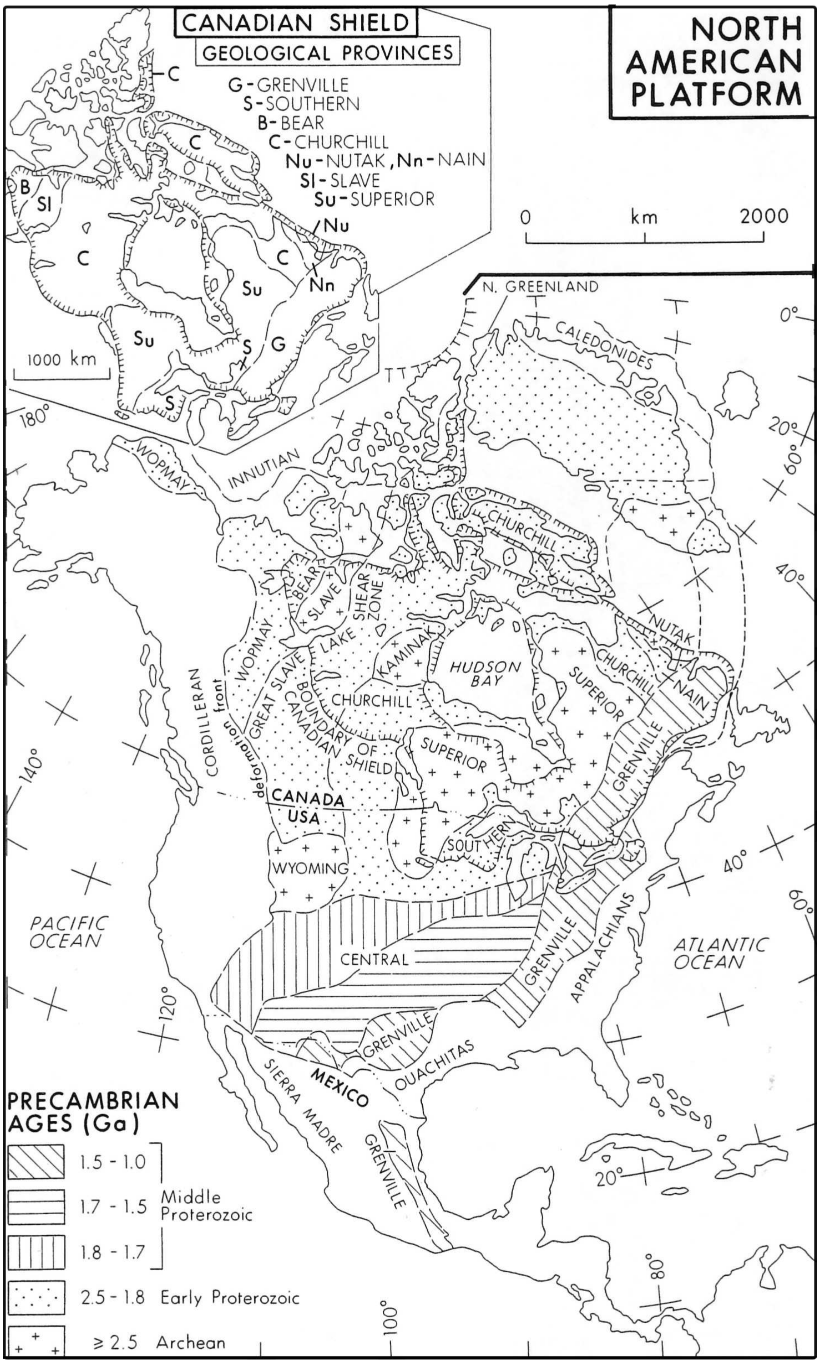

Fig. 2.6. Tectonic map of the North American craton (from Goodwin, 1991; after Hoffman, 1989).

The Canadian shield is a large craton, and at its center lies the Phanerozoic-filled Hudson bay. The Shield is divided into seven tectonic provinces. Of these, two (Superior and Slave) are Archean in age, three (Churchill, Bear and Southern) mainly early Proterozoic, one (Nain) Early mid-Proterozoic and one (Grenville) late mid-Proterozoic. Late Proterozoic rocks are confined to the continental margins.

Buried extensions of Superior province lies to the north in James bay and Hudson bay, of Slave province to the north in Arctic craton, of Churchill province to the north also in Arctic craton and southwest in Interior craton and Cordilleran belt, of Bear province to the north in Arctic craton and west in Interior craton and Cordilleran belt, and of Grenville Province to the south and southwest as far as Mexico in Interior craton and Appalachian belt. Central Province (belt) is a large structural province, which underlies the south-central USA. The rocks of these provinces are exposed only at a few places in Colorado and California. Large anorogenic magmatic activity is dominant along the entire stretch of this province.

Numerous Precambrian inliers are distributed in the adjoining Cordilleran, Appalachian and Innutian fold belts. Allochthonous slices are distributed in the Phanerozoic fold belts of the Innutian (eastern and Western Arctic Regions), Cordilleran (Yukon, Alaska, British Columbia, Alberta and western USA), Ouachitan and Appalachian (Canadian and US sectors) orogens.

2.2.7 African craton

North to south and east to west trending Pan-African belt system divides the craton into five cratons: southern (Kalahari), central (Congo), northwestern (West African), north-central (Saharan) and northeastern (Arabian-Nubian shield) (Fig. 2.7). The main intervening Pan-African belts, respectively (1) E-trending and (2) N-trending, are (1) from south to north, Damara-Katangan-Zambezi and Central African; and (2) from west to east, Rokelides (Mauritanides), Pharusian-Dahomeyan, West-Congo-Kaoko-Gariep and Mozambique. Notable contributions on the African geology are from Saggerson (1978), Black (1980), Cahen et al. (1984), Kröner et al. (1987) and Cooper (1990).

The Kalahari craton comprises three main parts: (1) in the east, the Archean Kaapvaal and Zimbabwe cratons, with intervening Limpopo belt; (2) in the west and south, the early Proterozoic Magondi and Kheis belts, mid-Proterozoic Namaqua-Natal belt with Koras-Sinclair-Ghanzi rift system; and (3) at the western margin, the small Nama basin.

Central Africa comprises a ring of ancient cratons surrounding the Congo basin. In clockwise succession from the south: the very large Kasai-Angolan composite, Chaillu, Gabon, Bouca, Bomu-Kibalian, Tanzania and Zambian. Proterozoic fold belts adjoining Tanzania craton in the east are Ubendian belt on the southwest, Usagaran belt on the south and Ruwenzori belt on the north. On the west side of Congo basin, lies West Congo belt. On the east side of the basin, Kibaran and Irumide belts lie respectively between and south of the Kasai and Tanzania-Zambia massifs.

Northwest Africa comprises (1) the West African craton with large central Taoudeni basin and smaller Volta basin to the east; (2) the smaller Tuareg and Benin Nigeria shields; both enclosed in (3) Pharusian-dahomeyan mobile belt. The West African craton contains Man shield in the south and Reguibat shield in the north.

The basement rock of Northeast Africa and Arabia is exposed in (1) the easternmost Arabain-Nubian (Egypt-Sudan) shield; (2) farther west , as isolated inliers – Uweinat, Tibesti, Tchad, Kordofan and Nuba mountains and (3) further south they merge with basement rocks of Central Africa.

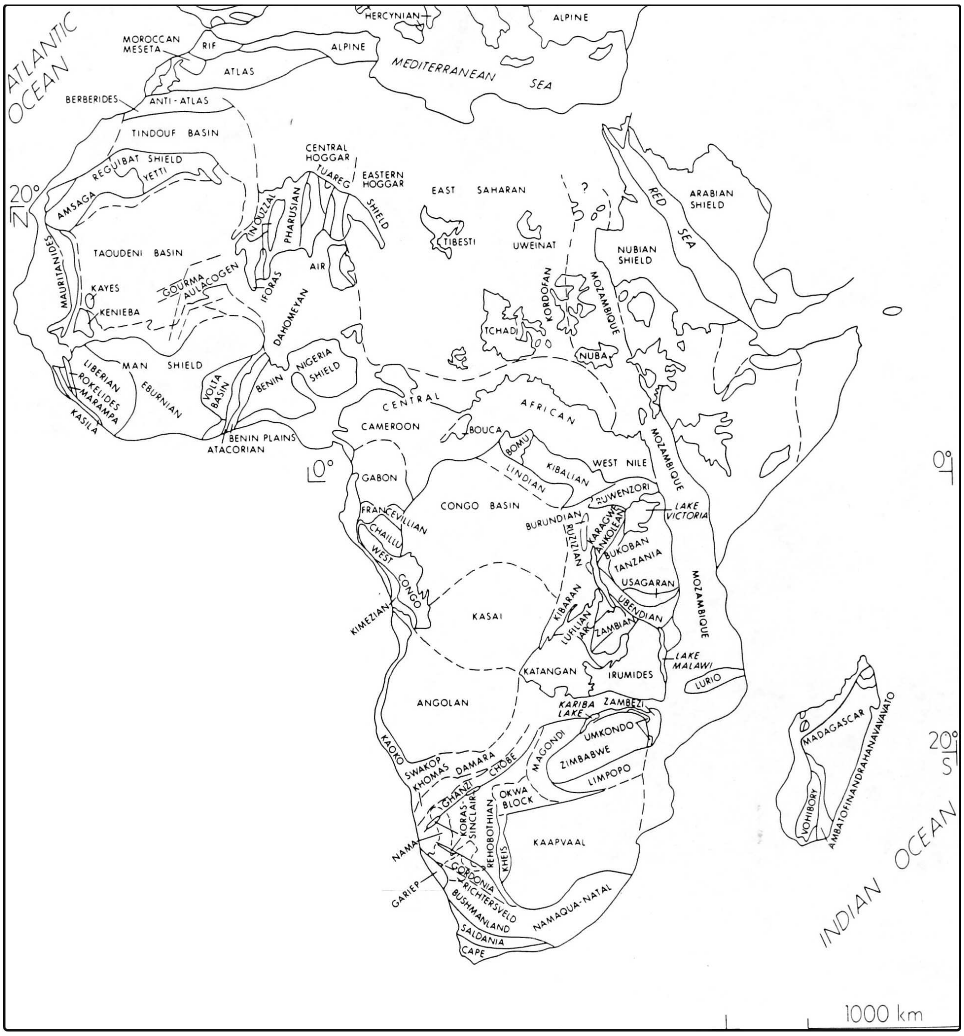

Fig. 2.7. Tectonic map of African craton (from Goodwin, 1991; after Saggerson, 1978).

2.2.8 Indian craton

Seven major tectonic regions, as shown in Figure (2.8) form the Indian craton. The Western Dharwar domain, the Eastern Dharwar domain, and Granulite domain dominate the south Indian regions. The major cratons are Bhandara craton, Chotanagpur-Singhbhum craton and Aravalli domain. The Eastern Ghats belt lies along the eastern coast of Indian peninsula. Numerous sedimentary basins include the Cuddapah in the southeast, small Chattisgarh in the northeast and very large Vindhyan in the north-centre. The island of Sri Lanka to the south is considered to represent an extension of southern India. Key references are Radhakrishna (1983), Taylor et al. (1984), Naqvi and Rogers (1987) and Moorbath and Taylor (1988).

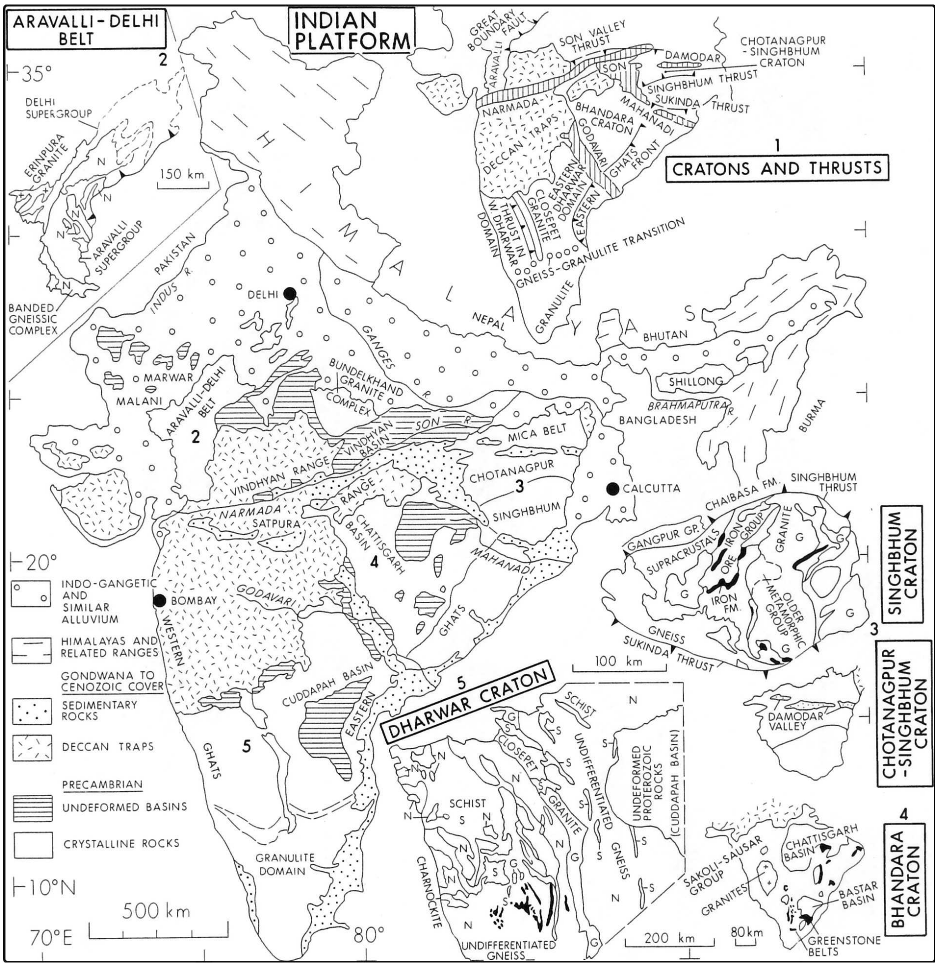

Fig. 2.8. Tectonic map of Indian craton (from Goodwin, 1991; after Naqvi and Rogers, 1987).

2.2.9 Australian craton

Precambrian rocks are divided into basement subprovinces and craton cover. Rutland (1981) recognizes three major basement subprovinces (Fig. 2.9): (1) Archean, mainly in the west, incorporating the Pilbara, Yilgarn and Kimberley provinces; (2) older Proterozoic, mainly in the central parts, incorporating the North Australian, Gascoyne and Gawler (-Nullarbor) provinces; (3) younger Proterozoic, in the south-central part incorporating the Musgrave-Fraser province which in part lies in the Amadeus transverse zone of the central Australian mobile belt.

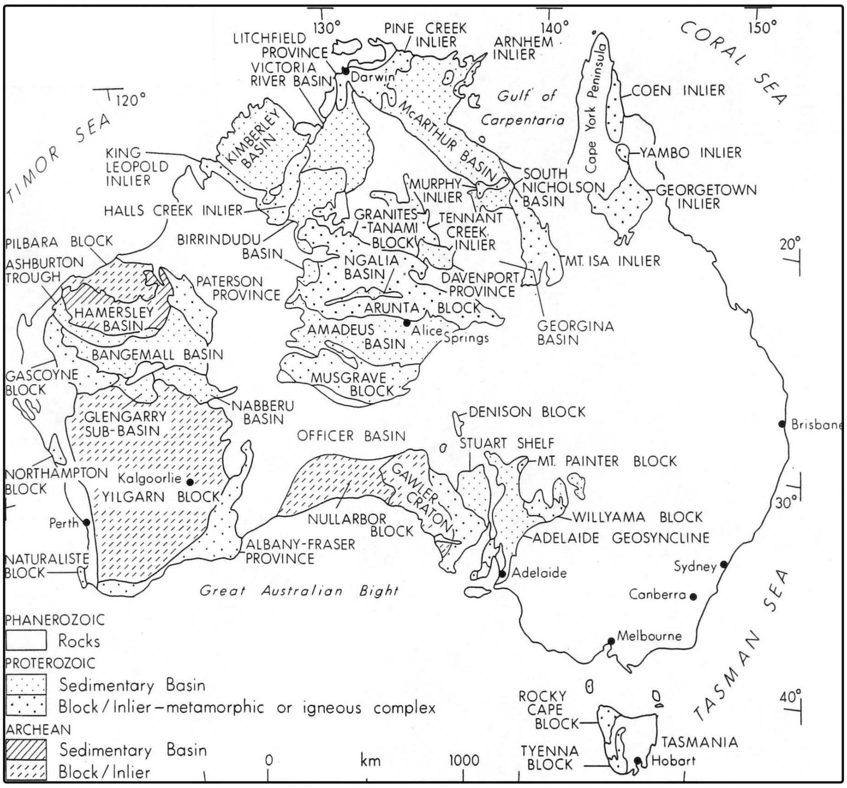

Fig. 2.9. Tectonic map of Australian craton (from Goodwin, 1991; after Wyborn, 1988).

2.2.10. Antarctic craton

Archean outcrops are present in Enderby Land and western Kemp land, the Prince Charles Mountains and Dronning Maud Land as shown in Figure (2.10). Detailed studies are available from Windmill Islands, Bunger hills, Vestfold Hills and in some specific location including Napier Complex and Rayner Complex in Enderby Land and Lutzow – Holm Bay (James and Tingey, 1983).

2.3 Oceanic crust

The oceanic crust is generally divided into three layers (Keary and Vine, 1990). Layer 1, 0-1 km thick, is sediment. Layer 2, the basement layer, is between 0.7 and 2.0 km thick and is made up of basalts. Layer 2 is subdivided into an upper portion of extruded basalt, layer 2A, and a lower portion of basalt, massively intruded by dikes, layer 2B. Layer 3 is gabbroic, with an average thickness of about 5 km. White et al. (1992) provided an accurate estimate of thickness of layer 2, (2.11 ± 0.55 km) and (4.97 ± 0.90 km) for layer 3. In the present work, the above simple 3-layered model by White et al. (1992) is used for modelling oceanic crust, of which the top sedimentary layer is considered non-magnetic.

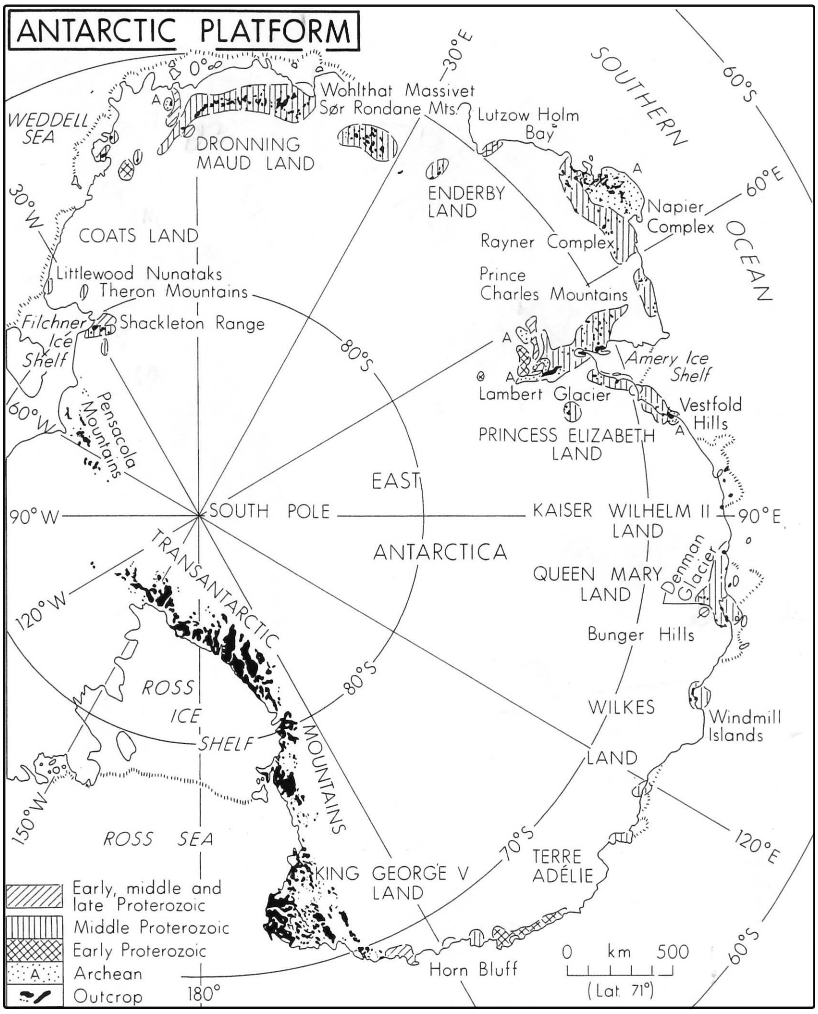

Fig. 2.10. Tectonic map of Antarctica craton (from Goodwin, 1991; after James and Tingey, 1983).

2.3.1 Oceanic plateaus

There are obviously anomalous features, showing up as strong oceanic magnetic anomalies which are caused by oceanic plateaus. Oceanic plateaus are the most puzzling of all the anomalies on the globe. The geology of the plateaus is poorly known and often there is a controversy about the origin of these plateaus, which cover almost 10% of the oceanic floor. Combining the information available from the Oceanic Deep Drilling Program (ODP), seismic constraints, and further literature (Carlson et al., 1980; Nur and Ben-Avraham, 1982), these anomalous features are represented in our model by 3 layers. layer (1)-basalts and dikes; layer (2)- gabbro; and layer (3) is largely inferred to be either ophiolites or serpentinised ultramafic (peridotites) or olivine rich gabbro. The plateaus, especially in the southern hemisphere, are significant as they can reveal the dynamics of Gondwana dispersion (Antoine and Moyes, 1992; Reeves and de Wit, 2000). It is therefore important for us to model these features accurately, based on their structure. Again, induced magnetisation is considered as the only source causing the magnetic anomalies over the oceanic plateaus. This turns out to be sufficient even though most workers have included remanence in modelling oceanic plateaus.

2.4 Continental and Island arcs

Arc systems occur above active subduction zones and are subdivided into island-arcs and continental-margin arcs. Island-arcs are chains of volcanic islands formed on oceanic crust such as Mariana, Kermadec and Lesser Antilles arcs. Continental-margin arcs are produced above subduction zones that extend beneath continental margins, such as the Japan and Andean arcs. Some arcs, like the Aleutian Islands, continue from continental margins into oceanic crust. These regions are marked in dark blue colour in the world geological map (CGMW, 2000) in Figure (5.1a). However, there are other regions also marked in blue in the world map, which are the continuations of continents into the oceans and are called continental margin. These margins should have the same geology as on the continental area of the same region. They have, however, not been delineated from the arcs due to the immensity of work that this would require. For our model, the entire region marked in dark blue has therefore been assumed to have the same structure. Arcs are composed dominantly of young volcanic and plutonic rocks and derivative sediments. The upper crustal layer consists of granite and granodiorites while the lower crustal layer is dominantly of quartz diorite (Condie, 1989). This is largely inferred from seismic investigations. Maximum susceptibility values of (0.056 SI units) for the upper crust and (0.0127 SI) for the lower crust (following Hahn et al.,1984) are used in the present modelling.

2.5 Phanerozoic cover

The Mesozoic-Cenozoic orogenic belts are similar in size and geologic character to Paleozoic orogenic belts. However, the former are tectonically less stable than the latter. They are composed of a variety of rock types (Condie, 1989). The surface rock types are typical continental types consisting of sedimentary rocks, volcanic and plutonic rocks. In most of the regions of the earth, this younger crust overlies the Precambrian basement. The Precambrian basement can be either Archean or Proterozoic in age. In our modelling, the Phanerozoic units are assigned a susceptibility value of 0.01 SI, which is the average of typical young continental rock types. For the lower crust below this young cover an average susceptibility value (0.016 SI) for all the lower Proterozoic units is found to be adequate. However, the assumption of basement being lower Proterozoic in age below the Phanerozoic cover is changed in some regions of the world where the basement is known to be of older age.

2.6 Modelling

Our first interest is to generate an *initial model* based on the information of the rock types exposed, their magnetic susceptibility value and the known stratigraphy for that region. The input data required for modelling is discussed subsequently.

- World geological map by CGMW (2000).
- Tectonic map of the continents (Goodwin, 1991 and others)
- The global seismic model (3SMAC, CRUST2.1).
- Volume susceptibility value for all the known rock types (compiled from standard tables).

The World geological map shows the distribution of geology based on their ages. However, it does not provide any detail about the rock types known in a particular geological region. This gap is filled in with the information of rock types from the compilation of various tectonic maps. Tectonic maps restricted to Precambrian geology also inform about the geology of the basement overlain by the younger sediments based on the information of rock types exposed locally. The detailed Precambrian geology is discussed by Goodwin (1991, 1996) and is outlined briefly in Section 2.1. Combining the geological and tectonic maps helps us to formulate a first order *initial model*. The global seismic model is incorporated to use the estimated thickness of the crust for a region. Two popular global seismic models are 3SMAC (Nataf and Ricard, 1996) and CRUST2.1 which is a refined version of the earlier model CRUST5.1 by Mooney et al. (1998). Both models are used initially to ascertain their consistency as a good crustal model for all the regions of the world. For this it is essential to compute the crustal anomalies with each of the models and compare it with the corresponding observed one and select the best seismic model for a particular region and reject the other. This analysis is done and is explained in Chapter 4. The last of the input is the standard volume susceptibility chart taken from standard sources (Clark and Emmerson, 1991; Hunt et al., 1995). Each of these inputs is combined to formulate an *initial model*, which is discussed in the following subsections.

2.6.1 Vertically Integrated Susceptibility model

The crustal layer is thin in comparison to the altitude of satellites. Hence satellite magnetic maps are incapable of resolving the parameters viz., depth and susceptibility distribution individually, the two parameters responsible for the crustal anomalies. Hence only bulk susceptibilities, susceptibility multiplied by the thickness, at each point of the globe, can be inferred, irrespective of the position of the magnetic body in that vertical column. The sources to the magnetic anomalies would be the variation of these integrated susceptibilities across the globe which is termed ‘Vertically Integrated Susceptibility’ or (VIS).

The steps involved in deriving the initial VIS model are as follows:

1. Consider all the known rock types for a particular geological region as reported in the literature and perform a mathematical average using their maximum volume susceptibility value from the standard charts (Appendix I). The actual susceptibility of all the rock types is assumed to be some percentage of this maximum value, which is considered to be a constant for all the geological provinces of the world.
2. The next step is to generate the vertically integrated susceptibility (VIS) model. This requires the thickness information for each geological stratum within a vertical column and is generally known from the stratigraphy of that region as shown in Fig (2.11). The thickness is multiplied with the bulk susceptibility of that stratum. Integrating the susceptibility times thickness information for various layers in a vertical column, provides the VIS value for that region. Generally the stratigraphy information is not available for the lower crust, except for some regions that are exposed (Fountain and Salisbury, 1981). In regions devoid of any stratigraphical information, the bulk susceptibility is multiplied with the crustal thickness of the upper crust of the global seismic model.
3. An important parameter in the *initial model* is to consider the susceptibility value for the lower crust to be a factor multiplied with the bulk susceptibility of the upper crust. This factor is assumed following the difference in the iron oxide content in the average composition of the upper and the lower crust (Taylor and McLennan, 1985). The average composition of iron oxide in upper and lower crust of the earth is shown in Appendix II. This gives a factor of 1.2 for the Archeans and 1.6 for the post Archeans units.
4. Each such geological province is modelled following the steps 1 to 3 and each such VIS value is knit together to generate the global VIS model, which serves as an initial VIS model. Modelling is done on the GIS ArcInfo 8.1 craton.

The computation of the maximum susceptibility value for the Gabon craton is shown here as an example. The rock types exposed at different regions within this Archean craton, central Africa (Goodwin, 1991) along with the basement rock types are reproduced below and their maximum susceptibility value from the standard chart (Appendix I) is shown in brackets.

Rock types: granodiorite(0.062), migmatite gneiss(0.025), granitoids(0.05)
Bandas Belt: basalt(0.18), gneiss rhyolite(0.038), quartzite(0.0044), banded iron formations(0.25), granitoid gneiss(0.025), granodiorite(0.062)
Dekoa region: mafic volcanic rock(0.12), banded iron formations(0.25), granitoid gneiss (0.025)

$$\text{Average susceptibility value of Gabon craton} = (0.062 + 0.025 + 0.05 + 0.18 + 0.038 + 0.0044 + 0.25 + 0.025 + 0.062 + 0.12 + 0.25 + 0.025) / 12 = 0.0896$$

This susceptibility value is the average maximum susceptibility value for the Gabon craton. The value is assigned to the polygon representing Gabon craton on the world geological map. Such computations were done for all the Precambrian region of the world and are compiled to derive the *initial model*. The parameters involved in generating the *initial model* are shown in the Appendix (III-XII). Table (2.1) describes the parameters common to all the continents.

2.6.2 Geographical Information System method

A Geographical Information System (GIS) is particularly convenient whenever more than one set of information for a particular region is to be combined. The utility of GIS method lies in its ability to perform various visual and statistical analyses between the different layers or stacks to compute new maps as desired. The present work exploits these capabilities of a GIS package to compute the global VIS model. The basic methodology is as follows:

The global seismic model is available as 2^0 X 2^0 grid and is taken as a layer in the GIS database. This grid map is considered as a raster image on the GIS craton. The bulk susceptibility value assigned to a geological region, as computed above in steps (1) in section (2.2.1), is a polygon on the geological world map (Fig. 2.11). This polygonal map is called a coverage map. All the polygons are assigned a susceptibility value similarly, and the world coverage map is converted to a grid map of 2^0 X 2^0. Based on the availability of geological stratigraphy of a region, susceptibility from the gridded world map is multiplied with the thickness from the seismic grid. The transformation from coverage to the grid format and the computation of VIS model is done using an algorithm developed for the purpose. The result is a global VIS model of resolution 2^0 X 2^0 as shown in Figure (2.12). This VIS grid map is then converted to an ascii formatted file on the GIS craton. This ascii formatted VIS model is fed as input in the modelling methods described in chapter (3), to compute the magnetic potential at the satellite altitude. Vertical component of the magnetic field is computed from spherical harmonic degrees 16-80 of the potential and compared with the corresponding vertical component of degrees 16-80 of the observed crustal field.

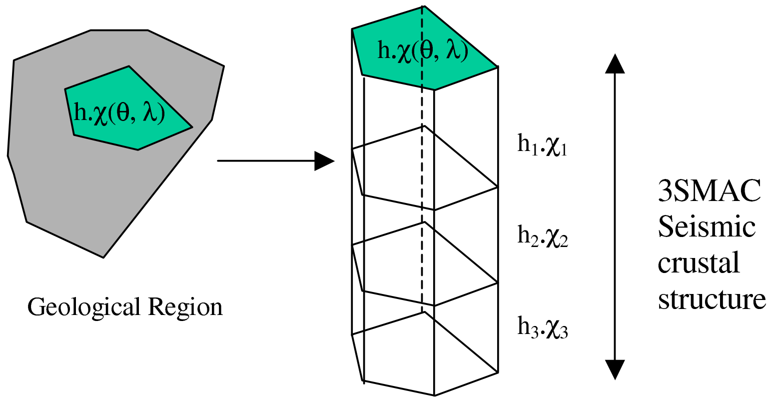

Fig. 2.11. Diagram shows a geological cross-section of a region, for which a VIS value is computed.

The parameters used in GIS based VIS modelling are shown in Table (2.1). The parameters used to represent a geological region are shown in Appendix (III-XI), one for each craton and Appendix (XII) for the oceans.

.ag : 0.55	: Percent of Maximum susceptibility value for Archean rocks
.wg : 0.55	: Percent of Maximum susceptibility value for post-Archean rocks
.cg : 0.55	: Percent of Maximum susceptibility value for Continental and Island arcs
.xa : 1.2	: The lower crust value is *xa* times the upper crust, if rock type is Archean
.xe : 1.6	: The lower crust value is *xe* times the upper crust, if rock type is Early Proterozoic.
.xm : 1.6	: The lower crust value is *xm* times the upper crust, if rock type is Mid Proterozoic.
.xl : 1.6	: The lower crust value is *xl* times the upper crust, if rock type is Lower Proterozoic.

Table 2.1. The parameters used for VIS modelling.

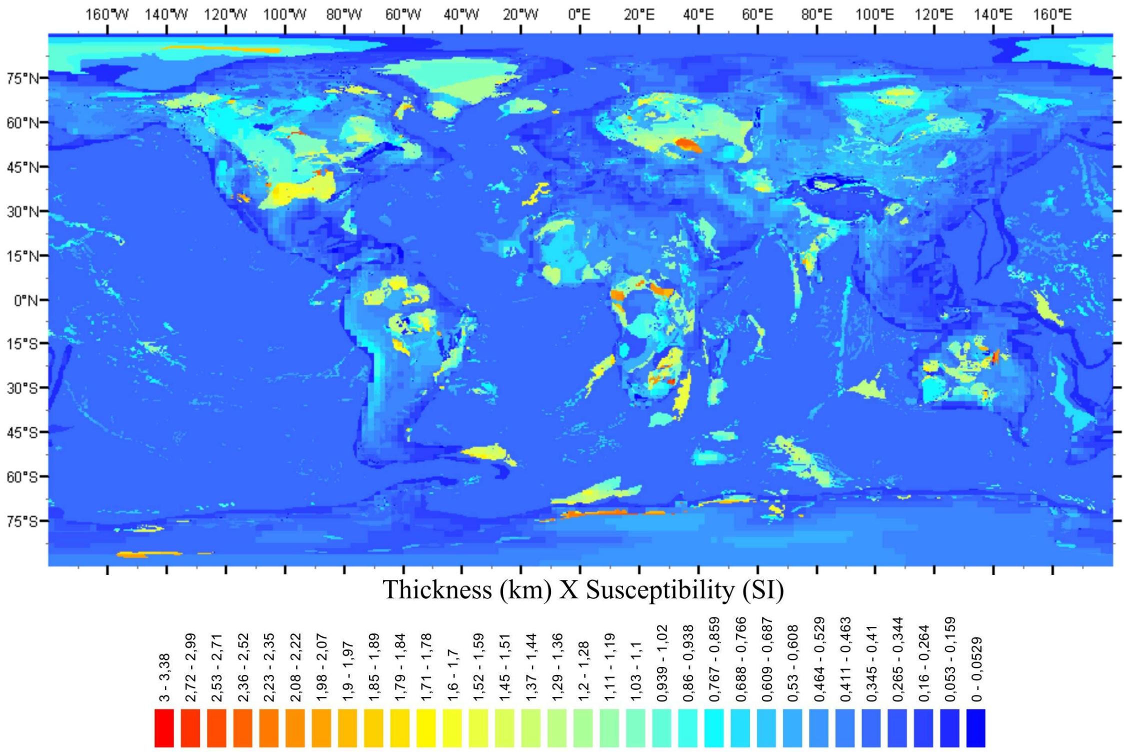

Fig. 2.12. *Initial model* Vertically Integrated Susceptibility (VIS) map of the world.

In our modelling procedure, it was desired to find a factor, which relates the maximum susceptibility to the actual susceptibility. This factor was to be assumed constant for all the geological regions and hence there was a need for a factor, which should be derived statistically. This factor is called *.ag*, *.wg* and *.cg* in Table 2.1.

To find the optimum factor, Gauss coefficients of *initial model* were computed for various factors: 0.0, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 1.0, times maximum susceptibility. These predicted Gauss coefficients are compared with the actual coefficients of the observed magnetic potential to compute the misfit. Misfit is computed using the following definition:

$$\text{Misfit} = \sum_{l=16}^{30} \frac{(l+1)}{(2l+1)l} \sum_{-l}^{+l} \left(g_{l\ observed}^{m} - g_{l\ predicted}^{m} \right)^2 \qquad (2.1)$$

Where, g_l^m are Gauss coefficients of the magnetic potential for the observed and the predicted magnetic potential. Misfit is computed using only degrees 16-30 which are particularly well predicted by the crustal model. The misfit curve is shown in Figure (2.13). The curve shows a pronounced minimum. The shaded region indicates the range of abscissa values for which the curve is almost flat. This range gives the admissible values that can be used in our modelling keeping the misfit minimal. We decided to take the value 0.55 for the parameters *.ag*, *.wg* and *.cg* in all the derivation of VIS models. This value is found to be the optimum value when modelling individual anomalies.

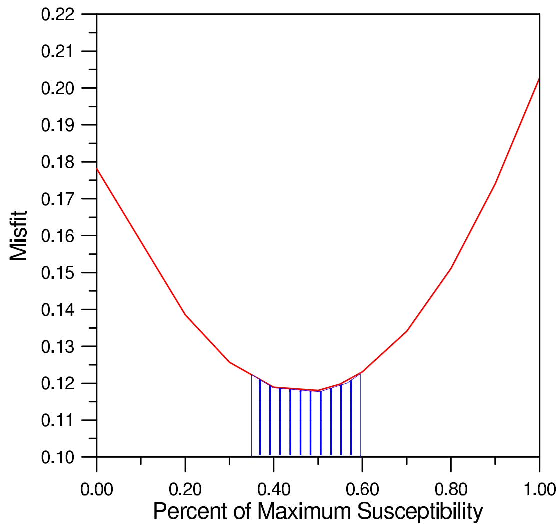

Fig. 2.13. The curve shows the admissible values for the factor of maximum susceptibility for a minimum misfit.

.xa, *.xe*, *.xm*, *.xl* parameters are values assumed based on the study of the percentage of iron oxides in the upper and the lower crust (Taylor and McLennan, 1985, Appendix II) of the Archean and post-Archean (Proterozoic and Phanerozoic) rocks, respectively.

2.7 Flowchart showing the present work

The entire sequence of methodology starting from the derivation of VIS model to the computation of anomaly maps is shown in Figure (2.14) in the form of a flow chart. The flow diagram shows that the modelling procedure starts with the non-satellite information viz., geology, crustal thickness, susceptibility values, and computation of the vertically integrated susceptibility. Following the modelling methods to be described in chapter 3, the *initial model* vertical field magnetic anomaly map for degrees 16-80 is computed. This predicted map is then compared with the CHAMP observed vertical field magnetic anomaly map. The mismatch of the anomalies in the two maps is again studied and the geology of the region is modified and the VIS value is recomputed. *First iteration* map is computed using this new VIS model following the same modelling steps. At present we have only modified the VIS model once for a *first iteration* model, but subsequent work in future would invoke further modifications of the model.

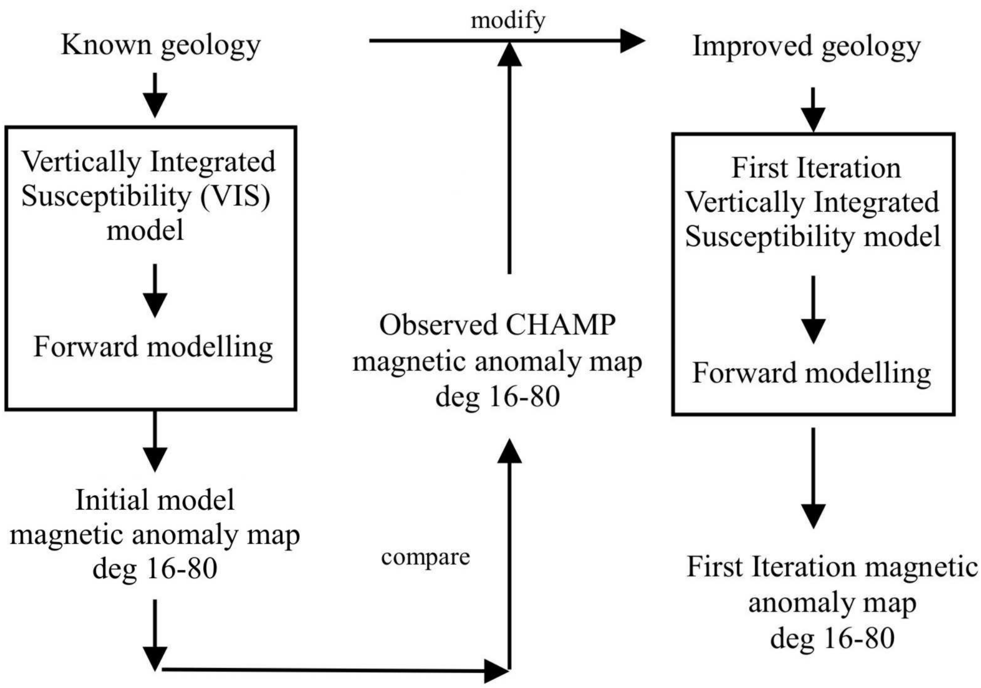

Fig. 2.14. Flowchart showing the modelling steps involved in the present work.